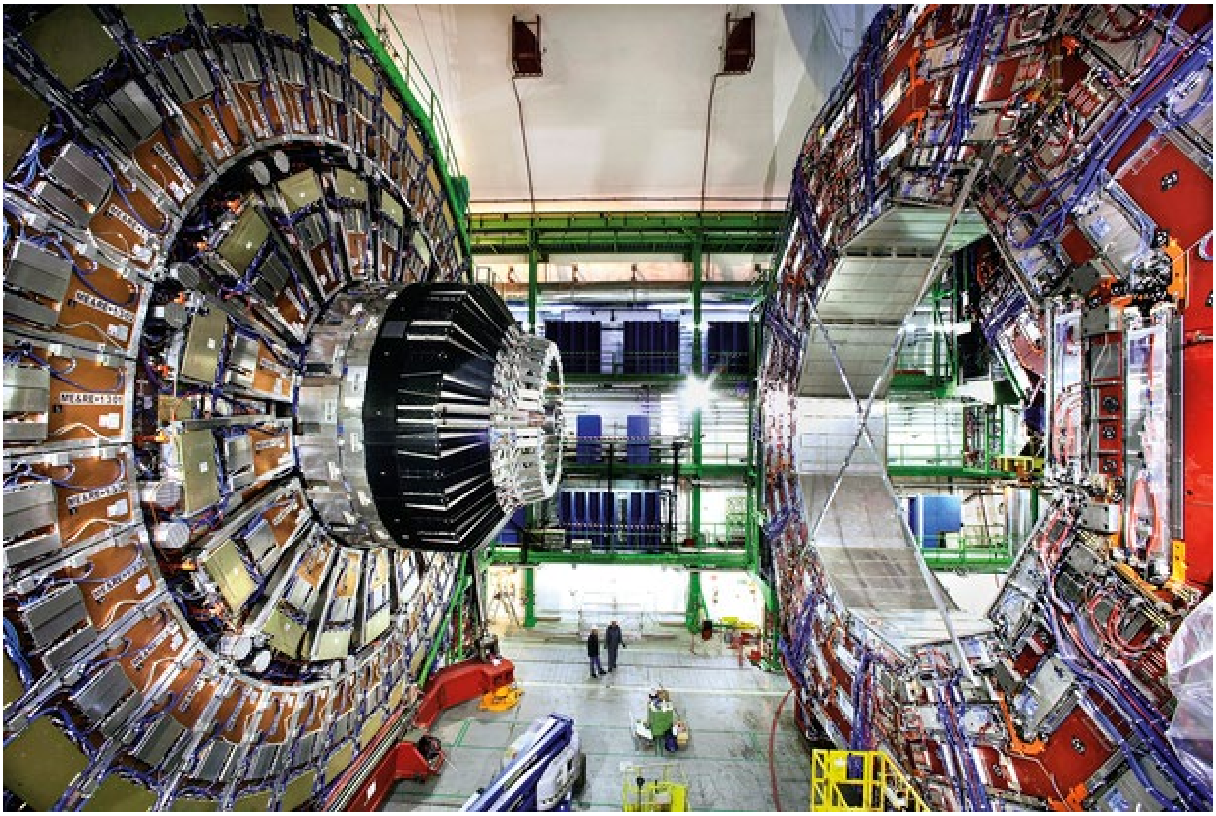
Evaluation of the benefits that the UK has derived from CERN

Evidence Document

August 2020



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1 Introduction

The UK's Science and Technology Facilities Council (STFC) commissioned Technopolis to undertake an **evaluation of the benefits that the UK has derived from CERN** (the European Organisation for Nuclear Research). The aim was to capture, demonstrate and measure the range of scientific, economic and social impacts emerging over the past decade, considering both direct UK involvement and use, as well as any wider influences of CERN on the UK. It was also to result in a monitoring and evaluation framework, which would build on the approach and tools developed through the current study, as well as any lessons learnt, in order to support the assessment of benefits and impacts in future.

This Evidence Document presents the full results from the evaluation. It is an accompaniment to the Main Report of the evaluation, which summarises the key findings and conclusions from the study.

The remainder of this document is structured as follows:

- **Section 2** – provides a brief overview of the **study scope and objectives**
- **Section 3** – outlines the **approach** taken to the evaluation and the main methods employed
- **Section 4** – then provides a short narrative piece on **CERN, its facilities and activities**
- **Section 5** – introduces the overall **framework** for the study, explaining how UK investment and involvement in CERN is intended to generate beneficial outputs and outcomes, which can lead to wider and longer-term socio-economic impacts. We then classify a series of **main areas of (UK) impact**, which form the overarching structure for the subsequent presentation of findings
- **Sections 6 - 9** – then present the **findings** from the evaluation, organised against the main areas of impact identified. We explore the benefits to the UK in terms of Research, Innovation, Skills and Science Diplomacy, drawing on evidence from desk research, surveys, bibliometrics and interviews, while also presenting illustrative case studies that explore particular examples in more depth
- **Section 10** - provides an overall **summary of monetised benefits**, drawing on results presented in previous sections, as well as additional approaches to monetising the value of benefits to the UK
- **Section 11** – presents a proposed **monitoring and evaluation framework** that STFC might use as the basis for tracking benefits and impacts from the UK's engagement with CERN in future

An **Appendix** then contains a series of supporting documents, which are drawn upon and referenced in the main body of the document. This includes:

A. Full details of the main impacts and impact pathways identified to structure the evaluation

B. A list of the stakeholders consulted through interview during the study

C. Full results from surveys of UK scientists and engineers and of UK-based CERN-suppliers

D. Full results of the bibliometric analyses

E. Full case studies, examining particular achievements, benefits and impacts in more depth

F. Additional details of calculations employed for the monetisation of benefits

2 Study scope and objectives

The study set out to evaluate the benefits that the UK has derived from CERN and to develop an evaluation framework for capturing benefits in the future. More specifically, the objectives were to:

- Capture, demonstrate and measure the range of impacts (scientific, technological, economic, social) that have emerged from the UK's investment in and co-development of CERN. This includes gathering quantitative and qualitative evidence to build a picture of outputs and impacts from:
  - Direct UK involvement and use, by UK researchers, staff, contractors, trainees, schools, etc.
  - Wider influences of CERN on the UK, e.g. through access to new knowledge, public engagement and adoption of CERN technology, as well as any global benefits in which the UK shares
- Develop a future monitoring and evaluation framework suitable for capturing and measuring the impacts and benefits of CERN to the UK.

The primary audiences for the evidence obtained and the conclusions drawn through the evaluation include the UK Government (BEIS, the Treasury and other departments), UKRI and STFC. However, the report will also be of interest to a wider group of stakeholders, including other research councils, science and engineering communities, and the public. More generally, the study is expected to provide a rich source of data and information that could be re-used by STFC for other purposes. The (future) monitoring and evaluation framework will also be of interest to government, but is targeted more towards STFC, as it is intended to be a practicable basis for future planning and activities.

In terms of scope, the evaluation focuses on the benefits of CERN from the UK's direct involvement, but also where CERN has had a significant influence on the UK more generally, including as part of global benefits. Evidence has mainly been sought relating to the benefits realised over the past ten years, although the evaluation was also asked to capture significant earlier achievements where appropriate.

3 Approach and methods

Following closely the initial specifications for the study, we employed a three-phase approach:

- An initial **scoping** and methodology phase was undertaken July-September 2018 and included an initial review of pre-existing evidence and a series of discussions with key stakeholders. These helped to better understand CERN's multi-faceted strands of activity, as well as to identify important areas of UK benefit that should be explored and captured in the study. The scoping activities also fed into the development of the framework, approach and tools for evidence collection. A scoping report marked the conclusion of this phase and provided the basis for the remainder of the study.
- An **evaluation** phase – including the main elements of evidence collection and analysis. The evaluation has employed a mixed-methods approach (see below), involving multiple strands of data collection and analysis that cut across the breadth of benefits and impacts identified. An interim report in February 2019 provided an update on progress and early findings from the evaluation. A draft final report in March 2019 then set out the full findings and analysis from the study.
- A **recommendation** phase – to develop a future monitoring and evaluation framework, along with lessons learned and recommendations for future assessment. This has been delivered as part of the final reporting and builds upon the tools and approaches employed during the current study.

The main methods employed during the study are briefly outlined below.

Various **documentation and data** were assembled by STFC and transferred to the evaluation team at the start of the study. This included monitoring data and pre-existing case material, alongside brochures, publications, previous studies and other material. This evidence base has been extended during the study through additional information and data highlighted during interviews or found through our own desk research – e.g. in the development of individual case studies. Evidence from these sources has fed in throughout this report – in introducing CERN, its facilities, capabilities and activities, in the discussion of impact pathways and in the evidencing of UK benefits. Many of the case studies also draw on pre-existing material and evidence, combined with further desk-research and consultation.

With STFC and Advisory Board support, a long list of 60+ stakeholders were identified for **interview**. This was extended during the study, as other contacts were identified. The purpose of the interviews was quite open to adapt to the knowledge and experience of the individual concerned. Conversations were instead guided by the impact pathways, with interviewees asked to identify areas they felt able to speak on. Questions then sought to explore: the accuracy and completeness of the impact framework; evidence and views of the extent of benefit derived by the UK; examples demonstrating particular benefits; and the availability of further information and evidence to support the study. In total, **64 interviews** were conducted. *(A list of all those consulted during the study is presented in Appendix B).*

Two online **questionnaire surveys** were launched in January 2019 - one addressed to UK scientists and engineers, the other to UK organisations that have provided goods/services for CERN. The surveys were closed at the end of February. Useable[1] responses were received from **262 UK scientists and engineers** and from **65 UK suppliers**. *(A full analysis of survey results is presented in Appendix C).*

A **bibliometric analysis** was undertaken by Science Metrix (Elsevier) to provide evidence against a number of the impact areas. The focus was on demonstrating the new knowledge being generated through CERN, and how the UK community has contributed to, made use of and benefited from this. However, the analysis also provides evidence relating to innovation benefits and to the discussion of impacts relating to science diplomacy. The analysis considers the past 20 years of publications, although the assessment of benefits looks specifically at the past 10 years. It also focuses particularly on the UK, but with comparisons also made with various other countries with different forms of CERN non-/membership. *(Full results of the bibliometrics analysis are presented in Appendix D).*

A series of **29 illustrative case studies** of major achievements, developments, benefits and impacts have been developed, based on existing material, desk research and evidence from a parallel programme of interviews. The cases (see below) were selected in consultation with the Advisory Board at the scoping stage. Each seeks to explore and exemplify a type of benefit that flows to the UK from CERN and support the quality of the overall story presented in the report. Brief summaries of each case are presented in the most relevant findings section *(while the full text of each case can then be found in Appendix E).*

Research 1. Higgs boson and completion of the SM 2. Trapping of antimatter and wider antimatter investigation 3. Quark Matter (Heavy Ions & Quark-Gluon Plasma) 4. The search for new physics beyond the SM 5. Development of crab cavities 6. GridPP Innovation 7. Geant series - simulations for space/radiotherapy 8. Linear proton accelerators & next gen radiotherapy 9. Gaseous detectors 10. Silicon detectors and ASICs 11. Medipix Collaboration 12. CMOS image sensors – enabling cryo-EM 13. Radiation-tolerant ASICs 14. Medical imaging technology (PET & scintillating crystals) 15. Field Programmable Gate Arrays	16. AWAKE and the potential of plasma wakefields 17. Oxford nanoSystems 18. Camstech 19. Croft Additive Manufacturing 20. CERN Cloud experiment & atmospheric aerosols 21. Arcade UK ltd 22. TG Engineering Ltd 23. HV Wooding 24. UHV Design ltd 25. Micron Semiconductor Ltd 26. Exception PCB 27. Stevenage Circuits Skills 28. CERN@School programme Science diplomacy 29. SESAME

[1] 'Useable responses' includes those who answered some of the questions, gave their consent for their answers to be used and (for suppliers) confirmed they had provided goods/services for CERN (directly to CERN, or through research groups/institutions).

4 CERN, its facilities and activities

CERN is a large, complex international organisation, with multiple strands of activity and engagement that have evolved over many decades. This section of the report therefore provides a short introduction to CERN, its main facilities and activities, highlighting key features and introducing some of the ways in which the UK (and others) are involved. This provides important background information for subsequent sections that then assess the UK benefits that flow from these various features and activities.

4.1 History and governance

The European Organisation for Nuclear Research (**CERN**), is an international research organisation that operates the world's largest physics laboratory. It is located on the Franco-Swiss border.

The **convention** establishing CERN in 1954 clearly laid down its main missions: "*The Organisation shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character… [It] shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.*" It also stated that CERN shall organise and sponsor international co-operation in research, promote contacts between scientists and interchange with other laboratories and institutes. This includes dissemination of information, and provision of advanced training for research workers.

CERN's main **missions** can therefore be summarised as follows:

Research	→	Seeking and finding answers to questions about the Universe
Technology	→	Advancing the frontiers of technology
Collaboration	→	Bringing nations together through science
Education	→	Training the scientists of tomorrow

CERN's highest authority is the CERN Council, composed of two delegates from each member state. CERN was one of Europe's first joint ventures, with 12 founding **members**, including the UK. Today, it has 23 member states[2], each of which contributes to the capital and operating costs of CERN's programmes and to its governance. In addition, CERN has various Associate Members[3] and observers.

CERN's **budget** (from agreed subscriptions based on national GDP[4]) covers the building, operation and maintenance of research infrastructure (e.g. the Large Hadron Collider), as well as the governance and administration of CERN. The construction, maintenance, upgrade and operation of the experiments ("the experimental programme") and the computing infrastructure is then mainly supported through funding from agencies of participating countries (in the UK, mainly through the STFC Core Programme).

The Council appoints the Director General, usually for five years, to manage CERN. They are currently assisted by four directors, for Accelerators & Technology, Research & Computing, Finance & Human Resources, and International Relations. There are also currently 10 **departments**: beams; engineering; finance and admin; experimental physics; HR; industry, procurement and knowledge transfer; information technology; site management and buildings; technology; and theoretical physics.

Currently, the laboratory **employs** around 2,500 people directly, who are involved in the operation of the facilities, the construction of new accelerators, and in supporting data preparation, analysis and interpretation. More than 13,000 researchers from over 75 countries (and 100+ nationalities) also

[2] Founding members: Belgium, Denmark, France, Federal Republic of Germany, Greece, Italy, Netherlands, Norway, Sweden, Switzerland, the UK and Yugoslavia. Additional members: Austria (1959), Spain (1961-1969, re-joined 1983), Portugal (1985), Finland (1991), Poland (1991), Czechoslovak Republic (1992), Hungary (1992), Bulgaria (1999), Israel (2014), Romania (2016) and Serbia (2019). The Czech Republic and Slovak Republic re-joined after independence in 1993. Yugoslavia left in 1961.

[3] Associate members: Cyprus, Slovenia, India, Lithuania, Pakistan, Turkey and the Ukraine (Cyprus and Slovenia are in the pre-stage to membership). Associate Members pay a reduced contribution and enjoy benefits that are reduced accordingly.

[4] The scale of contributions by each member state is calculated on the arithmetic average of Net National Income and average exchange rates over three years. In the UK, the CERN subscription is covered by governmental treaty.

conduct research at CERN[5] (January 2019 figures), including approximately 70% of the world's particle physicists[6], along with large numbers of nuclear physicists, astrophysicists and others. The Laboratory also hosts several hundred students, fellows, apprentices and scientists from other institutions.

⇨ Further analysis of the opportunities afforded to UK research are presented in Section 6.2.

The UK has been strongly and centrally involved in CERN throughout its history and is currently the second highest contributor to its budget, with a 2019 contribution (based on GDP) of CHF 184m (c.£144m), or 16.1% of the total.[7] Over the past decade, the UK has contributed £112m per year (on average) through subscriptions[8], which are coordinated and managed by the STFC. Through this subscription the UK secures a number of benefits. These include:

- Access for UK physicists/engineers to key research infrastructure and collaboration networks
- The opportunity for UK companies to bid for contracts, including those requiring a high intellectual and technical capacity, those that are non-technical but require high levels of expertise (e.g. financial services) and contracts for more standard supplies and services (e.g. cabling)
- Training and work opportunities, e.g. long-term attachments for students from UK universities; visit programmes for UK schools and teachers; and apprenticeships, secondments and fellow's schemes

It is important to note that CERN is not a user facility in the way that many other research infrastructures are (e.g. the ILL or ESRF). Rather, the UK is a partner in the co-development of the CERN facility and its programmes of work. CERN is also **the UK's national laboratory** for particle physics and the UK has played a key role in its strategy and development, while UK personnel have been involved in all the major experiments and discoveries. When the report talks about CERN's activities and achievements, therefore, these are really the results of cross-country collaborative efforts and endeavours.

In addition to the annual subscription to cover CERN's running costs, STFC's **Core Programme** also funds UK-based researchers to enable their participation in the experimental programmes hosted by CERN. Between 2008 and 2017, STFC made 608 awards relating to CERN, with a total value of £397m[9]. Other Research Councils and funders also award funds relating to CERN, but on a smaller scale.

4.2 Facilities and capabilities

CERN is the world's leading laboratory for physics. The main focus of its research programme is particle physics, which investigates the smallest detectable particles (e.g. quarks, Higgs bosons, tau leptons) and the fundamental interactions necessary to explain their behaviour. However, the physics programme at the laboratory is much broader, ranging from nuclear to high-energy physics, from studies of antimatter to the possible effects of cosmic rays on clouds.

Further analysis of the scientific progress enabled by CERN is presented in Section 6.1.

To carry out this research, physicists use three main types of tools[10]: Accelerators – powerful machines that accelerate charged particles to extremely high energies, causing them to smash into one another or fixed targets; Detectors - high-precision instruments that record data on the particles created during

[5] Within the context of this report, the term 'researchers' is used to refer to the academics accessing and using CERN facilities and data across a number of fields, including physics, engineering and computing

[6] The Impact of CERN (CERN, 2016). Available online: https://cds.cern.ch/record/2256277

[7] The other largest contributors (2019, CHF) were Germany (236M), France (160M) and Italy (118M).

[8] Average annual UK subscription, 2009 – 2018. Nominal values, converted from CHF to GBP based on yearly average exchange rates (https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/)

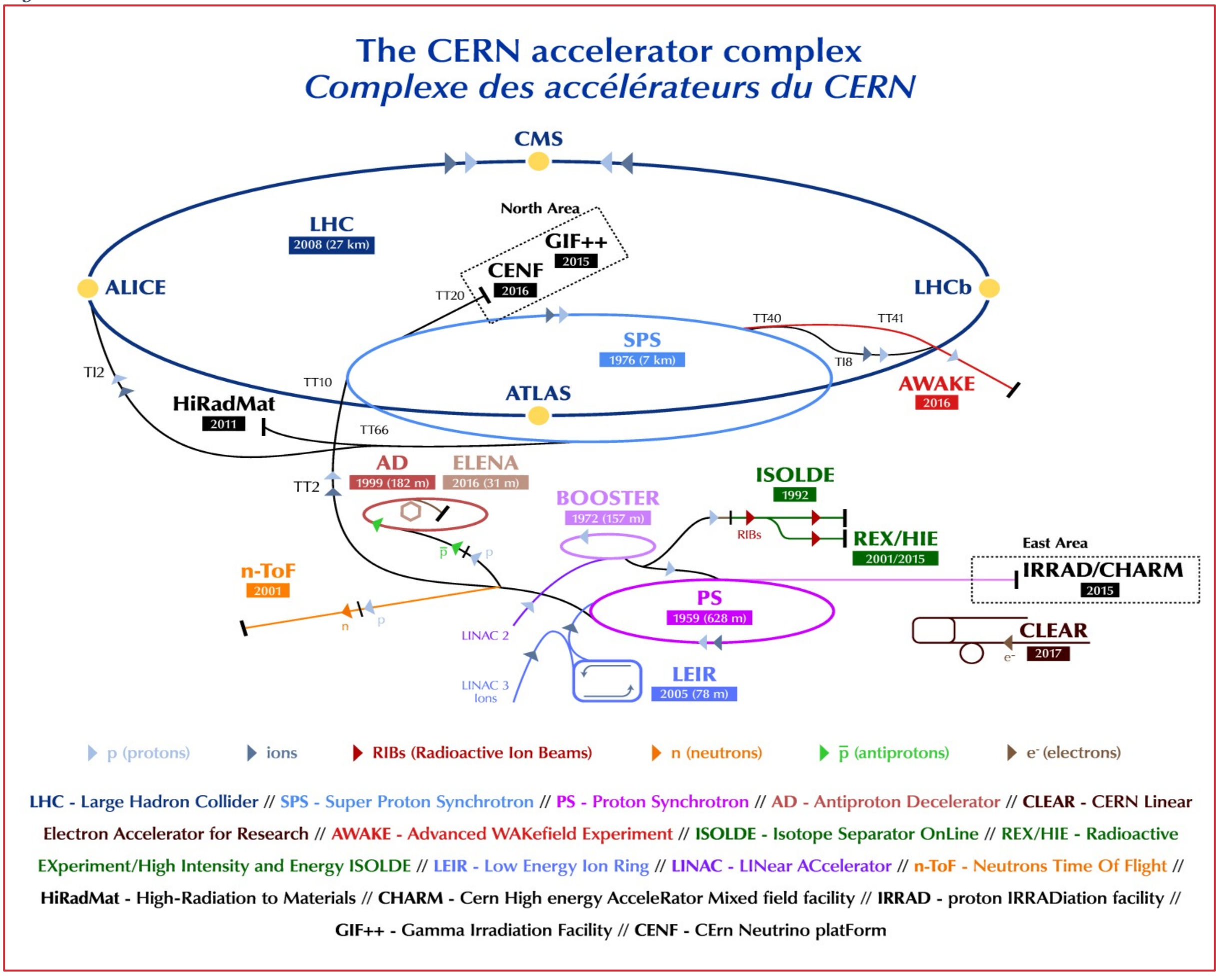
[9] Grants awarded by STFC, with an award start date 2008-2017, identified through Gateway to Research Portal. The data was extracted in June 2018 and only included partial information for 2018 awards. The ten year period 2008-2017 has therefore been used. The grants awarded in this period also include funding from the consolidated grants programme, where funds are given to university departments for three years per research programme. This would include CERN and non-CERN related projects. Experimental maintenance and operation (M&O) costs are included in consolidated grants, however some M&O costs, related to CERN, are not paid through the consolidated grants.

[10] https://voisins.cern/en/en-bref/what-equipment-does-cern-use

collisions; and <u>Computer hardware/software</u> - sophisticated computing technology that collates, stores, and analyses the data recorded by the detectors. Each is introduced below.

The accelerator complex at CERN (see Figure 1 and text box after) is a succession of machines that accelerate charged particles to increasingly higher energies, with each boosting the energy of a beam, before injecting it into the next in sequence. Not all beams 'end up' in the most well-known Large Hadron Collider (LHC) - most of the preceding accelerators also have their own experimental halls, where beams are used for experiments that can be conducted at lower energies.

Figure 1 CERN accelerators and detectors



Source: http://cds.cern.ch/record/2636343

<u>The Accelerator Complex at CERN</u>

For **proton beams**, the first accelerator in the chain is Linac 2, which accelerates protons to the energy of 50 megaelectronvolts (1 MeV = 1 million eV).[11] The beam is then injected into the Proton Synchrotron (PS) Booster, which accelerates the protons to 1.4 gigaelectronvolts (1 GeV = 1,000 MeV), followed by the PS, which pushes the beam to 25 GeV. Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV. The last element in this chain is the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator (and also the largest machine in the world), where beams reach the record energy of 6.5 teraelectronvolts per beam (1 TeV = 1,000 GeV). Within the LHC, proton beams circulate in opposite directions until they have reached the required

[11] 1 tera = 1000 gigavolts and 1 giga = 1000 megavolts

energy and are brought into collision, inside one of the four detectors (see next box below). The total energy at the collision point is equal to 13 TeV.

For **ion beams**, the first accelerator is Linac 3, which accelerates and strips lead ions of their electrons. They are then injected into the Low Energy Ion Ring (LEIR), the PS, the SPS and, finally, the LHC.

Not all accelerators increase a particle's speed. The Antiproton Decelerator (AD) instead slows down **antiprotons**, which are created when a proton beam is fired into a block of metal. These low-energy antiprotons can be used for studies of antimatter[12], and the "creation" of antiatoms. Since 2010, the AD experiments have published numerous measurements of antimatter characteristics, comparing them to those of matter, while in 2012, the first measurement of the antihydrogen spectrum was published.

The Isotope mass Separator On-Line facility (ISOLDE) provides beams of **radioactive nuclides**. A high-energy proton beam is directed into thick targets, yielding a large variety of atomic fragments. These nuclei are ionised and separated according to their mass, forming a low-energy radioactive beam. This can be further accelerated, allowing studies on a variety of nuclear reactions.

The neutron time-of-flight facility, nTOF, is a pulsed **neutron** source coupled to a 200-metre flight path, designed to study neutron-nucleus interactions. In a typical experiment, a sample is placed in the high-intensity neutron beam produced by nTOF and the reaction products are detected. The data produced are used in astrophysics to study stellar evolution and supernovae. Intense neutron beams are also important in hadron therapy and studies of how to incinerate radioactive nuclear waste.

Detectors are high-precision instruments that collect and record data that is generated by the particle beams at strategic points along the accelerator complex. Modern particle detectors consist of layers of subdetectors, each designed to look for particular properties, or specific types of particle. *Tracking devices* reveal the path of a particle; *calorimeters* stop, absorb and measure a particle's energy; and *particle-identification detec*tors use a range of techniques to pin down a particle's identity.

The largest detectors at CERN are the four LHC detectors. Each is introduced in the box below.

Largest Detectors at CERN

ATLAS (A Toroidal LHC Apparatus) is a general-purpose detector with a broad physics programme. It is a many-layered instrument consisting of six different detecting subsystems wrapped concentrically in layers around the collision point to record the paths (direction), momentum (when the path of particles is bent by magnets), and energy of new particles. This allows the particles to be individually identified and informs a wide range of studies, including the discovery and study of the Higgs boson through to searches for extra dimensions and particles that could make up dark matter. At 46m long, 25m high and 25m wide, the 7,000-tonne apparatus is the largest volume particle detector ever constructed.

The **CMS** (Compact Muon Solenoid) detector is also a general-purpose detector. It has a broad physics programme ranging from studying the Standard Model (including the Higgs boson) to searching for extra dimensions and particles that could make up dark matter. Although it has the same scientific goals as ATLAS, it uses a different approach and magnet-system design. It is built around a solenoid magnet, a coil of superconducting cable generating a field of 4 Tesla (~100,000x the magnetic field of the Earth).

ALICE (A Large Ion Collider Experiment) is a heavy-ion detector on the LHC ring, weighing 10,000 tonnes. For part of each year the LHC provides collisions between lead ions (also xenon), recreating in the laboratory conditions that are similar to those soon after the Big Bang. This allows protons and neutrons to "melt" and form a phase of matter called quark-gluon plasma. Finding experimental proof of the existence of this phase and its properties are key aspects for elementary nuclear physics research areas (quantum chromodynamics, confinement, and chiral-symmetry restoration).

[12] Antimatter research on the AD is funded by EPSRC.

The **LHCb** (LHC-beauty) experiment uses a series of subdetectors to detect mainly "forward particles" – produced at small angles when beams of protons or heavy ions collide. It consists of movable tracking detectors that are close to the path of the beams circling in the LHC, and which are able to identify particles containing "beauty and charm quarks". This type of particle allows investigation of new physics, focusing on the slight differences between matter and antimatter.

Smaller experiments at the LHC involve the detectors TOTEM[13] and LHCf[14], which (like LHCb) focus on forward particles. TOTEM uses detectors positioned on either side of the CMS interaction point, while LHCf has two detectors sitting along the LHC beamline, 140 metres either side of the ATLAS collision point. MoEDAL[15] uses detectors near LHCb to search for a hypothetical particle called the magnetic monopole, and other heavily-ionizing particles.

In fixed-target experiments, a beam of accelerated particles is directed at a solid, liquid or gas target rather than colliding with another beam. These experiments take lower-energy beams from accelerators preceding the LHC. The COMPASS[16] experiment, which looks at the structure of hadrons (particles made of quarks) uses beams from the SPS. NA61/SHINE studies the properties of hadrons in collisions of beam particles with fixed targets. NA62 also uses protons from the SPS to study rare decays of kaons. DIRAC investigated the strong force between quarks at the PS. The CLOUD[17] experiment (supported by NERC) is investigating a possible link between cosmic rays and cloud formation. ACE, AEGIS, ALPHA, ASACUSA, and ATRAP[18] all use antiprotons from the Antiproton Decelerator, while the CAST[19] experiment is looking for hypothetical dark matter particles coming not from collisions at the accelerators but from the Sun.

Sophisticated computing technology is required to collate, store and analyse the enormous flow of data recorded by the detectors. Famously, the need for automatic information-sharing between scientists around the world led to the development of the World Wide Web by UK scientist Tim Berners-Lee while working at CERN in the late 1980s. Ever-larger amounts of data captured by experiments at CERN continue to drive advances in computing storage and analysis to this day.

Trigger and data acquisition systems. In the LHC, billions of particles interact every second. Protons collide at high energies, creating new particles that decay in complex ways as they move through layers of subdetectors. The subdetectors register each particle's passage and microprocessors convert the paths and energies into electrical signals, combining the information to create a digital summary of the "collision event". Most are unlikely to reveal new phenomena – e.g. they might be low-energy glancing collisions, rather than energetic, head-on interactions – and detectors use specialised electronics and computing systems to select the potentially interesting events and 'trigger' recording of these data only.

These trigger systems (in which the UK has considerable expertise) typically use a two-stage approach. First, the number of events is filtered, with the trigger process identifying simple signs of 'interesting' physics, e.g. particles with a large amount of energy or in unusual combinations. This reduces the number of signals from some 600 million per second to almost 100,000 per second. Then, information from different parts of the detector is assimilated and synchronised by specialised algorithms to recreate the entire event, leaving only 1,000 events of interest per second. (With particles colliding at a rate of ~1

[13] TOTal cross section, Elastic scattering and diffraction dissociation Measurement at the LHC (TOTEM)
[14] LCH-forward (LHCf)
[15] Monopole and Exotics Detector at the LHC (MoEDAL)
[16] Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS)
[17] Cosmics Leaving Outdoor Droplets (CLOUD)
[18] Antiproton Cell Experiment (ACE); Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy (AEGIS); Antihydrogen Laser Physics Apparatus (ALPHA); Atomic Spectroscopy And Collisions Using Slow Antiprotons (ASACUSA); and Antihydrogen trap (ATRAP)
[19] CERN Axion Solar Telescope (CAST)

billion times per second, detectors must also have very good time resolution so that particles from two different events do not get 'confused'.) This raw data is recorded onto servers at the CERN Data Centre.

There are continuous improvements in trigger and data acquisition system technology. For example, the next phase of uptime of the LHCb experiment will have a software-only trigger, as well as triggerless readout of all of its detectors, meaning that the two-stage trigger system approach will not be required.

The computing grid. Even after data acquisition has been reduced by the trigger system, the experiments still produce huge amounts of data that must be stored for further analysis. The LHC employs a distributed computing and data storage infrastructure called the **Worldwide LHC Computing Grid** (WLCG). In 'The Grid', computer systems collaborate, providing more processing capacity than could be achieved by a single supercomputer, and giving access to data to scientists all over the world. The WLCG is composed of four Tiers (Tier 0 – Tier 3), each providing a specific set of services. Between them, the tiers process, store and analyse all the data from the LHC.

The UK has been at the forefront of Grid technologies through its national e-science programmes and strong involvement in the international Grid activities. The GridPP collaboration is a community of physicists and computer scientists who aim to "create, manage and oversee the evolution of the computing infrastructure needed to maintain the UK's position as a world leader in particle physics"[20].

Drawing on expertise from 20 UK institutions, the collaboration actively contributes to the development of open source software, applications and middleware to power large-scale distributed computing for particle physics and other needs. GridPP has successfully supported computing for the LHC and beyond, all the way from the first Monte Carlo collision simulations, through the LHC switch on in 2008, first beams in 2009 and the discovery of the Higgs boson in July 2012, to today. It also helps to meet the data processing needs for other STFC-supported experiments, beyond CERN (e.g. LZ, SKA, LSST[21]).

For example, the Distributed Infrastructure with Remote Agent Control (DIRAC) solution was developed by GridPP as a workflow management and data management system for the LHCb experiment, but it has since been developed to cater for multiple virtual organisations that represent the non-LHC users of GridPP resources. GridPP is explored further through a case study (see Appendix E).

4.3 Technology development

The two most important properties characterising the capability of a facility for physics are energy and luminosity. Energy is related to the acceleration of the beam of particles achieved by the facility's electric fields. Luminosity is a measure of the rate at which particles collide (i.e. the number of collisions that occur in a given amount of time). Luminosity is directly related to the intensity of the particle beams employed and, in a collider, to the size of a spot onto which the beams are focussed.

Research on elementary particles, or so-called sub-atomic particles, relies on accelerators operating at the highest energies and luminosities attainable with present technology — the "energy frontier" and "intensity frontier" respectively[22]. For continued progress, conditions need to be created under which elementary particles interact at extremely high energies and in quantities sufficient to allow observation of extremely rare processes (possibly due to yet-to-be-discovered physics phenomena). This need has driven the construction of ever-larger accelerator facilities and increasingly large and complex detectors.

Each upgrade of the CERN accelerator complex has entailed substantial investment in equipment and advances in technology development. For example, within the 27km ring of the LHC, superconducting magnets built from coils of special electric cable that operates in a superconducting state focus, direct and push particle beams to ever-higher energy levels. Particles travel within beam pipes – two tubes

[20] Financing for GridPP through 111 STFC funding awards has totalled £33.8m since 2006, with renewals every ~3 years; the current round is known as GridPP5 (2016-2020)

[21] The LUX-ZEPLIN (LZ) experiment, Square Kilometre Array (SKA) and Large Synoptic Survey Telescope (LSST)

[22] National Research Council. 1998. Elementary-Particle Physics: Revealing the Secrets of Energy and Matter. Washington, DC: The National Academies Press. https://doi.org/10.17226/6045.

kept at ultrahigh vacuum. Magnets also need to be chilled to -271.3°C, requiring much of the accelerator to be connected to a cryogenic distribution system, as well as to other supply services. New materials have had to be developed to cope with the vacuum and cryogenic systems. A number of new or upgraded accelerators and experiments are being developed (introduced below).

⇨ Further analysis of the wider application of CERN technologies is presented in Section 7.1.

New/upgraded accelerators and experiments (in progress)

High-Luminosity LHC (HL-LHC) upgrade and Linac4 - The HL-LHC project aims to increase the luminosity of the LHC by a factor of 10, enhancing the performance of the accelerator to increase the potential for discoveries. The design study ran 2011-15, before civil engineering work started in April 2018. The HL-LHC is scheduled to be in operation from 2026. A key element for increasing the LHC's luminosity is the replacement of Linac 2 with Linac 4 as the source of proton beams. Linac4 is currently being tested and started to produce beams in 2013. It reached the milestone energy of 160 MeV in 2016 (compared to Linac 2's 50 MeV), and is scheduled to replace Linac 2 for the LHC in 2020. The HL-LHC project is being led by CERN with the support of an international collaboration of 29 institutions, including many UK universities (Southampton, Royal Holloway, Liverpool, Manchester, Huddersfield, Lancaster, Dundee), as well as STFC and the Cockcroft Institute.

HIE-ISOLDE (High Intensity and Energy ISOLDE) - is an ongoing upgrade of the existing ISOLDE facility. For HIE-ISOLDE, a new linear accelerator accelerates radioactive beams to higher energies than were previously possible, enhancing the performance of the facility. Currently, ISOLDE takes proton beams from the PS Booster and fires them into a target. The target then sends out many radioactive isotopes, which can be directed down beamlines to various experiments. HIE-ISOLDE's new linear accelerator takes these radioactive beams and accelerates them again, before sending them on to secondary targets, where nuclear reactions occur. The HIE-ISOLDE upgrade started in 2008, with a first physics run in 2015. Since then, 3 new cryomodules have been installed (accelerator sections composed of normal conducting and superconducting cavities), further accelerating and increasing the energy of the beam.

CLEAR (CERN Linear Electron Accelerator for Research) - is a facility located at CERN for general accelerator R&D and component studies, to inform existing and possible future machines at CERN. After the completion of the CLIC Test Facility program at the end of 2016, one of its electron beam lines was converted into the CLEAR test facility, open for external researchers. CLEAR saw its first beam in August 2017. The CLEAR programme covers the prototyping and validation of accelerator components for the HL-LHC upgrade and its injector chain, and studies of high-gradient acceleration methods. CLEAR also provides training possibilities, as well as irradiation test capability.

New/upgraded accelerators and experiments (planned)

ELENA (Extra Low ENergy Antiproton) - is a deceleration ring that is being commissioned. Coupled with the AD, it will slow antiprotons down further, reducing their energy by a factor of 50. It will include an electron cooling system to increase beam density and improve the efficiency of the experiments.

The Compact Linear Collider (CLIC) study - is an international collaboration working on a concept for a machine to collide electrons and positrons (antielectrons) head-on at very high energy. The energy range is similar to the LHC, but using electrons and their antiparticles (not protons) will provide a different perspective on underlying physics. The test facility CTF3 (now closed), provided the electron beam for the study. In a related project, the CLIC detector and physics collaboration (CLICdp) is developing a detector to record collisions at the high-energy CLIC.

The Future Circular Collider Study (FCC) - is developing designs for a higher-performance particle collider to extend the research being conducted at the LHC once it reaches the end of its lifespan in around 2035. The long lead-time reflects the fact that some technology and materials for components will still need to be invented. The goal of the FCC is to push the energy and intensity frontiers of particle colliders, with the aim of reaching collision energies of 100 TeV and high-luminosity electron-positron collisions. This will require larger accelerator rings, placed in an 80-100 km proton-proton tunnel. The FCC Study delivered a conceptual design report in early 2019.

4.4 Contracts and procurement

There are two distinct elements to CERN-related procurement: (i) the central procurement for the CERN facility (coordinated internally by the Procurement and Industrial Services group of CERN and only open to contractors from Member and Associated States); and (ii) procurement for the Experimental Programme (largely organised within the States that are members of the respective collaborations - although many visiting teams utilise CERN's procurement process to place contracts).

Central procurement for the CERN facility

Products and services are procured for the building, maintenance and operations of the facilities at CERN, with an average annual budget of approximately £350m[23]. Individual development projects may take place over many years (e.g. the HL-LHC construction spans ten years and will cost around £950m).

The CERN procurement process varies depending upon the expected price range of the contract:

- For contracts under 200k CHF, only a limited number of companies are approached for a price enquiry. Contracts under 50k CHF are distributed through CERN's internal database, while contracts worth 50k-200k CHF are circulated through the member state Industrial Liaison Officers.
- Contracts worth over 200k CHF are preceded by Market Surveys to define eligibility, which are later followed by Invitations to Tender, limited to firms established in Member and Associate States.

  Contracts over 200k CHF are also adjudicated through one of two processes. Those for supplies will usually be awarded to the firm submitting the lowest bid compliant bid, while those for services are usually awarded on a best value for money basis, to the most economically advantageous bid.[24]

In **the UK**, an STFC Industrial Liaison Officer (ILO) coordinates between UK companies and CERN, providing assistance and advice, and facilitating access to contracts, including through the circulation of tender notifications and recommendation of relevant companies for contracts. The ILO also organises targeted events (e.g. the CERN Mechanical Engineering Meet the Buyer event, March 2019) and provides assistance to activities led by others (e.g. the CERN-funded HiLumi Industry day in Warrington, May 2017, or the DIT-led UK@CERN Trade Mission, November 2018). Finally, the ILO can also work with CERN to influence the procurement rules to ensure fairness to member states.

An alignment rule seeks to help CERN distribute *supply* contracts to member states in proportion to their investment (the rule is not used where best value for money is the criteria – i.e. for services). The rule affects the priority given to companies from particular countries when applying to CERN (for contracts over 100k CHF) and is based on the calculation of a "return coefficient". This return coefficient is (a rolling 4-year average of) a ratio between a member state's share of the value of all contracts and its percentage contribution to the CERN budget. Using this coefficient, countries are categorised as being well-, poorly-, or very-poorly balanced, with supplies and service contracts categorised separately (the UK is well balanced for services, but poorly balanced for supplies).

The parameters for categorising countries are different for the two different contract types (for service contracts a well-balanced country has a return coefficient of 0.4+, while for supplies a well-balanced country has a return coefficient of 1+ and a very poorly balanced country has a return coefficient of <0.4).

[23] Budget fluctuates according to requirements each year.
[24] More information on this process is available at: https://procurement.web.cern.ch/en/procurement-process

The rationale lies within the logical advantage for companies in the host countries (e.g. in France or Switzerland) in obtaining many service contracts. The parameters have also changed over time.

Procurement for the Experimental Programme

Procurement for each experiment is organised within the countries that are members of that experiment. These contracts are largely let locally, by individual universities and laboratories (and no centralised figures are available), but a small proportion of the total spend (some £36m per year) now goes through CERN's procurement process and is therefore recorded in the CERN procurement report.

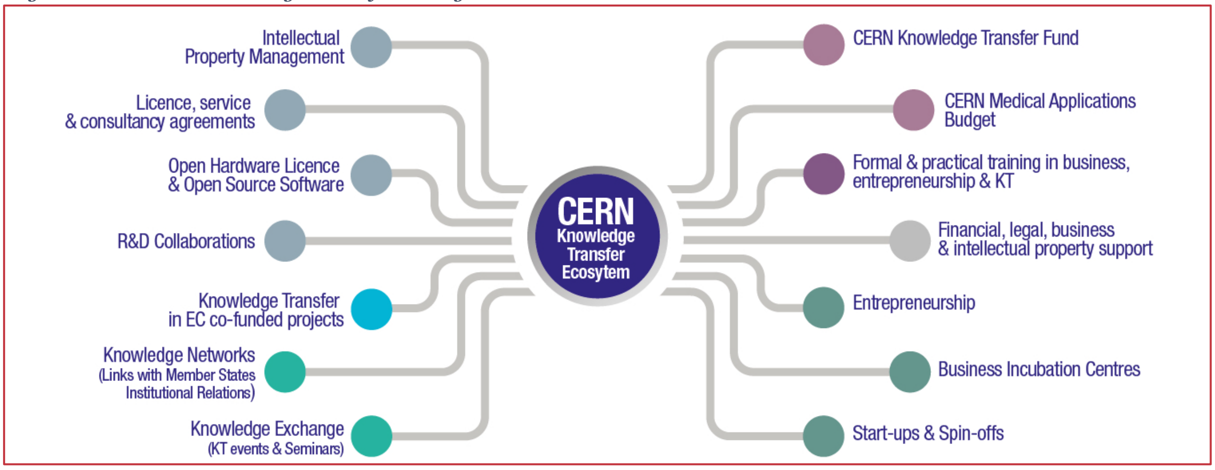
- ⇨ Further analysis of procurement outcomes is presented in Section 7.3.

4.5 Knowledge transfer

Over time, CERN's knowledge transfer (KT) activities have expanded and become more formalised, particularly through the establishment of a KT Group. This aims to engage with experts in science, technology and industry in order to promote the technological and human capital developed at CERN and to create opportunities for the transfer of this technology and know-how. The ultimate goal is to accelerate innovation and maximise the global positive impact of CERN on society. The current range of mechanism through which CERN engages in KT are shown in Figure 2. They include the provision of funding, advice, support, events, and support to collaborations and networks, amongst other activities.

- ⇨ The wider application and benefits of CERN technology are explored in Section 7.1.

Figure 2 CERN knowledge transfer ecosystem



Source: CERN Knowledge Transfer Report 2017

In **the UK**, the **STFC-CERN Business Incubation Centre (BIC)** was set up in 2012 as a pilot to get more IP and expertise from CERN into industry (other countries have since followed this example and there are now 9 member state BICs in total). The intention is to facilitate a step change for participating companies, bringing them closer to further funding or self-sufficiency. To do so, the BIC provides money, support and technical assistance to accelerate their business concept.

In order to be eligible for the programme, applicants must be young technology companies aiming to utilise CERN technology in a way that will benefit from the relationship with CERN. These companies are typically less than five years old and are pre-revenue, however they must also demonstrate their capability, proof of concept and plan to deliver the project. Through the STFC-CERN BIC, companies are able to access the incubation experience of STFC and the expertise, technology and IP held by CERN. Companies can receive up to £40,000, which can be used for CERN IP, IP protection, design and prototyping, market studies and access to CERN/STFC scientific and technical expertise.

- ⇨ The STFC-CERN BIC is explored further in Section 7.1.

4.6 Education and training

CERN provides an inspiring **training ground for the STEM workforce**. CERN employees and researchers, as well as staff within supplier organisations, can acquire skills and knowledge 'on the job', and in informal exchange with team members. CERN also offers a number of dedicated training schemes for students, as well as for professionals more advanced in their careers. This includes:

- The CERN Summer Student Programme (for undergraduate students, lasting 8-13 weeks)
- The Openlab Summer Student Programme (a public-private initiative for students, lasting 9 weeks)
- The Doctoral Programme (for the preparation of a PhD thesis over a period of 6-36 months)
- The Technical Programme (for undergraduate students, lasting 4-12 months)
- The Administrative Student Programme (for Bachelor or Master degree students, 2-12 months)
- Short Term Internships (undergraduate students, 1-6 months)
- Fellowship Programme (Junior, Senior, Senior Research and Post-Career Break options)
- Technician Training Experience Programme (for newly qualified apprentices)
- The Entrepreneurship Student Programme (Master degree students, 5 weeks)

In addition, the (STFC) Long-Term Attachments (LTA) programme provides (UK) students with the opportunity to continue their PhD at CERN whilst receiving training. More experienced professionals can also apply to the Scientific Associates and Corresponding Associates programmes to make use of the research facilities and participate in its programmes and activities.

⇨ The uptake and impact of these training activities are explored further in Section 8.1.

CERN runs on-site **programmes for teachers and students**, while also providing additional resources to support further work in the classroom. Initiatives include:

- The CERN National Teacher Programme - a four-day programme available to teachers from Member and Non-member countries (in the UK it is organised by the national STEM Learning Centre)
- The CERN International High School Teacher Programme and International Teachers Weeks Programme – both two-week schemes, open to teachers from around the world
- On-site visits for schools – including talks, films, exhibitions and guided tours. Students can also visit the S'Cool LAB, a Physics Education Research facility at CERN that gives students the opportunity to participate in experiment sessions and physics in education research.
- CERN also provides educational materials for teachers to use in schools via the internet. These range from presentation slides to videos and from simple word documents to interactive tours.

In addition, the UK's CERN@school initiative (which has since evolved into the Institute for Research in Schools) brings technology from CERN into UK classrooms to aid with the teaching of particle physics.

⇨ CERN's role in enthusing and educating young people is explored further in Section 8.3.

CERN also undertakes various activities to increase its profile and **engagement with the wider public**, for instance through: public (and media and VIP) visits to the facility; two onsite permanent exhibitions; the use of social media outlets (Twitter, Facebook, YouTube, Instragram and LinkedIn); newsletters; special events (such as Researchers' night and TEDxCERN); press kits; and the provision of background information about particle physics (for example, the Higgs boson and the LHC restart).

STFC employs a dedicated communications professional based full time at CERN to champion examples of British involvement. Building on this, STFC also supports scientists with public engagement fellowships and grants (e.g. nucleus awards, spark awards), encouraging them to work across schools and universities – for example to create research projects via the CERN@school initiative. STFC and other organisations (e.g. museums and galleries) also develop exhibitions, events and other activities relating to CERN for the UK public.

⇨ The role of CERN in increasing public appreciation of science is explored in Section 8.2.

5 Evaluation framework

CERN's strands of activity and engagement are multi-faceted (fundamental research, industry contracts, student placements, school visits, and so on) and the benefits to the UK may flow both directly (e.g. via UK contractors, training attendees or researchers of the facilities) and indirectly (e.g. through the uptake of published knowledge or the adoption of technologies developed at or for CERN).

There are therefore **a wide range of types of benefits and impact, flowing through a series of interrelated impact pathways**, which the study has sought to explain, explore, capture and measure.

To structure the evaluation and ensure that it covered the full range of outputs and impacts that the UK's involvement in CERN has produced, we first developed a **logic model** for the UK's investment in CERN (see next page). This sets out the logical sequence between: the rationale, aims and objectives for investment in CERN; the resources (inputs) used and the activities undertaken; and the results (outputs) and changes (outcomes and ultimately impacts) that it is hoped or intended will be realised for the UK.

This model allowed the study to more clearly define the types of expected benefits, which in turn underpinned efforts to capture and assess relevant evidence to demonstrate these benefits.

Based on this overarching model, the study then identified and defined **12 main areas of benefit and impact** that should flow to the UK from CERN. Table 1 shows the basic structure: four objective areas, with three main areas of benefit under each. In line with the study objectives, the focus is on benefits *to* the UK, rather than benefits *from* UK involvement (although though the two are often linked).

Table 1 Overall structure for impact areas – benefits from UK investment in CERN

Area	Benefits to UK
1. World-class research	1.1 Pushing the frontiers of knowledge and enabling UK scientific progress 1.2 Access to facilities and opportunities for UK research excellence 1.3 Attracting investment and talent to the UK
2. World-class innovation	2.1 The wider application of CERN technologies 2.2 The wider application of CERN research findings 2.3 Improved performance amongst UK suppliers
3. World-class skills	3.1 Increased skills and capabilities of the UK workforce 3.2 Increased UK public appreciation of science 3.3 Increased UK STEM uptake
4. Science diplomacy	4.1 The UK's influence in the international S&T landscape 4.2 Improved diplomatic relations and engagement 4.3 The UK's image as a 'great science and innovation nation'

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Taking each of these identified areas in turn, we have then expanded upon their meaning and scope, and traced the pathway back, from the benefit to the UK, through intermediate outputs and outcomes, to the originating activities of CERN and the UK's investment in the facility. These **impact pathways** –which are presented in full in Appendix A - were the starting point for the evaluation and provide the outline structure for the reporting of evidence, including the findings presented in the sections that follow.

Figure 3 Logic model for the benefits to the UK of investment in CERN

Rationale: The UK needs to be a major player in shaping the world class scientific facilities of the future. CERN provides world-class facilities, unique scientific instruments and research opportunities, and enables participation in a large international user community.

Objectives	Inputs	Activities	Outputs	Short- to medium- term outcomes		Long term Impacts
World class research: Sustain the UK's position as one world's leading research nations and support the growth of a high technology UK economy	CERN subscription fees	Fundamental science research projects Technology R&D	New knowledge, expertise, technology, and methods UK researchers / companies & wider community collaborate on CERN-related activities	Enhanced understanding of the physical world New collaborations in CERN projects and beyond	UK leadership in scientific areas relevant to CERN Wider application of CERN technology	UK research base remains world-leading in physics, engineering and computing
World class innovation: Realise the innovative capacity of STFC's facilities to support the growth of a high technology UK economy **and deliver benefits to UK society**	Funding for UK research community from STFC Core Programme	Technology transfer support / Industrial engagement (e.g. STFC business opportunities team, STFC-CERN BIC) IP licensing / open access Construction & operation of facility (incl. upgrades)	Start-up / spin-out companies using or developing CERN-STFC IP Advice related to policy and / or public services Industrial return to UK via contracts (+ prestige)	Products based on CERN IP enter the market Income to UK from CERN-related activity and outcomes	Enhanced public services or policy	The UK benefits from applications based on CERN related R&D: products, services, policies The UK is home to a strong and growing high tech economy
World class skills: Deliver the scientific, technical & digitally-skilled workforce that will sustain the UK as a leading research nation and support the growth of a high technology economy	Funding from other Research Councils Expertise	Training / education schemes Work experience Engagement activities / visits Dissemination activities / media	New / enhanced skills and capabilities of individuals involved in CERN–related activities, contracts & schemes Individuals engaged / reached through dissemination activities are aware of CERN's work and the value of science	UK workforce has key skills and capabilities to develop cutting-edge technology Increased interest in STEM subjects in UK schools, students and public	Increased uptake of STEM subjects in schools, HE and FE	The UK has a workforce with the right technical skills and of suitable size The UK public is inspired by science and in a position to make better decisions
Science Diplomacy: The UK develops and maintains global influence and key relationships	Funding for supporting infrastructure (Grid, BIC, etc.)	Engagement of UK in CERN operations governance and activities	UK experts in key positions in international science community and beyond	UK has influence in international science and policy arena	Strong crosscultural relationships (science diplomacy)	UK is seen as a leading S&T nation open for partnership UK is internationally influential

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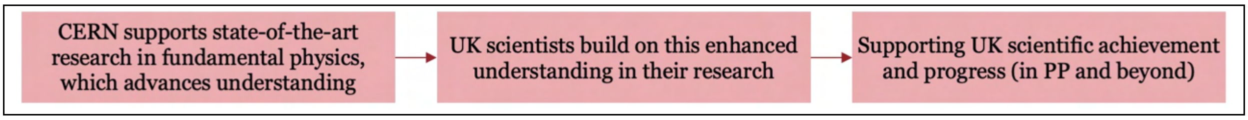
6 Impacts relating to world-class research

6.1 Pushing the frontiers of knowledge and enabling UK scientific progress



The first impact pathway begins with the international community's pooled investments in CERN's next-generation accelerators and ever-more powerful detectors that allow scientists to carry out experiments that were not possible previously and explore fundamental concepts that have so far only been theorised. CERN is the world's largest particle physics laboratory, making available complex, purpose-built particle accelerators and detectors as well as computing technology for its large, global research community that spans various fields (particle physics, nuclear physics, astrophysics, and so on). In turn, CERN draws on the international community to develop and build new technologies, state-of-the-art instruments and experiments, enabling the continual pushing of the boundaries of research.

CERN has enabled significant advances in knowledge and understanding

There are various studies and reports that attest to the critical contributions that CERN has made to advances in understanding over its history,[25] whether speaking in general terms or more concretely itemising notable breakthroughs, for example: "Researchers at CERN have advanced our knowledge of the basic building blocks of matter and hugely improved understanding of how the Universe works and how it began."[26] "From a purely scientific perspective, there is no question that the CERN laboratory has, during the past half-century, been one of the top institutions in its field"[27]; and "the core benefit of the LHC is the generation of experimental data that sustain the opportunity to publish new research."[28]

Nearly all respondents to our survey of over 260 UK scientists and engineers claimed that CERN (the facility and experiments) had been critical to advancing knowledge in the field of fundamental physics. In fact, 91% rated CERN as 'critical' in this regard, with the remainder saying that it was 'important'.

Those consulted through the study (interviews and survey) were also asked to identify **notable scientific advances enabled by CERN**. Most mentioned verification of the Standard Model and confirmation of the Higgs boson (2012), but other advances were highlighted, including the discovery of weak neutral currents (1970s) and electroweak (W and Z) gauge bosons (1980s), the measurement of the number of lepton generations (1990s), observation of CP violation in charm quarks (2019) and the (to date) null result showing lack of supersymmetry.

We have developed a series of illustrative case studies, focusing on a selection of major breakthroughs that have been made possible by CERN, and where the new knowledge and understanding generated is benefiting wider research communities in the further progress of scientific endeavour. Brief summaries of these are presented below, while the full text of these case studies can be found in Appendix E.

The full impact of these discoveries is as yet unknown, but may well be very significant in the long-term, given the fundamental importance of the new knowledge. Impacts from advances in fundamental physics are typically on a long-term horizon, and difficult to forecast and assess. For example, while

[25] 'Benefits of Research in Particle Physics,' Phil Allport, et al. UCL. Available online: http://www.hep.ucl.ac.uk/~markl/pp2020/KnowledgeExchangeDocument.pdf

[26] STFC Impact report 2014. Available online: https://stfc.ukri.org/files/impact-publications/stfc-impact-report-2014/

[27] OECD (2014) The Impacts of Large Research Infrastructures on Economic Innovation and on Society: Case studies at CERN . Available online: http://www.oecd.org/sti/inno/CERN-case-studies.pdf

[28] Florio, M., et al., Forecasting the socio-economic impact of the Large Hadron Collider: A cost–benefit analysis to 2025 and beyond, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.03.007

Planck and Einstein's work on wave-particle dualism and photons formed the basis of lasers and digital cameras, these applications were realised with a time lag of many decades.

Case Study 1 - Discovery of the Higgs boson and refinement of the Standard Model

On 4 July 2012, the ATLAS and CMS collaborations at CERN's Large Hadron Collider announced the discovery of a unique new particle in the mass region around 125 GeV, later confirmed to have properties consistent with those of a Standard Model Higgs boson. The importance of this momentous experimental discovery, destined to become one of the cornerstones of scientific knowledge, cannot be overstated. Its significance has been acknowledged in many ways, not least through the award of the 2013 Nobel Prize in Physics to François Englert and eponymous British physicist Peter Higgs.

Over the decades the Standard Model has become established as the theoretical paradigm for particle physics, explaining most, if not all, of the available data. Its success builds as much on the wealth of precise and ground-breaking experimental results as it does on all the key theoretical advancements that have led to its development. It is the basis for seeking deeper understanding of the Universe. With the discovery of the Higgs boson at the LHC, the last outstanding gap in the Standard Model has been filled.

The discovery of the Higgs boson did not happen as a serendipitous event in CERN's distinguished history of scientific exploration, but rather it represents a crucial milestone in a long journey of discovery that has seen CERN taking centre stage for decades. CERN's state-of-the-art facilities (which are and will remain world-leading at the energy frontier for many years yet), together with other facilities around the world, are being exploited to unravel the secrets of the physical world at its most fundamental level.

Case Study 2 – Trapping of antimatter and wider antimatter investigation

In 1931, British physicist Paul Dirac predicted the existence of antimatter, winning him the 1933 Nobel Prize in Physics. Classical physics only allowed systems to have positive energy, but Dirac's new theory allowed for a particle, now interpreted as an antimatter electron, as a counterpart to the familiar positive-energy electron.

Today, it is understood that all particles have an equivalent antimatter particle with opposite charge and quantum spin, however hardly any antimatter is seen in the observable Universe. The mechanism underlying this asymmetry, i.e. favouring matter over antimatter, is called the "charge-parity (CP) violation". The question of why there should be vastly more matter than antimatter is one of the great unsolved problems in physics, and one that research at CERN is investigating as part of the LHCb experiment and by examining the properties of antiatoms at CERN's Antiproton Decelerator (AD).

The LHCb experiment has investigated CP violation in beauty quarks since data-taking began, with a suite of measurements that improve our knowledge of matter dominance at the fundamental particle level. In addition, the LHCb experiment has identified a range of new 'exotic particles' and characterised their decays. This has included the discovery of two pentaquarks (particles containing five quarks) in 2015, three tetraquarks in 2016, five baryons (particles containing three quarks) in 2017, and three additional particles in 2018. Most recently, in 2019, the LHCb experiment announced the discovery of CP violation in charm quarks. The collaboration has also reported findings that do not fit the Standard Model, providing tantalising hints at new physics beyond the Standard Model. The UK is the largest contributing country to the experiment, accounting for around one-eighth of its registered researchers.

Since 2010, the AD experiments have published numerous measurements of antimatter characteristics, comparing them to those of matter. For example, in June 2011, the ALPHA experiment, located on the AD storage ring successfully trapped atoms made up of antimatter for over 16 minutes (300 anti-hydrogen atoms). This is long enough to begin to study their properties in detail. This was a world first: previous antimatter traps had lasted merely two-tenths of a second. UK researchers were instrumental to the achievement. For example, the Swansea Atomic, Molecular and Quantum Physics group played a leading role, with the largest representation of any institution in CERN's antihydrogen experiments.

Case Study 3 – Quark Matter

CERN announced in 2000 that experiments at its SPS accelerator had collected indirect evidence of a new state of matter (quark–gluon plasma) that exists at extremely high temperature or density.

Artificial quark matter, produced at CERN's Large Hadron Collider, can only be made in minute quantities. It is also unstable and impossible to contain, and will 'freeze out' within a fraction of a second into stable particles. The hadrons produced or their decay products and gamma rays can then be detected. CERN has been studying the properties of quark–gluon plasma on four experiments, ALICE, ATLAS, LHCb and CMS. The much greater energies available at CERN's LHC allow physicists to study the physical phenomena of the hadrons and their decay products a lot more extensively than before, in turn yielding a more detailed experimental characterisation of the quark-gluon plasma at the energy frontier – ultimately gleaning insights into the physics of the early Universe.

The advances made at CERN undoubtedly represent major milestones in scientific understanding, but they are not the end of the story. The discovery of the Higgs boson at CERN may have filled the last remaining gap in the Standard Model's elegant theoretical construction, but far from representing the arrival point in the quest to understand the most fundamental laws of physics, the ground-breaking discovery has instead given a strong impulse to continue the exploration of the microscopic world of elementary particles. The Standard Model also remains an incomplete theory, which in itself is insufficient to explain (or, in some cases, even to begin to address) several key outstanding problems in experimental and theoretical particle physics.

Processes that cannot be explained using the Standard Model are often grouped together under the common umbrella of "**beyond the Standard Model physics**" (see case below).

Case Study 4 – The search for new physics beyond the Standard Model (BSM)

Thanks to its unparalleled capabilities, especially through the LHC's physics capabilities, CERN very much leads the way in the search for BSM physics at the energy and intensity frontiers.

In some "vanilla-type" BSM scenarios, evidence for the existence of new physics may be expected to emerge as some striking experimental "signature" in data, which could in principle be used to easily set aside "signal" processes from the more conventional Standard Model "background" processes.

Alternatively, in harder-to-find BSM scenarios, new physics phenomena might manifest themselves through a combination of less striking (potentially rather subtle) deviations from Standard Model expectations, whose compounded significance could ultimately also amount to a positive discovery.

Either way, before any statement can be made about consistency or not between observations and theory predictions, Standard Model processes (and the detector response to those) need to be understood in great detail, often through painstakingly careful, unbiased analysis of very large samples of data.

For example, understanding the nature of dark matter remains one of the most intriguing challenges in fundamental physics and the search for dark matter particles is one of the most exciting aspects of the vibrant ongoing programme of BSM physics searches at the Large Hadron Collider.

Supersymmetry is one elegant extension of the Standard Model that could provide a viable candidate for a dark matter particle constituent. Dark matter candidates may also arise in other BSM theories alternative to supersymmetry. Some of these, for example, postulate the existence of additional spatial dimensions, while others suggest the existence of a "hidden valley" where dark matter particles live having very little connections with ordinary matter.

These and other theories are all being studied vigorously by CERN experiments taking data at the Large Hadron Collider. If one of these theories were shown to be true, the discovery would not only herald a new age for BSM physics, but also potentially shed light on one of the biggest outstanding puzzles in fundamental physics, the origin of dark matter. This would ultimately gain us a deeper understanding of what the Universe is made of and how it is kept together.

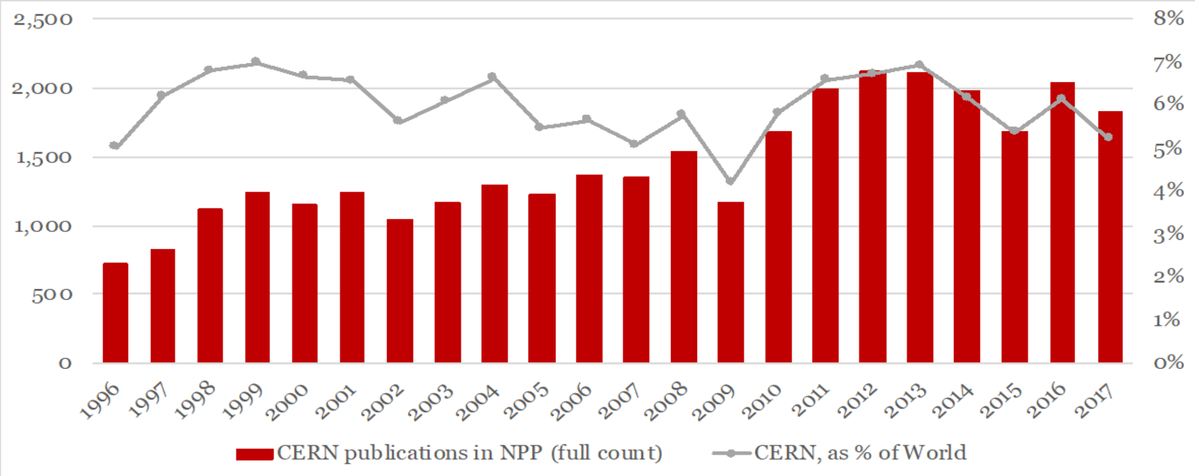
The experiments at CERN produce **massive volumes of observational data** that can be analysed to test hypotheses and produce new insights, advancing our understanding of the basic properties, materials and forces of the Universe. These typically result in peer-reviewed publications and theses.

CERN is leading the way with regard to Open Access, reflecting values enshrined within its Convention ("results of experimental and theoretical work shall be published or otherwise made generally available") and it issued its Open Access Policy in 2014, requiring all CERN physics results to be published Open Access (i.e. available to readers free of charge). This has since been extended to cover instrumentation articles. CERN has set up the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP3)[29], a partnership of over three thousand libraries, funding agencies and research centres. Through the redirection of journal subscription funds, it works to convert leading publishers in High-Energy Physics to Open Access at no cost to the authors. This pioneering model also provides central support for Open Access journals to remove financial barriers to publication for authors.

Given the central importance of refereed articles within physics, bibliometric and citation analyses provide a good basis from which to trace **CERN's contributions to global knowledge and understanding.** Through the bibliometric analyses undertaken specifically for this study (set out in full in Appendix D) we have looked in more detail at the publication output (number of papers) and scientific impact (various citation measures) of CERN research over the past 20 years.

This analysis has identified a total of 40,740 CERN publications (articles connected to CERN research) over the past 20 years (i.e. 1996 – 2017). Unsurprisingly, these publications are highly concentrated in one specific scientific subfield: Nuclear & Particle Physics (NPP)[30]. Indeed, more than 77% of the 40,740 papers were assigned to this area. These 31,898 CERN NPP publications account for almost 6% of the total world output over the 1996 to 2007 period (Figure 4 shows the annual breakdown of CERN NPP papers, as a count and as a proportion of the world total in NPP). Indeed, CERN's specialisation index (an entity's research output in a field compared to the world average[31]) for NPP is a full order of magnitude above that of many of the individual countries that were looked at in the analysis.

Figure 4 Number of CERN publications in NPP, and as a proportion of world total (1996 – 2017)



Source: Technopolis / Science-Metrix, based on Scopus data. The decrease in 'CERN, as % of world' seen between 2000 and 2009 aligns with the period between the closure of the LEP (2000) and the start of the LHC (2008).

[29] https://scoap3.org/

[30] The analysis has not looked in more detail *within* the NPP sub-field at differences between e.g. theoretical and experimental physics, but it is likely that these would show different behaviours. For example, being part of an international collaboration (e.g. as a CERN member) is likely to have a significant impact on a country's bibliometric performance in experimental physics (both in terms of publication outputs and citation metrics), while theoretical particle physics - often undertaken in smaller scale collaborations or independently - is likely to be less directly influenced by CERN membership.

[31] The specialisation index (SI) indicates how much research output a given entity produces in one field or subfield, relative to the global average of output produced in that field. For instance, if 20% of a given country's publications are in physics, but at the global level only 15% of papers are in physics, then the country is said to be specialised in physics, producing more output in that field than is normally the case elsewhere around the world.

The NPP subfield has been a particular focus of the bibliometric analysis. However, we have also considered publication activity in a wider set of 15 subfields (S15) where CERN is most active. Between them, the S15 fields cover 97% of the 40,740 scientific articles published by CERN-affiliated authors between 1996 and 2017 (the 15 subfields and number of CERN publications are shown in the figure below). The remaining 3% of CERN papers are distributed in a long tail of 95 other subfields.

In this wider set of S15 subfields in which CERN is active, CERN papers account for just 0.4% of the total world output over the 1996 to 2007 period (in contrast with the 6% rate for NPP alone).

Figure 5 Subfields (S15) where 97% of CERN publications can be found

• **Nuclear & Particle Physics (31,898)**	• AI & Image Processing (201)
	• Optoelectronics & Photonics (154)
• General Physics (3,641)	• Energy (153)
• Applied Physics (1,164)	• Mathematical Physics (135)
• Astronomy & Astrophysics (731)	• Distributed Computing (132)
• Nuclear Medicine & Medical Imaging (411)	• General Science & Technology (131)
• Fluids & Plasmas (393)	• Materials (130)
• Electrical & Electronic Engineering (312)	• Networking & Telecommunications (103)

Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

On citation metrics for NPP publications, CERN achieves performances that are above world levels, especially for Highly Cited Papers (HCP) indicators (which show higher than expected CERN contributions to the top 10%, 5% and 1% of most highly cited papers in the field). CERN's Citation Distribution Index (CDI)[32] is also substantially better than the world reference.

In addition, within the overall NPP publication portfolios of most of the countries considered (including the UK), the CERN-related share of papers has a much higher impact than that of remaining national NPP publications. This is explored further in Section 6.2.

UK scientists build on CERN research, supporting further scientific progress

The data and papers produced through CERN are freely available to the global scientific community for re-use in their own research, and in so doing, CERN breakthroughs reframe understanding more generally and underpin other scientific advances (see the example of Bell's Theorem below).

Scientists in the UK (and elsewhere) are able to build on this enhanced understanding in their research, enabling them to better address complexity, ask the 'right' questions and set up experiments that continue to push the boundaries of knowledge. In this way, CERN supports the community's further progress and scientific achievements, in particle physics and beyond.

Bell's Theorem

John Stewart Bell, a theoretical physicist from Northern Ireland, is widely considered one of the most important physicists of the twentieth century. After joining CERN in 1960, he remained a CERN staff member for thirty years and contributed significantly to accelerator design and elementary particle physics theory, including one of the first derivations of the CPT (charge conjugation, parity inversion, time reversal) theorem. His work on the foundations of quantum mechanics and modern quantum information theory is now considered to be his most important, including "Bell's Theorem".

Named in his honour, Bell's Theorem makes an important distinction between quantum mechanics and classical mechanics. In particular, the theory deals with the issue of quantum entanglement[33], a paradox

[32] Which compares the distribution of an entity's papers by their level of research impact, relative to worldwide performance.

[33] Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated, interact, or share spatial proximity in ways such that the quantum state of each particle cannot be described independently of the state of the others, even when the particles are separated by a large distance.

described by Einstein, Podolsky and Rosen. Bell's Theorem appeared to show that quantum mechanics could allow the possibility that physical measurements occurring at one place could determine instantaneously results at a distant location. Bell's inequality provides a means to test experimentally the predictions of quantum mechanics and disprove alternatives based on local theories with a deeper, but so far hidden, classical explanation. To date, all tests of Bell's inequality have been consistent with the predictions of quantum mechanics, and appear to require some form of non-locality.

Bell's work provoked many experimental studies to try to establish whether quantum mechanics is a fundamental theory, and has had enormous implications for the field of quantum information theory. This subject has important practical applications in cryptography, for secure communications and (in future) for quantum computation. Quantum computing has the potential to unlock near-limitless processing power, and the ability to deal with calculations, codes and models of unimaginable complexity at unprecedented speeds. The implications for financial markets, security, AI and machine learning are profound. The overall quantum computing market is also expected to grow rapidly, from $93m in 2019 to $283m by 2024 (a CAGR of 24.9%)[34].

Our survey of the UK scientific and engineering community asked about the extent to which the respondents currently **read, reference and / or cite publications that are based on CERN** experiments and data. The great majority (93%) reported that they did so to some degree, or that they had done so in an earlier period (3%). This included a quarter of respondents who said that they utilised CERN publications on a daily basis, while a further quarter did so at least once a week.

The bibliometrics analysis can help gain a broader sense of the share of **UK research that has built on findings from CERN experiments** to build hypotheses or mobilise evidence and experimental results. This shows that between 1996 and 2017, 29,221 scientific articles (13,613 by fractional counting) authored by at least one UK-based researcher made reference through direct citation to CERN articles published during this period[35]. NPP papers were unsurprisingly the main source of citations to CERN articles (representing 71% of UK papers citing CERN). However, there were also hundreds of articles published in, for example, the areas of astronomy and astrophysics, applied physics, and fluids and plasmas, which also referenced CERN articles.

Figure 6 shows the annualised totals for just the last decade (2008-17). In this period, there were 19,400 UK-authored papers (full count) that cited CERN papers published since 1996.

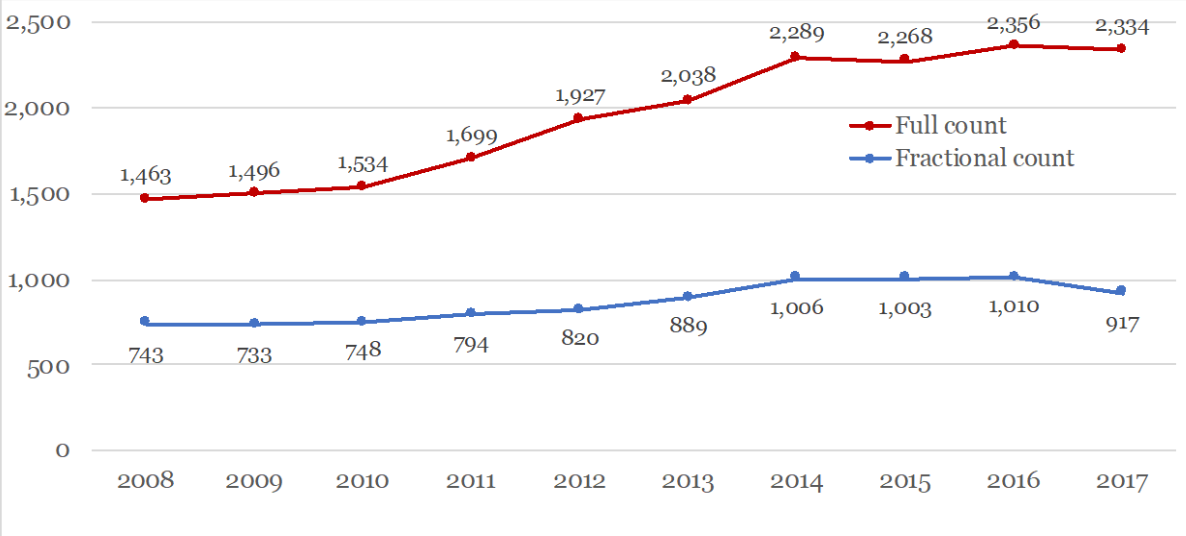
It is also important to note that UK uptake of CERN research is made by some of the most influential scientific articles in physics. A quarter (25%) of UK papers citing CERN research fell among the 10% **most-cited publications** in their field between 1996 and 2017. This figure has been increasing over time and grew to 28% for the 2011–2015 period. In addition, 14% of UK papers citing CERN research between 1996 and 2017 fall among the 5% most highly cited papers; and 4% of them among the top 1%. By any measure, these are excellent figures for both CERN and the UK based research groups involved.

Another impact measure - the Citation Distribution Index (CDI) - provides similarly positive indications. A CDI above 15 is indicative of strong performances (a set of papers tends to be cited skewed toward higher-impact performances), and CDI figures above 20 indicate exceptional achievements. UK papers citing CERN research between 1996 and 2017 achieved an impressive CDI of 21.

[34] Quantum Computing Market – Report SE 5490. Markets and Markets, May 2019.

[35] Note that it has not been possible to include CERN papers published before 1996 into the analysis. The quoted number of UK papers citing CERN papers will therefore be an underestimate, as it excludes citations of earlier papers.

Figure 6 Number of UK scientific papers (published 2008–2017) citing CERN papers (published 1996 – 2017)



Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

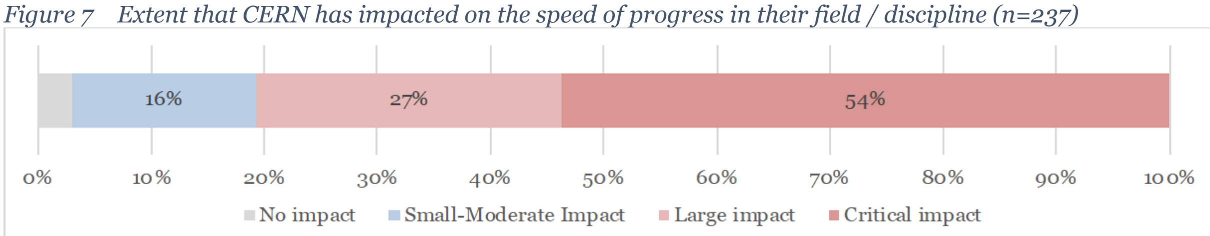
When researchers spend time on a project, they have an 'opportunity cost' from not working on an alternative.[36] This can be estimated with salaries, and we have used this as the basis for putting a monetary value to the production of the 4,600 CERN papers (with a UK author) in the past decade (see first table in Section 10.3.2). The knowledge produced in these CERN papers can then also serve as the basis for the production of further knowledge – indicated by citations in other papers published by UK authors (there were an estimated 20,275 UK papers making reference to a CERN paper between 2009 and 2018 - see second table in Section 10.3.2). A proportion of the value of the production of these (secondary) papers can then also be ascribed to CERN following a similar opportunity-based approach. Based on these assumptions, we have estimated that the **total value to the UK of the *production of knowledge*** *(i.e. not the wider impact of advances and innovations that this may underpin)* **produced within CERN in the last decade is £495.1m** (in 2018 prices). The approach (including assumptions and limitations) is explored further in section 10.

The survey of UK scientists and engineers conducted for the study has also provided testimony more generally on the value, role and importance of CERN-generated knowledge and understanding to the wider UK scientific and engineering community. For instance, of those responding:

- 62% reported that it had been critical to their ability to pursue particular research questions
- 57% said that it had been critical to their research capacity
- 56% claimed it had been critical to the direction of their research
- 55% said CERN been critical to their understanding of their research area

Overall, 81% of the community surveyed said that CERN had had a significant (large or critical) impact on the speed of progress in their field or discipline more widely (see figure below).

Figure 7 Extent that CERN has impacted on the speed of progress in their field / discipline (n=237)



[36] In knowledge valuation, opportunity cost is used a proxy for marginal societal benefit.

Source: Questionnaire survey of UK scientists and engineers

6.2 Access to facilities and opportunities for UK research excellence

Pooled resources enable instruments, facilities and infrastructure that could not be developed alone → Investment enables UK access (national PP lab) and offers opportunities to participate in R&D → Supports strength of UK research community, helping sustain UK excellence and leadership

Pooled investments have enabled facilities that couldn't be developed alone

As already mentioned, CERN is the world's leading laboratory for physics, with 70% of the global particle physics community conducting research there, alongside large numbers of other scientists and engineers from a variety of fields and disciplines. It is also the **UK's national laboratory** for particle physics.

Pooled resources and expertise (including UK investments and leadership) have enabled state-of-the-art instruments, facilities and infrastructure to be built that could not have been developed by one country alone (the LHC on its own, for example, cost over £3bn to construct and has an annual operating cost of several hundred million pounds[37]). The costs for upgrades, as well as maintenance and operation of CERN facilities, are also split between countries, drastically reducing the cost to the UK (which now contributes just 16% to the ~£1bn annual cost of the facility, down from 25% fifty years ago[38]). This allows the UK to make leading contributions to upgrades through in-kind contributions, whilst further building expertise in its research community and industry.

CERN therefore allows the UK to take advantage of world leading facilities and expertise, undertake world-class research and benefit from all of the scientific output, whilst sharing with its partners the substantial price of building and running the facility.

> *"The field of particle physics has reached a point where no single country alone can provide the necessary infrastructure and community for the field to flourish. CERN is about the only organisation left in the world that is able to provide the required expertise and facilities."* (quote from survey of UK scientists and engineers)
>
> *"The vast majority of UK Particle Physics research would not be possible without the UK CERN subscription and UK involvement in international collaborations based at CERN."* (quote from survey of UK scientists and engineers)

This investment provides the UK with unique opportunities

The UK's investment provides UK scientists with the **opportunity to access** co-developed (and co-owned) instruments and facilities and to participate in (or lead) research underpinning CERN's technology development projects. This includes access to:

- Technology and capabilities not otherwise available (even more important, as research is becoming more capital-intensive and infrastructure dependent)
- International collaboration networks and knowledge sharing/building with leading scientists
- World-leading / frontier science and experiments
- The latest theories and developments in understanding the physical world
- New methods and techniques
- Training / learning opportunities

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[37] https://www.forbes.com/sites/alexknapp/2012/07/05/how-much-does-it-cost-to-find-a-higgs-boson/#3e568e523948

[38] UK share of member state subscriptions. The UK's share of costs has reduced over time, as additional countries have joined. For example, in 1960 (when there were just 13 member states) the UK contribution was 25% of the total.

However, the **unique properties of CERN** go well beyond the facilities and instruments. We asked the UK science and engineering community through surveys and interviews what they thought CERN offered that was unique, or special, when compared to other international bodies and platforms, and they came forward with a wide range of answers that we have sought to encapsulate in the figure below.

Figure 8 UK science and engineering community's view of the special nature of CERN's 'offer'

- CERN is **open to all**, regardless of nationality, sex or religion
- It exposes **young scientists** to new skills, opportunities and international working
- It offers a collaborative **environment** for working, which has a scope and intensity that is not replicated elsewhere, which inspires and motivates creative endeavour
- It has a work **culture** that makes things happen, on time, on budget, while still at the cutting edge
- It is a **truly international** centre, rather than a national centre with "add-on" international collaboration
- It fosters and demonstrates successful **international collaboration** – whereby the world comes together to overcome challenges and make progress towards common goals
- It acts as an international hub for meeting and **interacting** with colleagues from across the globe, offering the largest network, where researchers, engineers and students can come together easily
- It supports the **pooling of multidisciplinary expertise** from a wide range of areas and countries, combining new technologies, new discoveries and theoretical explorations
- It provides **focus and coherence** to entire fields, offering a central hub for science and engineering
- It is the largest scientific organisation performing **fundamental research** and maintains a strong belief in the importance of advances of fundamental science for its own sake. This 'blue skies' spirit is embedded in the organisation's DNA and is increasingly rare in the modern world
- It is an unusually open and **democratic** organisation, with little top-down management, in which all participants are able to pursue new ideas without prejudice. "Vertical" managerial structures exist (and are necessary), but these are not rigid and preserve an element of "democracy"
- It provides the exemplary case of how to arrange scientific collaboration on a **long-term and large-scale project**. Its long-term stable funding (via the treaty) is unique and provides a framework for long-term, large-scale projects that might otherwise be susceptible to political and financial fluctuations [contrast this with US model and the cancellation of the Superconducting Super Collider (SSC), discussed at the end of this section]

Source: Questionnaire survey of UK scientists and engineers

These opportunities are enjoyed by a broad base of UK scientists and engineers

Through its subscription, the UK secures access for UK scientists and engineers to key research infrastructure and collaboration networks. STFC's Core Programme (alongside investments by other UK research councils) then funds UK-based researchers to enable their participation in the experimental programmes hosted by CERN.

Through a planned long-term strategic research programme, UK universities receive significant funding from STFC. **Funding data** shows that since 2005 STFC has made 670 awards related to CERN, or using CERN facilities, for a total of ~£514m. In addition, 39 awards (£23m) were made by EPSRC for projects containing the term 'CERN' within the title or abstract. We have also identified a small number of awards made by AHRC, BBSRC, ESRC, Innovate UK and NERC to projects with "CERN" in their title.

Overall, 35 **UK universities** have received funding directly relating to CERN (where the "grant" title contains the term 'CERN') since 2005. The top six institutions in terms of total value of funding are shown in Table 2. The UK is also home to two university-based **accelerator institutes**: the Cockcroft Institute (CI), which is located at the Daresbury campus and is a partnership between the Universities of Lancaster, Liverpool, Manchester and Strathclyde, as well as the STFC's Accelerator Science &

Technology Centre (ASTeC); and the John Adams Institute for Accelerator Science (JAI), which is a joint venture between the University of Oxford and Royal Holloway University of London (plus Imperial College London, as of 2012). The Particle Physics Department (PPD) at the STFC's Rutherford Appleton Laboratory (RAL) also participates in and supports the UK particle physics experimental programme, including through the design and construction of large detector systems and by providing accelerator expertise. STFC Daresbury also participates in the UK nuclear physics programme, including ALICE.

Table 2 Top institutions for CERN-related STFC funding

UK institutions	Total funding in £ m
University of Liverpool	64.0
University of Oxford	63.6
Imperial College London	53.7
University of Manchester	37.9
University of Cambridge	30.7
University of Glasgow	30.4

Source: Awards identified by STFC from GtR (CERN-related or evidence of use of CERN facilities)

As of 28th January 2019, there were 793 **UK CERN researchers** (based on *nationality*). This is 10% of all member state researchers, fourth highest behind Italy (2,050), Germany (1,319) and France (850). Data from 2017 (latest available) shows that the UK-nationality researchers at this time (n=706) included research physicists (86%), scientific engineers (9%) and technicians (5%).

The number of researchers *from UK host institutions* is higher (1,042). On this measure, the UK accounts for 13% of researchers from member states, third highest behind Italy (1,627) and Germany (1,383)[39]. The hosting of ~200 non-national researchers within UK institutions is only surpassed by Switzerland amongst CERN member states (providing an indicator of the attractiveness of the UK – discussed in the next section).

Around 900 UK physicists[40] are *currently* CERN researchers. For a sense of scale, this is equivalent to nearly one-fifth of all the academic staff in UK physics departments (n=5,385)[41]. The UK is therefore accessing and using CERN's instruments and facilities on a significant scale.

Our survey of the UK science and engineering community demonstrates the **breadth of the UK research community that benefits from CERN**. While half of the respondents work mainly in the field of experimental physics, there are also a range of other disciplines represented (engineering, computer science, theoretical particle physics, astrophysics, nuclear physics, and so on). The vast majority had worked (on site) at CERN as part of their research work for sustained periods and / or on a frequent basis (indeed a third are currently working at CERN). Most (83% of) respondents had also made some use of CERN experimental data in the past few years, including 29% that reported they had done so constantly (100% of the time). Respondents come from over 30 different organisations, including 23 different UK universities, 5 public research institutes, and 6 commercial organisations.

UK personnel have been **involved in all the major experiments** and discoveries at CERN. For example, the UK is one of only a few member states with scientists, engineers and technicians involved in all four large LHC experiments. It is particularly heavily involved in the ATLAS, CMS and LHCb experiments (see Table 3). Beyond these, there is also a particularly strong UK research contingent involved in ISOLDE (59 UK researchers and 6 institutions) and in HiRadMat.

[39] Note that the level of available national funding is a strong determinant of the number of CERN researchers

[40] CERN personnel statistics suggest that 'Research Physicists' account for ~90% of all (1,024) CERN researchers from UK institutions

[41] HESA. Academic staff by cost centre, 2016/17 – 2017/18.

Table 3 Researcher data for the four large LHC experiments

Experiment:	ATLAS	CMS	ALICE	LHCb
UK researchers 2017	307	105	26	110
Total registered researchers 2017	3,912	3,076	1,314	870
UK Authors 2016/17	199 out of 1856	60 out of 1,400	9 out of 615	89 out of 488
STFC Investment into Experiments and Upgrades	£145m (1997-2018)	£41m (1998 – 2017)	£12m (1999– 2017)	£31m (2001 – 2017)
Institutes and Universities Involved in Experimental Upgrades funded by STFC	(15) Birmingham, Cambridge, Edinburgh, Glasgow, Lancaster, Liverpool, Manchester, QMUL, RHUL, Oxford, Sheffield, Sussex, UCL, Warwick, STFC RAL.	(5) Bristol, Brunel, Dundee, Imperial, STFC RAL	(3) Birmingham, Liverpool and STFC Daresbury.	(11) Birmingham, Bristol, Cambridge, Edinburgh, Imperial, Glasgow, Liverpool, Manchester, Oxford, Warwick, STFC RAL

In turn, UK engineers and scientists have also made **major contributions to CERN technology**. For example, UK researchers were centrally involved in the development of 'crab cavities' to rotate a beam of protons, a critical component for the LHC upgrade (see below – full case in Appendix E). Due to the specific and exacting requirements of this technology, the development process encouraged the UK contributors and contractors to push boundaries and develop new solutions to the challenges posed.

Case Study 5 – Development of crab cavities

The High-Luminosity LHC (HL-LHC) project aims to increase the luminosity of the LHC by a factor of 10. The higher the luminosity, the more collisions, and the more data the experiments can gather to allow them to observe rare processes. The materials budget for the accelerator has been set at £735m for the period 2015 to 2026, at which point the HL-LHC should be operational.

As part of this project, special 'crab cavities' have been developed. These tilt proton bunches, forcing every proton of the bunch to pass through the whole length of the opposite bunch and thus increasing the probability that it will collide with another particle and maximising the number of particle collisions.

The UK collaborated on the development of these crab cavities, with STFC acting as one of the coordinators for the work. Researchers from the UK also took a leadership role in the development and construction of the technology. This included engineers from Lancaster University designing and testing a number of sub-systems, researchers at the Universities of Manchester and Liverpool modelling the beam dynamics and measuring the 'crabbing', and engineers from STFC's Daresbury Laboratory developing the cryomodule that encloses the crab-cavities. Half of the budget for UK work is coming in the form of inward investment from CERN.

The two first crab cavity prototypes were assembled and tested at CERN in 2017, and on 23 May 2018, a proton beam from the Super Proton Synchrotron (SPS) accelerator was rotated for the first time, showing that bunches of protons could be tilted using these superconducting transverse radio-frequency cavities. In total, 16 crab cavities will be installed in the HL-LHC – eight each near ATLAS and CMS.

CERN has also often been at the cutting edge of **large-scale computing and software innovations**, with UK personnel often in the vanguard. UK influence has continued through its national "e-science" programmes and strong involvement in Grid activities (see GridPP case study, summarised below).

Case Study 6 – GridPP

Computational grids are arguably the most significant development in Information Technology since the creation of the World Wide Web. In essence, the grid promises to do for computer hardware what the World Wide Web did for software.

The Large Hadron Collider (LHC) at CERN was the first project to require processing of petabyte scale datasets (a million gigabytes). The scale of the data and the international nature of the LHC, led to the development of grid computing and the Worldwide LHC Computing Grid (WLCG). The UK was at the forefront of this emerging Grid computing paradigm and has contributed its share of WLCG computing resources through GridPP - a collaboration of 20 research institutes and data centres across the UK.

GridPP comprises not only the Tier 1 and Tier 2 physical-infrastructure (computing nodes, storage and networking) but also the sophisticated software-infrastructure and tools needed for supporting collaboration, managing petabyte scale data sets, managing workloads across the CPU power available across the globe and deploying software across the Grid.

GridPP also now works with diverse communities outside the immediate LHC context, including other particle physics experiments (NA32, T2K, SNO, LuxZeplin Dark Matter Experiment and now the DUNE Neutrino experiment), as well as astronomy projects (SKA and LSST). GridPP also supports other physics (e.g. the ITER fusion experiment); health (e.g. modelling disease epidemiology (EPIC), proteomics, phylogenomics and drug development); and geography (e.g. through geographic modelling of landscapes (MoSSaiC) and populations (GENESIS)). A medical proton therapy project (PRaVDA) performed Geant4-based solutions on GridPP and, as a result, has been able to run five times more particles per simulation, while reducing total run times from weeks to hours.

GridPP also benefits UK businesses. Through a range of collaborative projects, GridPP has supported the development and testing of new technical solutions. This has included the improvement of a powerful platform for commodities trading provided by Econophysica. Imense, a Cambridge start-up company developing image search algorithms, also used GridPP infrastructure to accelerate the processing of 12.4 million images, which led directly to venture capital funding for the company. GridPP is also working to support future industrial applications, for example supporting Total Oil's Geoscience Research Centre based in Aberdeen to test the potential of Grid computing to analyse the seismic response of marine tests.

CERN opportunities support the strength of the UK research community

The opportunities and access afforded at CERN support the strength of the UK research community and its achievements and progress, helping to sustain the UK as a world leading research nation (e.g. boasting 5 of the top 25 research universities[42] and ranking fourth in the global innovation index[43]). Indeed, a majority of the UK science and engineering community responding to our survey claimed that CERN had been 'critical' in supporting the UK's science and engineering community in undertaking R&D that is (each of) cutting edge, world-leading, international, significant, innovative and ambitious.

The bibliometrics exercise undertaken for this study (see Appendix D) has measured **publication performances in Nuclear & Particle Physics** (NPP) research across seven countries (the UK, France, Germany, the Netherlands, the US, Canada and Australia). For each, the analysis has compared: (i) the overall performance; (ii) the performance of papers from CERN-affiliated authors; and (iii) the performance of papers from non-CERN-affiliated authors. In other words, it has aimed to tease out the specific contributions brought about by CERN research to national performance.

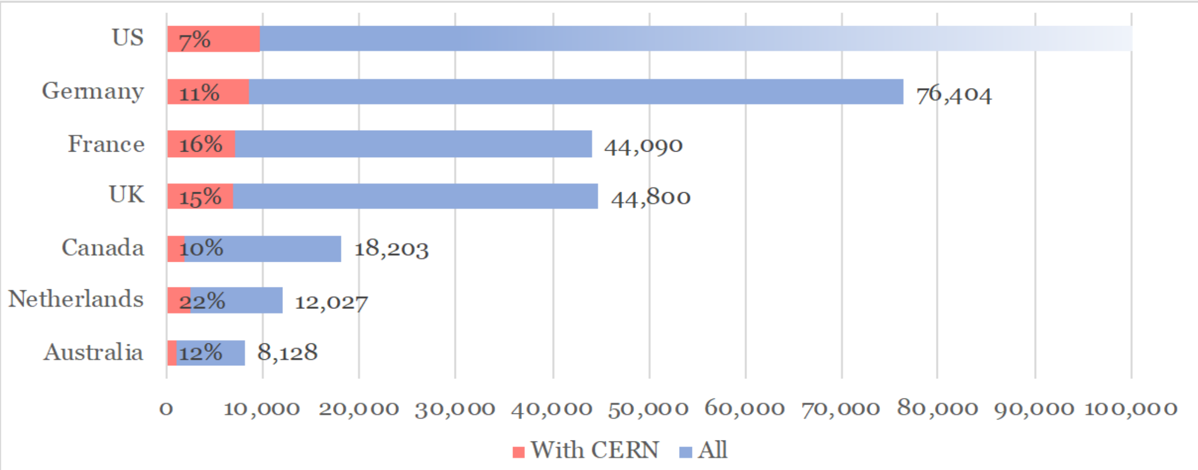
Across all the countries considered, CERN papers contribute relatively small volumes to the overall national publication portfolios in the NPP field (see Figure 9). CERN papers amounted to roughly 15% of the full UK output in NPP between 1996 and 2017 (6,783 articles out of 44,800, based on full

[42] Times Higher Education World University Rankings for Research, 2019

[43] Based on overall scores. Global Innovation Index, 2018

counting) – a rate that has remained relatively stable throughout this twenty-year period. NPP outputs for Germany, the US, Canada and Australia all contain a smaller proportion of CERN papers (7%-11%), while this proportion is higher for France (16%) and the Netherlands (22%).

Figure 9 Number of NPP papers per country (1996-2017) and proportion with CERN affiliation

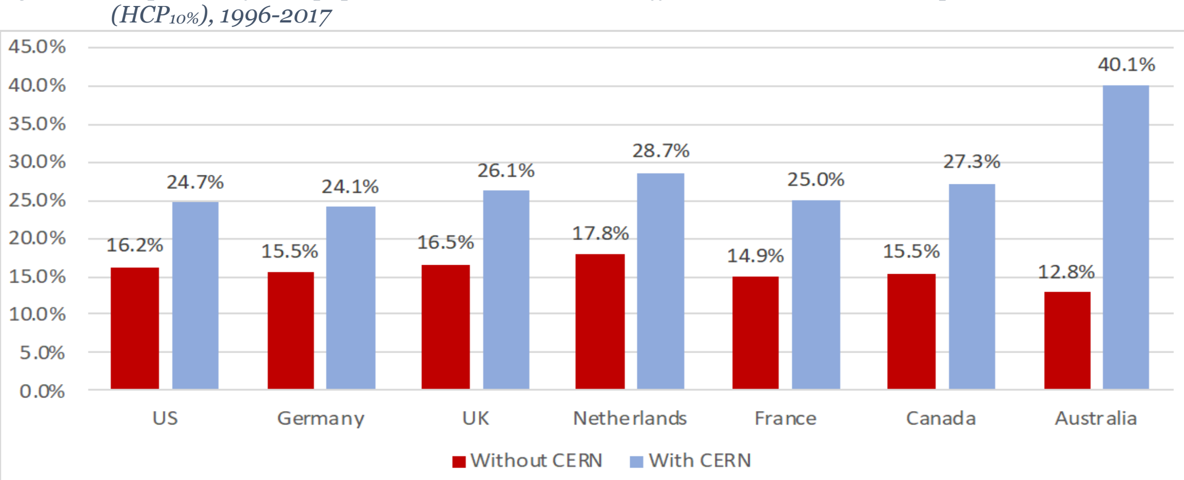


Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

Despite the relatively small volumes, however, the CERN-affiliated NPP papers **significantly pull citation metrics upwards** across all the countries considered (Figure 10), providing an indication of the high-quality and importance of research that has been enabled by access to world-leading infrastructure.

Increases in the shares of $HCP_{10\%}$ publications (the 10% most cited in their field) range from an additional 8 or 9 percentage points (for the UK, Germany and the US) to as much as 25 percentage points (for Australia[44]), when moving from the non-CERN to CERN publications. The same general trend can be observed on all citation indicators.

Figure 10 Proportion of NPP papers (with / without CERN-affiliation) that are in the top 10% most cited ($HCP_{10\%}$), 1996-2017



Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

44 It should be noted that Australia's exceptionally high performances recorded for CERN papers are based on a rather small data set of 54 papers that may be susceptible to wider swings brought about by outliers.

For its citation-based performances in the NPP subfield (overall), the UK ranks at number two, behind the Netherlands, in our selection of seven countries, and these rankings remain nearly unchanged when all countries are compared for their scores excluding CERN papers. However, in a hypothetical situation where the UK's performance was measured without its CERN papers, but scores from other countries would still include CERN papers (i.e. if the UK no longer had access to CERN), the UK would slip into fifth position (out of this subset of seven) when considering the $HCP_{10\%}$ indicator.

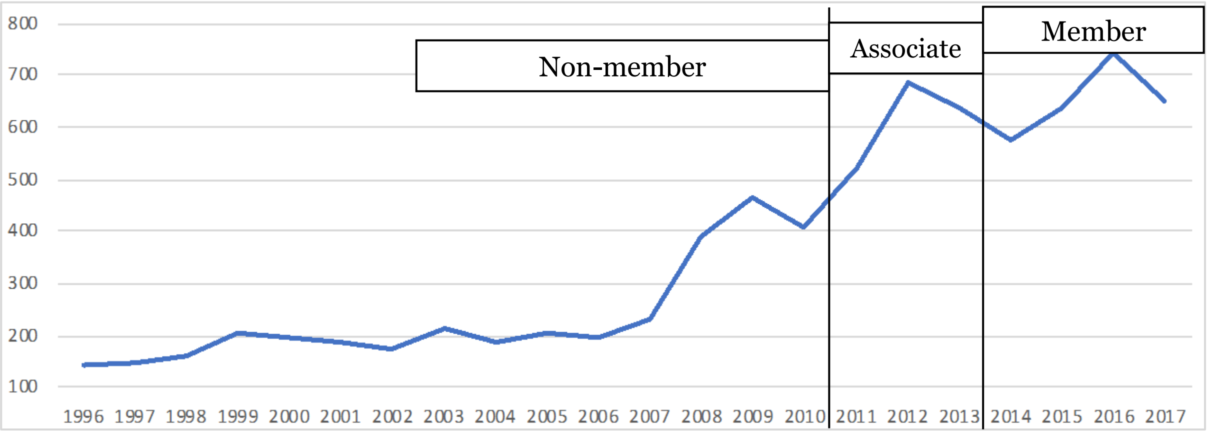
The findings also show that the impact performance of CERN papers have consistently contributed to rising overall country scores, beyond the global increases seen in NPP research. The UK is no exception.

Finally, because the opportunities offered by CERN are so closely tied to access to instruments, CERN-related performances appear to be affected by the life cycles of its facilities. For example, some performance metrics for CERN publications experienced a drop between 2006 and 2010, which is presumably as a consequence of a steering of efforts toward instrument development rather than experimentation in the period immediately leading up to the Large Hadron Collider launch in 2008.

The impact of CERN on national research communities can be seen more clearly by considering the **experiences of two countries that became member states** of CERN in recent years. Specifically, the bibliometric analysis has assessed what has happened to the output and impact of NPP papers in Israel and Romania as these countries increased their access to CERN facilities and opportunities. (Spain was another possible case to explore, having left and re-joined CERN for a period of time. However, this occurred in the 1960s and 1970s, and the lack of robustness of the bibliographic records for this period ruled this out as a credible comparator).

Firstly, Israeli scientists have been involved in CERN since 1991, but Israel became an Associate Member in 2011 and a full Member in 2014. The following figure charts the rapid increase in Israeli publications in the NPP subfield over this period.

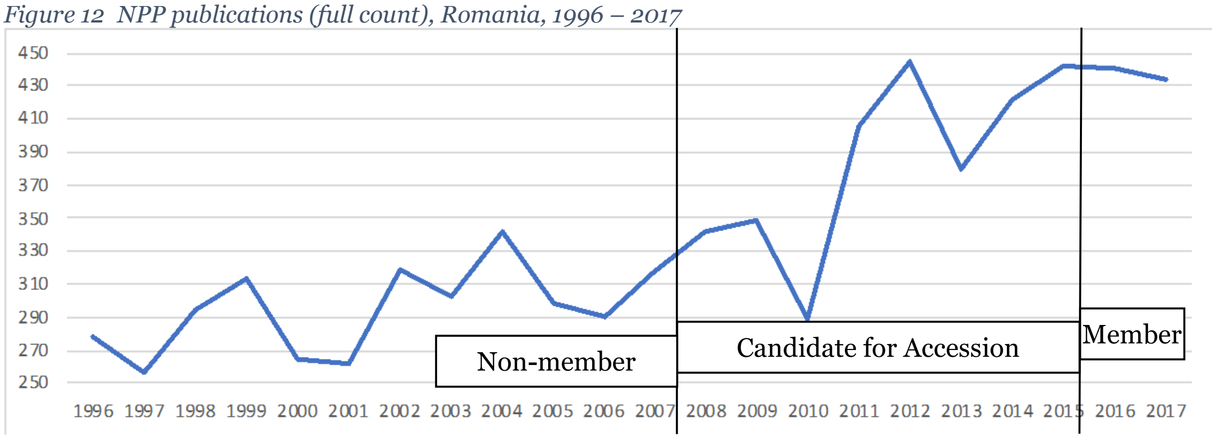
Figure 11 NPP publications (full count), Israel, 1996 – 2017



Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

Romania also began direct collaboration with CERN in the 1990s. It was then granted the status of Candidate for Accession to Membership in 2008 (ratified by the Romanian Parliament in 2010) and then gradually increased its contributions to CERN (and participation in CERN projects) to normal member state levels by the time it became a full member state of CERN in 2016. The following figure charts the rapid increase in Romanian publications in the NPP subfield over this period.

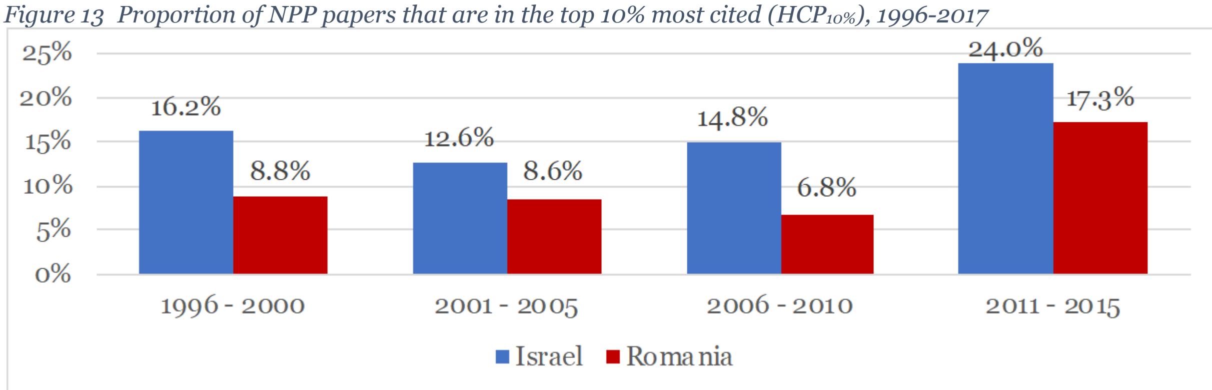
Figure 12 NPP publications (full count), Romania, 1996 – 2017



Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

Both countries have also seen a significant increase in their share of NPP publications in the top 10% most cited ($HCP_{10\%}$) during the period in which they became Associate / Candidate Members (see below).

Figure 13 Proportion of NPP papers that are in the top 10% most cited ($HCP_{10\%}$), 1996-2017



Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

CERN supports sustained UK excellence and leadership

More generally, **UK bibliometric performance** in the NPP subfield and in the wider set of S15 CERN-relevant subfields is strong, both in terms of output and citation metrics.

The data shows that the UK is a leading country in the NPP subfield, and even has a slight specialisation compared with the other countries considered. It is among the top tier (top 10) of countries for the volume of its publication output in this area, irrespective of the use of fractional (24,538 papers, 1996-2017) or full (44,800 papers) counting methods.

Turning to impact metrics, the UK consistently came in third rank (behind Switzerland and Spain) within the top tier of large publication volume countries, across most of the indicators computed. When including countries with smaller volumes of NPP publications, the UK is still a leading country on citation metrics, however, it falls slightly outside the top 3 group. It is generally difficult to maintain a very high impact as production volume goes up. As such, the UK's combination of high output volume and high citation profiles in NPP can be considered a strong achievement.

The UK's longitudinal trends for its citation metrics have also been almost uniformly upwards. Its Citation Distribution Index (CDI) has increased from 11.0 (1996-2000) to 17.3 (2011-15), while shares of $HCP_{10\%}$ increased from 15% to 22%.

In the wider S15 set of subfields, the UK contributed close to 557,000 articles in the 1996-2017 period (full count). The country also posted a positive growth rate of 1.50 between 1996–2000 and 2000–2017. Its publications in the S15 placed the country among the top tier on citation metrics performances, usually only behind Switzerland, the Netherlands and the United States. If examination of citation profiles is restricted to just the top 10 countries with the largest outputs in S15, the UK moves up and takes second rank for its citation metric performances (across all indicators), only behind the US. Again, a combination of high output volume and high citation profiles in the UK is a significant achievement.

Surveys and interviews have also provided **testimony from the UK science and engineering community** as to the impact of CERN on their research and technology activities. Most respondents claimed that access to CERN facilities and opportunities had a significant (critical / large) impact on: their ability to participate in international collaborations (90%); the strength of their international networks (82%); and the quality of their R&D (79%).

For their wider groups and departments in the UK, CERN was also rated as having a significant impact on their opportunities to access world-class facilities (86%) and international networks (85%). Indeed, half of respondents (55%) claimed that UK membership of and involvement in CERN was critical to maintaining a large and active community in their field within the UK. Similarly, over half (57%) claimed that CERN was critical to the very existence of their group or department. As one commentator put it, *"The UK particle physics community would simply die and be isolated without CERN"*.

Some took the opportunity to provide further details of an area where CERN had a particularly significant impact on their activities. Most focused on their ability to pursue their research. E.g.:

> *"CERN experimental results are the foundation upon which my phenomenology research is built. I consistently use CMS/ATLAS public results and papers to build on and inform my research"*
>
> *"CERN operates globally unique machines which enable my field of research. It would literally be impossible to pursue this line of research elsewhere at present"*
>
> *"My theoretical work is motivated and driven by the experimental achievements made at CERN"*

Benefits without a market price can be estimated using a range of techniques, including the so called 'stated preference' or contingent valuation techniques. To explore this, we invited UK scientists and engineers through survey to provide a financial view as to the research benefits of CERN to them. Specifically, we asked what the maximum is that they would personally be willing to pay (WTP) each year (for the next 20 years) to ensure the continued existence of CERN in its current form and all of the research benefits that flow from it to them. Responses varied, but the majority opted for a figure in the range £10 to £100 each per year (£50 median, £493 mean). These are high valuations if we note that the UK's subscription to CERN currently only costs the average UK tax payer £2.10 each a year.

We used the average WTP figures (£50 and £493) and the number of relevant academic staff in the UK to arrive at grossed-up estimates for a ten-year period. The results suggest that members of the UK scientific community would (personally) be **willing to pay £30.2m over a decade** (in 2018 prices) **for the continued existence of CERN** and the benefits to them that flow from this.

The approach to monetising the value of CERN to the UK scientific and engineering community (including assumptions and limitations) is explored further in the summary of monetised benefits (section 10).

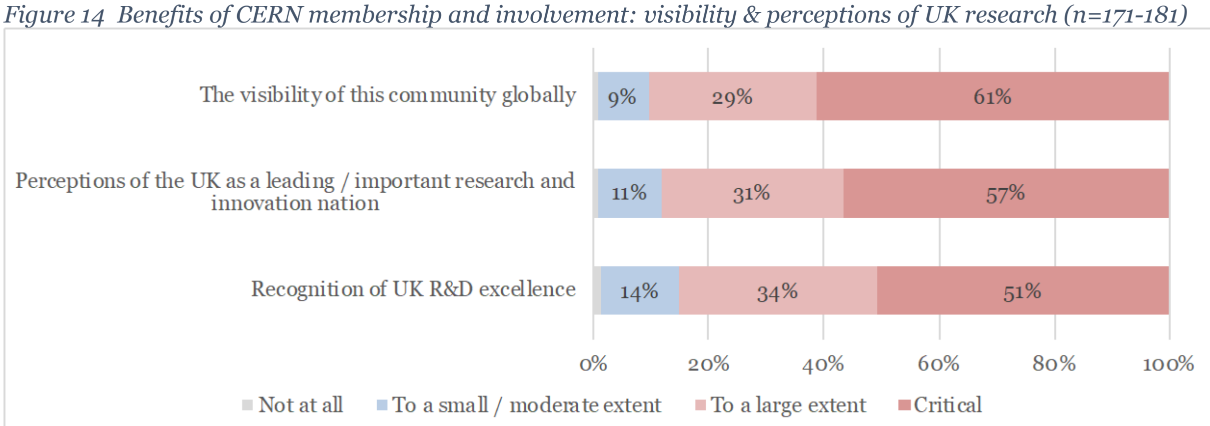
6.3 Attracting investment and talent to the UK

CERN contributes to the UK's international presence, visibility and reputation

The UK's involvement with CERN increases its international presence and visibility, including through its network of collaborations and connections in science and technology. It helps to enhance recognition of the UK's research excellence and increase its perception as a great research nation (innovative, world-leading, cutting edge, international, etc.) and the place to do science and innovation at the highest level.

This is certainly the view of the UK science and engineering community. They were asked to rate the impact of CERN membership/involvement on the **UK 'science brand'** (see figure below). The great majority reported that CERN was significant (large or critical impact) for the international visibility of the UK science and engineering community, for perceptions of the UK as a leading research and innovation nation, and for international recognition of UK R&D excellence.

Figure 14 Benefits of CERN membership and involvement: visibility & perceptions of UK research (n=171-181)



Source: Questionnaire survey of UK scientists and engineers

Most of the individuals responding to our survey (82%) also reported more specifically that their involvement with CERN had a significant impact (31% 'large' and 51% 'critical') on **their own national and international reputation**. Some went on to give examples of ways in which CERN membership allows the UK to put the quality of its work on international display. For example:

> *"The leading role of the UK in development of GRID computing concepts essential to the large quantity of data produced by CERN experiments"*
>
> *"Leading roles for the UK in CERN experiments (UK people as spokespersons, leading analysts in discovery papers, leading roles in collaborations …)"*
>
> *"The UK science and engineering community's vital role in the construction of the ATLAS detector and in key analyses performed with the data collected."*
>
> *"The UK's dominant role in some vital projects, such as the ATLAS trigger system."*

As noted in previous sections, the bibliometrics analysis has shown that participation in CERN has had positive ramifications for the **UK's publication output and impact**, particularly in Nuclear & Particle Physics (NPP). It has also shown that the UK would lose places in international rankings in NPP if it was to stop its CERN involvement. CERN can therefore be said to be supporting the UK's (and its research community's) international standing.

In addition, the bibliometrics analysis has considered **international co-publication indicators** as another relevant indicator for visibility and reputation (see Appendix D). Higher global visibility and reputation is often acquired through intensive co-publication, with the papers resulting from such partnerships also tending to be cited at higher rates.

The majority (62%) of all CERN papers are written as international co-publications (whether we look at just NPP or the wider set of S15 sub-fields). For the UK, 67% of all NPP papers are international co-publications, but this rate increases to 92% for those NPP papers relating to CERN (see Table 4). In fact, UK-CERN NPP papers have a mean number of 14 contributing countries, and a median of 7, while non-CERN UK papers have a mean of 3 and median of 2. As such, it can be concluded that in the UK (as in all other countries included in the analysis), participation in CERN clearly provides researchers with unique opportunities for engagement in highly collaborative and international projects.

Table 4 Rates of international co-publications, 1996-2017

	CERN papers	UK papers	UK-CERN papers
Nuclear & Particle Physics	61.7%	66.8%	92.0%
S15 selected subfields of science	62.3%	53.2%	

Source: Technopolis / Science- Metrix bibliometric analysis, based on Scopus data

Scientific publications resulting from highly collaborative and international research tends to be cited at higher rates than national collaborations or single-author papers, and therefore achieve greater levels of visibility. The performance of all countries examined appears to have benefited from sizeable gains in impact brought about by the CERN-related component of their publication portfolio.

The UK is perceived as a place to do science and innovation at the highest level

The positive 'brand' of the UK as an important science nation, as well as the opportunities open to its scientists, engineers and institutions through CERN, help to attract funding, talent and other forms of recognition. It also supports the UK's continued involvement in international research and collaboration, as a partner of choice for international projects and in the development of new facilities.

Available data suggests that the UK is an **attractive destination for top scientists from abroad:**

- We showed earlier that the number of CERN researchers that are from UK institutions (1,042, as of January 2019) is higher than the number of CERN researchers with UK nationality (793). In fact, despite being one of 23 member states, the UK hosts 1 in 8 CERN researchers in these countries
- According to Universities UK (UUK), the UK is able to recruit some of the top minds in their fields to teach in universities and conduct world-leading research, with 28% of all academic staff coming from outside the UK (the figure is 40% for engineering and technology subjects)[45]
- HESA time-series statistics on the nationality of UK-based academics also show that non-nationals constituted ~40% of all staff in the physical sciences and for engineering (making this the most international of all cost centres covered, and well above the ~30% average for all disciplines)
- There are also currently 437,000 international students (non-EU) studying at our universities, and UUK have found that 80% of international graduates in the UK are planning to develop professional links with UK organisations
- In 2016, 68% of all Ernest Rutherford Fellowship[46] applications were from outside the UK, while 46% of the fellows appointed were from EU or non-EU countries

[45] https://www.universitiesuk.ac.uk/facts-and-stats/impact-higher-education/Pages/universities-attract-talent-from-across-the-globe.aspx No further breakdown available for the figure for engineering and technology subjects.

[46] The Ernest Rutherford Fellowship is an STFC fellowship programme to enable early career researchers within STFC core science areas to establish their research programmes, with funding for 5 years.

Our own survey of UK scientists and engineers connects this international talent attraction with CERN. Nearly all respondents (90%) claimed that the UK's involvement in CERN was significant (large or critical impact) for attracting top scientific and engineering talent to the country.

Many also provided further details in their response on the role of CERN in attracting and retaining talent within their group, institution or field in the UK. A selection of examples is shown below:

"The vast majority of the members of my group (PhD students, postdocs, faculty) are either very talented UK researchers who have worked at or with CERN before returning to the UK, or are excellent foreign scientists who have decided to come and work in the UK because of the excellent reputation that, through its affiliation to CERN, the nation has as a world-class science hub internationally."

"Much of modern particle physics requires the use and interpretation of current experimental data, the most important of which comes from the experiments at CERN. A country that does not have membership to CERN is automatically discounted as a working environment for a large number of particle physicists"

"Universities would struggle to attract brilliant scientists if they did not have a presence at CERN"

"40% of the 40 highly skilled researchers in my group are from outside the UK, attracted by CERN and the perceived openness to international collaboration."

"The top scientific talent in particle physics wants, generally, to work on the questions that are at the cutting edge of particle physics. That physics is being done, almost entirely uniquely, at CERN. If the UK wishes to continue to attract such talent, membership in CERN is necessary."

There is also some limited evidence of CERN playing a role in **talent retention**. In 2016 STFC collected information on the first destinations of 941 STFC-funded PhD students who had completed their doctorate in the previous four years. The majority were funded in the area of astronomy, particle astrophysics, cosmology and solar system science (n=521), however the data also includes some from experimental particle physics (186), theoretical particle physics (126) and nuclear physics (73). There is no information on the extent to which they had interacted with CERN – however, the survey found that at least 45% went on to postdoc positions, and that half of these (51%) were in the UK. The proportion staying within the UK is also significantly higher for the experimental particle physicists sub-set (~64%).

As a point of comparison, the decision to **cancel the building of the US Superconducting Collider (SSC)** in October 1993 (after some $2bn of investment) had a significant negative impact on the US particle physics community. A survey conducted by *Science* magazine in 1994 found that around half of the scientists involved in the SSC left the field of physics following the cancellation of the project.[47]

[47] https://www.scientificamerican.com/article/the-supercollider-that-never-was/

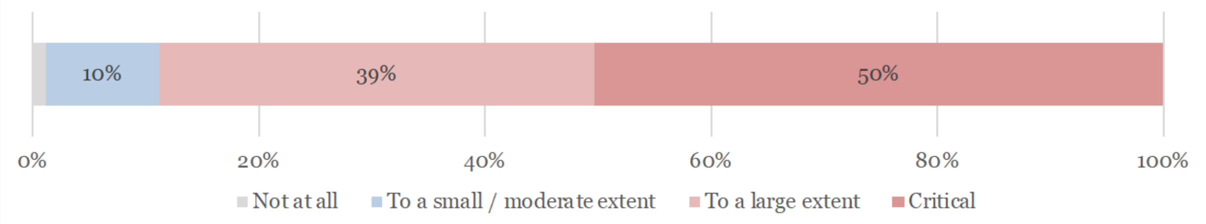
For further discussion, see 'A bridge too far: the demise of the SSC', Physics Today 69, 10, 48 (2016): "When the US Congress terminated the Superconducting Super Collider (SSC)... it ended more than four decades of American leadership in high-energy physics.... the SSC cancellation was the ultimate blow that put Europe unquestionably in the driver's seat and opened the door to the discovery of the Higgs boson at CERN."

The available data also suggests that the UK is also overall an **attractive destination for international R&D funding.** For instance:

- The UK has the highest share (around 20%) of externally funded R&D amongst the major industrial economies and is an extreme outlier in this respect[48]
- It is an economy with an exceptionally high overseas ownership of businesses carrying out R&D[49]
- At the end of 2018 there had been 116 H2020 grants awarded to projects that mention "CERN" in their objective statement. In a third of these cases (n=43), there is at least one UK participant. The UK participants have been awarded in the region of €35M (£30m) through these projects[50]. Some of the largest awards are for ERC grants, of which the UK has received 15 (mentioning CERN), with a total value of around €22M (£19m)

Our survey respondents were also generally positive about the impact of their involvement with CERN on their own ability to attract public or private funding. Some 99% reported that CERN had had some impact – including 50% reporting that it been 'critical' and another 37% reporting a 'large impact'.

Figure 15 Benefits of CERN membership and involvement– ability to attract R&D funding & investment (n=171)



Source: Questionnaire survey of UK scientists and engineers

Some of the more detailed examples given are shown below for illustration:

> *"The large number of non-EU countries currently applying for membership of CERN demonstrates that this is seen as a KPI for scientific excellence and a hi-tech society / industry, in order to attract inward investment in these sectors.*
>
> *"Several researchers have joined our group with ERC grants. If we were not involved in CERN, they would not have joined us, and instead would have taken their expertise (and funding to create jobs and PhD places) to other EU countries."*
>
> *"The UK has been extremely successful in attracting high value ERC grants for CERN-related research, including my own ERC Advanced Grant which is entirely based on CERN research. Without CERN membership I would probably have had to leave the UK for an overseas university, depriving my university of a research group of 40 members, built up by me from approx. 4 members in 2004."*
>
> *"UK-based scientists have been very successful in obtaining funding outside the main research council route for research that relies on involvement in CERN experiment (e.g. EU starting / consolidator / advanced grants). Securing this funding would not have been possible without CERN membership."*

[48] Hughes, A. and Mina, A. (2012). The UK R&D Landscape, Revised March, UK~IRC and CIHE, Cambridge and London.

[49] The economic significance of the UK science base – A report for the campaign for science and engineering. UKIRC, 2014

[50] Publicly available data does not provide a breakdown of project funding by individual participant organisations. Nor does it identify if there is more than one participating organisation from the same country. In half of the projects identified, the UK is partnered with other organisations and we have divided the funding evenly amongst countries for the calculation.

7 Impacts relating to world-class innovation

7.1 The wider application of CERN technologies

CERN's development and scientific goals drive technical advances in facilities and infrastructure	→	New innovations emerge, underpinned by technologies developed at / for CERN	→	Wider application brings benefits to UK researchers, consumers, patients, society

CERN's scientific breakthroughs have often required **major technological advances**, both in terms of the core facility technologies (e.g. the accelerators and detectors) and the supporting infrastructure (e.g. microelectronics, GRID computing, data analytics, machine learning, modelling).

These technologies, developed for CERN, are often suitable for **take-up and development for applications elsewhere**, in other research facilities and beyond. In several notable cases, they have provided the platform for a major new technology that has come into general use and had a transformative effect in all walks of life. However, there are numerous other examples, with a good proportion of these involving UK researchers and businesses and the realisation of commercial benefits.

Developments based on CERN technologies and methods can hence lead to economic impact for UK businesses and the UK economy. New applications underpinned by technologies developed at CERN can also deliver societal impact by bringing benefits to UK consumers, patients, the environment, and so on, depending on where and how these are applied.

The most well-known example of the wider application of CERN technology is the World Wide Web, which was invented by British scientist Tim Berners-Lee in 1989, while working at CERN. Originally conceived and developed to meet the demand for automated information sharing between scientists in universities and institutes, CERN put the World Wide Web software in the public domain in 1993 and later made a release available within an open licence, ensuring its maximum dissemination and uptake. The World Wide Web is now estimated to contribute 2.9% to global GDP (2011) and to have accounted for 21% of GDP growth in mature economies over recent years.[51]

In her book 'The Entrepreneurial State: Debunking Public vs. Private Sector Myths", Mariana Mazzucato dedicates a chapter to how state-funded research made possible Apple's 'invention' of the iPhone and iPad. This identified 12 technologies that are integrated features and act as enablers or differentiate these products from rivals on the market. This includes the Hypertext Transfer Protocol (HTTP), which was first successfully implemented for computers at CERN, and the touchscreen, which was invented with support from Government R&D (and with one of the first notable developments at CERN, in 1973).

Other examples of the wider application of CERN technology include technology used in medical imaging, (e.g. PET and superconducting magnet technology), and in cancer treatment (e.g. hadron therapy). Software developed at CERN, such as the GEANT series for the simulation of the passage of particles through matter, is also used in other fields. We have developed a series of case studies covering each of these major examples of the wider application of CERN-derived technologies. These are briefly summarised at the end of this section and presented in full in Appendix E.

UK scientists and engineers were also asked (through survey) for *other* examples of technologies that originated at CERN and that have had wider application and benefit. Suggestions included:

- Software tools developed at CERN (e.g. ROOT, PAW, FLUKA) that are used both in physics and in other fields (e.g. **the space, nuclear, medicine and aviation sectors**). For example, ROOT is an object-oriented program and library originally developed by CERN for particle physics data analysis, but now also used in other applications, such as astronomy and data mining. The GeneROOT project (run by CERN openlab in collaboration with King's College London) aims to use the ROOT data processing framework to develop a platform that will support a complete data-analysis life cycle, from data discovery, through to access, processing and end-user data analysis.

[51] The great transformer: the impact of the internet on economic growth and prosperity. McKinsey Global Institute, 2011

The first use-case for this platform relates to genomics, with ROOT being used to store and process genomics data sequences. A minimal viable platform was created in 2017 and KCL is currently carrying out initial tests. Another example is FLUKA, which is a particle transport and interaction simulation code that was developed at CERN and which has also found application in e.g. the medical domain. In 2016, FLUKA was used to study the possible advantages of radioactive beams of Carbon 11 or Oxygen 15 for hadron therapy. A FLUKA licence was also given in 2016 to a UK company (Innocryst) for fingerprinting natural and man-made gemstones.

- CAD packages developed at CERN (as open source code) that are being used routinely by electronic industry. For example, with donations from industry, CERN experts have adapted the open-source software KiCad to make it an efficient **tool for designing open-source hardware**. This free software makes it easier for electronics engineers to share their printed circuit board designs. Newbury Electronics (Berkshire) designated KiCad as the best free PCB Design software of 2018[52].
- Various other advances in computing, e.g. grid computing and distributed processors, as well as advances in machine learning, pattern recognition, server networks and big data analyses, which have been made at CERN and brought wider benefits. To take some specific examples: (i) CERN recently ran a four-day training course for a global life science company to share its expertise on machine learning and help **improve vaccine production**; (ii) CERN collSpotting software was developed through an FP7 project that involved CERN, STFC and various UK universities. It provides a visualisation and navigation platform for large and complex datasets, and is now being used to support large-scale visual analytics as part of applied research in pharmaceuticals, IT networks analytics, neurology and education; (iii) Global IT companies collaborating with CERN have also used the challenging performance demands of the facility to **stress-test their products**.
- Statistical techniques developed at CERN are now used within other sectors. For example, the neurobayes technique (a sophisticated neural network, based on Bayesian statistics) has been successfully **applied in medicine** (undesirable effects of drugs, early tumor recognition), **banks** (evaluation of derivatives, risk-minimised trading strategies) **and insurance** (fraud recognition).
- Fibre optic sensors to help **manage water shortages**. CERN is leading the FOSS4 project, funded by the UK Lebanon Tech Hub, to develop a system for optimised irrigation, based on technologies developed for high-energy physics. The irrigation system will use fibre-optic sensors designed to measure parameters such as temperature, humidity, concentration of pesticides, fertilisers and enzymes in the soil. All hardware will be released under CERN's Open Hardware Licence and the software will be released under an open source licence within two years of the project termination.
- Electrochemical sensors for **water pollution measurement**. A low-cost version is being developed by the STFC-CERN-BIC company Camstech Ltd. – which is the focus of a case study.
- Radiation hardened robotics for **decommissioning/disaster relief**. Robotics Software is used at CERN to manage autonomous movement, allowing a modular robotics platform to perform sophisticated tasks. CERN developed this technology to protect its personnel against hazards in the accelerator facilities. Ross Robotics (UK), a start-up company, is now developing a sophisticated robotics platform, exploiting CERN's robotics software based on a licencing agreement with CERN.
- Radiation testing facilities for **satellites**. For example, in 2018 CHARM was to undertake irradiation tests of CubeSat systems and to develop radiation tolerant micro-cameras for satellites. ESA has also used CERN to evaluate the effects of high-energy electrons on state-of-the art electronics considered for flying on the JUICE (JUpiter ICy moons Explorer) mission.
- Medipix chips (pixel radiation detectors), used for various **imaging applications** (medical, art restoration, artefact analysis, nanosatellites). Medipix chips are the focus of one of the case studies.
- Pipe-cutting tools (compact universal orbital cutter) developed by a CERN technician for the inspection and repairs of awkwardly located pipes in tight spaces, and possibly surrounded by radioactive components. The cutter is now finding wider application for **oil and gas pipelines**.
- The Train Inspection Monorail (TIM), is a mini vehicle autonomously monitoring the 27-km long LHC tunnel and moving along tracks suspended from the tunnel's ceiling. Similar robots are being considered for the **autonomous monitoring of utilities** (e.g. underground water pipelines).

[52] http://www.news.newburyelectronics.co.uk/newbury-blog/which-pcb-layout-software-is-best-2017/

Other technologies and applications briefly mentioned by respondents included:

- Tracker ball and computer-programmable knob
- Capacitive computer screens (touchscreens), developed for tightly spaced server rooms at CERN SPS
- High-speed digital optical transmission lines
- Underground superconducting power transmission, which is leading to the development of large-scale power grids with negligible resistive energy loss
- Fast & compact electronics which were designed for use in trigger systems for the large experiments but have applications in any area requiring fast processing of large data sets
- New high precision welding techniques for cooling tubes being repurposed for use in aircraft turbine blades. This is cutting the cost, and therefore should make air travel cheaper
- Steel developed at the CERN PS, widely used for electrical motors.
- Vacuum technology for solar thermal panels
- Muon tomography is used for border protection
- The invention of Wire Chambers (Charpak) led to the modern security scanners at airports
- Radiation damage modelling for nuclear decommissioning operations (including simulations of expected human doses from human activity in such environments)

We have case studied a range of these examples to showcase wider applications of CERN-derived technologies, and explored how these have been taken up and developed further, both in the UK and beyond. These are summarised below and presented in full in Appendix E.

Innovation Case Studies – Summaries

Case Study 7 – GEANT series and simulations for space and radiotherapy

Geant4 is a toolkit used to simulate the passage of particles through matter and is currently the leading toolkit for detector simulation. It has its roots in the GEANT system, a Monte Carlo-based detector and simulation tool developed at CERN for the purposes of evaluating high energy physics experiments. Now it is a world-wide collaboration of 136 scientists and software engineers (many based at CERN), who develop, maintain and provide support to the toolkit.

UK researchers have been able to make use of Geant4 outside the particle physics domain, using the model for a range of wider applications. For instance, the University of Cambridge has adapted Geant4 to create GHOST (Geant Human Oncology Simulation Tool), which simulates radiation deposition in a patient throughout an entire course radiotherapy treatment. Using GHOST, researchers are looking to improve the modelling of late toxicity and the risk of second cancers caused by radiation exposure, potentially enabling clinicians to rethink proposed treatments. Geant4 has also contributed to the development of the ESA LISA (Laser Interferometer Space Antenna) mission, which will observe gravitational waves in space. A team at Imperial College London has used Geant4 to model the potential build-up of charged particles on the LISA spacecraft to enable the development of proofing mechanisms.

Case Study 8 – Linear proton accelerators and hadron therapy

Radiotherapy is a key aspect of cancer care. Approximately half of all cancer patients could benefit from some form of radiotherapy as part of their treatment and it is estimated to contribute to 40% of cases where cancer is cured. However, conventional radiotherapy using X-rays not only kill cancer cells, but also damage healthy surrounding tissues causing significant side effects.

The use of hadron beams instead causes less damage to healthy tissues as they pass through the body. This is especially important when treating tumours in critical areas, such as the brain, mouth, oesophagus, liver and prostate, or near the optic nerve or spine, particularly in children. Facilities offering such hadron therapy started appearing in clinical settings in the 1960s and an estimated 165,000 cancer patients have now been treated. However, with a price tag of around £120m per system, the cost can be prohibitively high. To lower the cost and enable more widespread use, more compact accelerators have started to be developed.

A first prototype of a linear proton accelerator (rather than circular, so causing significantly ess stray radiation and allowing for a more compact architecture) was designed and built under the leadership of

CERN. This linac-booster for proton therapy ("LIBO") was successfully tested at CERN in 2003 and was followed by other proton accelerators in Italy and Austria (again with CERN involvement). To further develop the LIBO design into a commercially available system, a CERN spin-off - ADAM ("Application of Detectors and Accelerators to Medicine") - was then founded in 2007. ADAM continued to receive crucial support from CERN, via its testing facility, as well as involvement in the LHC experiment. ADAM improved on LIBO's design, building and testing the first accelerator modules for the LIGHT accelerator from 2008 to 2010.

In 2013, Advanced Oncotherapy, a UK company, acquired ADAM to continue development of the LIGHT system for commercialisation. It now has 129 staff across the UK, Switzerland and the US and a market capitalisation of £80m ($100m). In 2018, Advanced Oncotherapy also established an assembly and testing centre for the LIGHT system at STFC's Daresbury Laboratory. The first patient treatment is currently expected by 2021, in cooperation with the UHB NHS Trust. The fit-out of the first proton clinic equipped with the linear system on Harley Street, London, is in progress (within the space of two traditional terrace houses) and will be operated by the London Clinic.

Proton therapy currently represents only 1% of all external radiotherapy systems installed worldwide and only 0.1% of all cancers treated, but recent forecasts project that the global proton therapy market will grow from $0.9bn in 2017 to $2.33-$4.3bn by 2030, with up to 1,300 particle therapy treatment rooms open to patients. The relative ease of installation combined with a cheaper production process could give Advanced Oncotherapy's LIGHT system a competitive edge against cyclotrons, synchrotrons, and more conventional LINAC systems - and allow it to secure a substantial share of this global market.

There would also be wider public / societal benefit. There are over 300,000 new cases of cancer diagnosed in the UK every year, with around 40% of these being treated with radiotherapy. Annual NHS costs for cancer services are £5bn, but the cost to UK society as a whole, including costs for loss of productivity, is estimated at £18.3bn. In 2013, the Government committed £250m capital investment for UK's first NHS proton therapy centres. The two centres will be able to treat up to 1,500 patients per year at half the cost of what the NHS is currently paying for this treatment.

Case Study 10 – Silicon Detectors and ASICS

Silicon detectors and high density readout electronics are now crucial for particle physics experiments, and have had a large impact on other scientific fields and applications outside particle physics. Over almost 40 years, silicon detectors have evolved from simple, small area diodes to huge systems, measured by channel count. This has been driven the requirements, and efforts, of particle physics aided serendipitously by the evolution of the electronics industry.

While these detectors have found applications for CERN experiments, they are used increasingly in other applications as well. Silicon detector technologies have been developed in numerous directions, resulting in Charged Couple Devices (CCDs), Microstrip detectors, silicon vertex detectors, pixel detectors, avalanche photodiodes and Silicon Photomultipliers (SiPM) and Monolithic Active Pixel Sensors. All of these different detector types have found applications in a range of research and industry areas, including synchrotron science (see next case study), nuclear physics, medical physics, astronomy, as well as developments and upgrades of CERN experiments themselves.

Case Study 11 – Medipix / Timepix detector chips

Medipix chips are hybrid pixel detectors, consisting of two thin layers of an absorbent material (e.g. silicon or Gallium arsenide). In the case of the silicon detectors, incoming particles create electron-hole pairs in the pixelated silicon sensor layer; the resulting charge is transferred to, and recorded in, the second layer, an array of readout electronics channels. This enables capturing of high-resolution, high-contrast, noise free images, making the chip uniquely suitable for imaging applications.

Hybrid pixel detector technology was initially developed to address the needs of particle tracking at CERN. The aim was to develop a 2D detector capable of time stamping high energy physics events at the expected collision rate of the LHC. In the course of this research, however, it became clear that such technology could also be useful for other applications. This is when the Medipix collaboration was born.

The initial partners of the Medipix collaboration were CERN, the University of Glasgow, the University of Freiburg and the INFN in Pisa and Napoli, but over the years the collaboration has been through various iterations and reconstitutions to further develop this technology and take it to new fields. As the cost of developing and prototyping these devices is challenging, each collaboration allows the partners to focus their efforts on developing chips with new features to support new applications.

The Medipix technology is one of CERN's most successful examples of knowledge transfer. Each collaboration has triggered a significant number of commercial activities in a range of application areas, including medical imaging, space dosimetry, education, and material analysis. The family of read-out chips (Medipix 1-4 and Timepix 1-4) have, for example, been applied in X-ray computed tomography (CT), in prototype systems for digital mammography, in CT imagers for mammography and for beta- and gamma-autoradiography of biological samples. Other fields of application include electron microscopy, background radiation monitoring, dosimetry and education.

The Medipix Collaboration has also led to a UK spin-off, Quantum Detectors, based at the Harwell Science and Innovation Campus. The company was founded in 2007 to promote a wider exploitation of detectors developed for synchrotron radiation, LASER and other large-scale facility applications. One of Quantum Detectors' products, the Merlin photon counting detector system, is based on the Medipix3 ASIC and was adapted for electron microscopy applications (MerlinEM) in collaboration with the University of Glasgow. This is a primary example of how CERN developed technologies have found their way, through UK companies and universities, into other research fields.

Case Study 12 – CMOS image sensors – enabling cryo-electron microscopy

Cryo-electron microscopy (cryo-EM) is a novel image technique for visualising the structure and shape of biomolecules and macro-molecular complexes at near atomic resolution. So ground breaking is this development, that British biochemist Dr Richard Henderson was one of the recipients of the Nobel Prize for Chemistry for his pioneering work with cooled electron microscope technology.

Dr Henderson worked in collaboration with engineers from STFC's CMOS Sensor Design Group (based at RAL) and scientists at the Max Planck Society to improve cryo-EM's image resolving power, replacing the existing detectors in the microscope with CMOS image sensors. The STFC CMOS Sensor Design Group, itself established in response to CERN requests for ASICs for particle physics experiments, was able to apply the expertise it had gained working with CERN in the design of large area, radiation-hard sensors to produce the first high-resolution CMOS devices for cryo-EM.

These devices are now available in cryo-EM machines on the market and are found in a wide range of the world's leading electron microscopes. Moreover, cryo-EM is a rapidly progressing field in which the UK has positioned itself as world leader. For instance, with the establishment of the eBIC at STFC's Diamond Light Source, the UK is set to be a world leader in providing large-scale industrial access to the cryo-EM for drug and materials research. This demonstrates the ways in which the knowledge and expertise generated at CERN can support the wider research capabilities of UK academia and industry.

Case Study 13 – Radiation tolerant ASICs

The CERN LHC experiments required detectors to tolerate high radiation levels, especially close to the colliding proton beams. During the 1990s, it was established that so-called "radiation hard" electronic technologies developed for military and space applications were expensive, relatively antiquated, and would likely prove problematic. Following intensive R&D, CERN engineers therefore demonstrated that an alternative solution was to use commercial state-of-the-art CMOS technology and special transistor design techniques. Several LHC experiments have since worked on the further development of radiation tolerant ASICS, including LHCb for its RICH and VELO detector systems, as well as ATLAS and CMS.

Beyond CERN and the field of particle physics, there has been a growing demand for radiation-tolerant electronics in the space sector. Today, the radiation tolerant ASICs developed through LHC experiments are able to meet space specifications at an affordable unit price while achieving high performance levels. The TimePix detectors, an example of radiation tolerant ASICS (and the focus of one of the other case studies above), are being used by NASA aboard the International Space Station.

Case Study 14 – Medical imaging technology: PET and scintillating crystals

Another example of how CERN has supported the development of medical technologies is found within the development of Positron Emission Tomography (PET) for medical imaging. Current high-performance PET scanners comprise over 20,000 detector elements originally developed for CERN experiments. Moreover, other work at CERN has contributed to the development of algorithms and software for image reconstruction, as well as new scanners (the Advanced Rotation Tomography scanner) to better support the combination of PET scanners with CT scanners.

Continuous development at CERN and other research collaborations that utilise CERN findings have also served to improve PET technology, and in some cases developing new medical imaging technologies. One example of this is in the development of a new PET scanner, ClearPEM (Positron Emission Mammography), a dedicated breast PET scanner to clarify breast cancer diagnosis.

The combined PET-CT scanner combination has proven more accurate than either scanner independently and is one of the most effective imaging tools in oncology. In 2016, the global PET-CT scanner device market was valued at USD$1,454m, and it is estimated to reach USD$2,108m by 2023, growing at a CAGR of 5.0% (2017-2023). Furthermore, the combined PET-CT scanner has shown significant promise in reducing the cost of cancer treatment through earlier diagnosis and improved staging to determine the appropriate treatments, as well as improving patient quality of life.

Case Study 15 – Field Programmable Gate Arrays (FPGAs)

Field Programmable Gate Arrays (FPGAs) are a type of semiconductor that can be reprogrammed for specific applications and functionality requirements after they have been manufactured. FPGAs are used in HEP experiments to collate streaming data from front-end electronics and in low level trigger systems. Due to the increasing needs in data acquisition and processing in HEP experiments, the use of FPGAs has become more essential. At CERN, specifically, the upgrades of the LHCb are creating challenges in terms of data acquisition and algorithm acceleration and the University of Manchester has been involved in developing FPGA firmware for the LHCb silicon vertex detector (VELO) upgrade.

Due to their lower cost as compared to ASICs (Application Specific Integrated Circuits), FPGAs are used for a wide variety of purposes including consumer electronics, data processing, automobiles, aerospace, defence and telecoms. Based on efforts at CERN, developments are taking place in other domains as well (e.g. the data processing and distribution model used at CERN will be adopted for the SKA).

Case Study 16 – AWAKE (the potential of plasma wakefields)

The Advanced Proton-Driven Plasma Wakefield Acceleration Experiment (AWAKE) is a proof-of-principle accelerator R&D project at CERN. It investigates the use of protons to drive plasma wakefields for accelerating electrons to higher energies than can be achieved using conventional technologies.

While it is likely that many decades of development will still be needed, the use of plasma wakefields has the potential to drastically reduce the distance needed to accelerate particles to the required energy, and would thus be a smaller - and hence lower cost - alternative for future accelerators, e.g. compared to projects currently in planning such as the CERN Compact Linear Collider (CLIC).

AWAKE is a promising first step towards the development of future high-energy particle accelerators using plasma wakefields; the collaboration now aims to achieve 1,000 MV/m, and address other requirements such as the intensity and quality of the accelerated beam and the distance over which acceleration can be sustained. While the impact and benefits of this work will still take many years to emerge, it illustrates the potential of ongoing cutting edge R&D at CERN.

The UK's involvement in the AWAKE project has also supported involvement in subsequent international plasma acceleration projects, positioning it to capitalise on future developments.

Finally, the **STFC-CERN Business Incubation Centre (BIC)** is another source by which CERN innovation may have wider uptake within the UK. As introduced earlier, the STFC-CERN BIC was set up in 2012 as a pilot to get more IP and expertise from CERN into industry (other countries have since followed this example and there are now 9 member state BICs in total). The intention is to facilitate a step change for participating companies, bringing them closer to further funding or self-sufficiency. To do so, the BIC provides money, support and technical assistance to accelerate their business concept. The STFC-CERN BIC currently hosts 2 companies and has 7 alumni, as follows.

Current STFC-CERN-BIC Incubatees

- Artemis Analytical was set up in 2016 to further develop and commercialise research conducted at CERN by Dr Kieran Flanagan. The company's focus is technology to enable much-accelerated carbon dating of modern and ancient samples. It is envisaged that the same basic techniques will also be extremely helpful to a range of related disciplines including forensics, artworks, identifying counterfeit wines and whisky. The company has filed two patents and secured funding from the ERC and STFC to work on a prototype mass spectrometer for the detection of radiocarbon.
- A20 Innovation Solutions provides composite material manufacturing processes and a material diagnostic structural health monitoring system, known as CHASM, which supports weight reduction, operational efficiency and CO2 emissions reduction. These innovations are primarily directed at the transport sector, particularly autonomous vehicles. The company is utilising STFC and CERN IP, technologies and expertise, in the design and integration of electronics and sensors.

STFC-CERN-BIC alumni

- D-BEAM, a spin out from the Cockcroft Institute, provides optical diagnostics for accelerator and clinical facilities, light sources and reactors. Having collaborated with CERN for a number of years, the firm now has access to specific CERN IP though the BIC. It hopes to translate its experience into commercially available tools that will improve understanding and control of particle beams.
- Oxford nanoSystems is a nanotechnology business that produces coating technologies to improve heat transfer in components used in industrial, transport and electronics platforms. It has developed nanoFLUX, a structured metal surface which enhances heat transfer in two-phase systems. This has potential applications in refrigeration and waste heat energy, automotive heat management and energy recovery, and heat dissipation in electronics. Through the BIC, the firm received advice and support from experts, as well as access to specialist equipment and funding. These all played an important role in enabling the company's progress and growth, as well as the rapid development and refinement of their product. Since graduating from the BIC in 2016, Oxford nanosystems has continued to grow and it has secured financial backing from two major investors. The company is now working with fridge manufacturers to produce more compact refrigeration devices that will provide more space for food storage. They are also investigating the nanoFLUX technology's use in geothermal systems, as well as its potential in cooling data-processing hardware.
- Camstech is an early stage company developing novel biochemical sensing technologies used for point-of-care diagnostics. The firm identified IP at CERN that would enable them to scale up and manufacture their sensors more cost effectively. It licenced the technology from CERN and joined the BIC in 2016. Working with CERN shaped the company's approach and supported further funding applications including an Innovate UK grant valued at £100k.
- Croft Additive Manufacturing is an SME specialising in the additive manufacturing of complex metal components. It benefited from CERN experts through validation of the vacuum readiness of their products. This approval from CERN is expected to support saleability of their products to vacuum markets, as well as providing wider reputational benefits for their work in other areas.
- 2D Heat is an R&D company working to commercialise a novel 'flat' electric heating system, which can be sprayed onto any suitable surface. After graduating from the BIC in 2016, the technology demonstrated significant energy efficiency improvements, and the firm has secured funding through the North West Eco-Innovation programme, as well as £180k of additional funding.
- InnoCryst is a CERN spin-off, established in 2013, providing R&D consultancy for X-ray-based imaging, diffraction and analytical technologies for materials science (X-ray-based 3D Materials Characterisation), applying CERN technology for product development.
- Ross Robotics joined the CERN BIC in December 2016. It specialises in modular robotics and has exploited CERN robotics software to develop and manufacture a robotic delivery platform that is an adaptable, robust and cost-effective, allowing robots to be rapidly re-configured.

How successful these companies may become in the future is not yet known, but the STFC-CERN-BIC is playing an important role in ensuring that early stage high-tech companies in the UK are best able to benefit from the innovation and expertise emerging from CERN.

7.2 The wider application of CERN research findings

CERN enables scientists to advance knowledge and understanding	→	Scientists (in the UK and elsewhere) build on this in their research	→	Further research may lead to new developments and innovations that bring benefit

The UK's investment in CERN enables scientists to advance knowledge in the field of fundamental physics, which leads to a better understanding of the basic properties, materials, and forces in the Universe. As set out in previous sections, scientists in the UK (and elsewhere) can then build on this enhanced understanding in their research, enabling them to address complexity, ask the 'right' questions and set up experiments that continue to push the boundaries of knowledge. This further research may lead to developments and spin-offs of high societal and economic value in the long term.

Impacts from advances in fundamental physics are typically on a long-term horizon, however, and difficult to forecast and assess. For example, while Planck and Einstein's work on wave-particle dualism and photons formed the basis for lasers and for digital cameras (now a $2bn global market[53]), these applications were realised with a time lag of many decades. The intuition of the Higgs boson took nearly 50 years to confirm experimentally at CERN – and it cannot be predicted if and when this might lead to any practical application.[54] Impacts are also difficult to evaluate retrospectively, since science typically advances over a broad front, with many separate but interlinked discoveries producing overall societal change.[55] The impact of any individual scientific result is hard to separate from others.

Some research conducted at CERN has a more direct link to potential application beyond the laboratory. For example, experiments performed with the CLOUD (Cosmics Leaving Outdoor Droplets) chamber demonstrated the role of atmospheric aerosols in cloud formation, an important factor affecting climate change.[56] [57] Research findings from these types of experiments may have a shorter impact horizon and feed into policy decisions within the 10-year timeframe of this review. A case study on CERN's CLOUD experiment and the role of atmospheric aerosols is presented in Appendix E and summarised below.

Case Study 20 – CERN's CLOUD experiment and the role of atmospheric aerosols

CERN has contributed to a better understanding of climate science through its work to understand how atmospheric aerosols affect cloud formation and therefore their role in the Earth's climate. Atmospheric aerosols and their effect on clouds are recognised as the largest source of uncertainty in climate projections over the 21st century. Yet, despite this, aerosol formation is currently poorly understood.

The Cosmic Leaving Outdoor Droplets (CLOUD) experiment at CERN measures the underlying microphysics in controlled laboratory conditions, important for a better understanding of atmospheric aerosol. It recreates a realistic atmospheric environment and is the first and only facility in the world capable of measuring these processes under controlled conditions. Its results comprise the most comprehensive laboratory measurements of atmospheric aerosol nucleation and growth so far achieved.

In 2014, it discovered that biogenic vapours emitted by trees and oxidised in the atmosphere have a significant impact on the formation of clouds, thus helping to cool the planet. Then, in 2016, data collected by CLOUD was used to build a model of aerosol production based solely on laboratory

53 https://www.technavio.com/research/digital-camera-market

54 Florio, M., et al., Forecasting the socio-economic impact of the LHC: A cost–benefit analysis to 2025 and beyond, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.03.007

55 OECD report

56 http://cloud.web.cern.ch

57 https://www.see.leeds.ac.uk/research/icas/research-themes/atmospheric-chemistry-and-aerosols/groups/aerosols-and-climate/projects/cloud-eu-marie-curie-itn-project-on-cosmic-rays-clouds-and-climate/

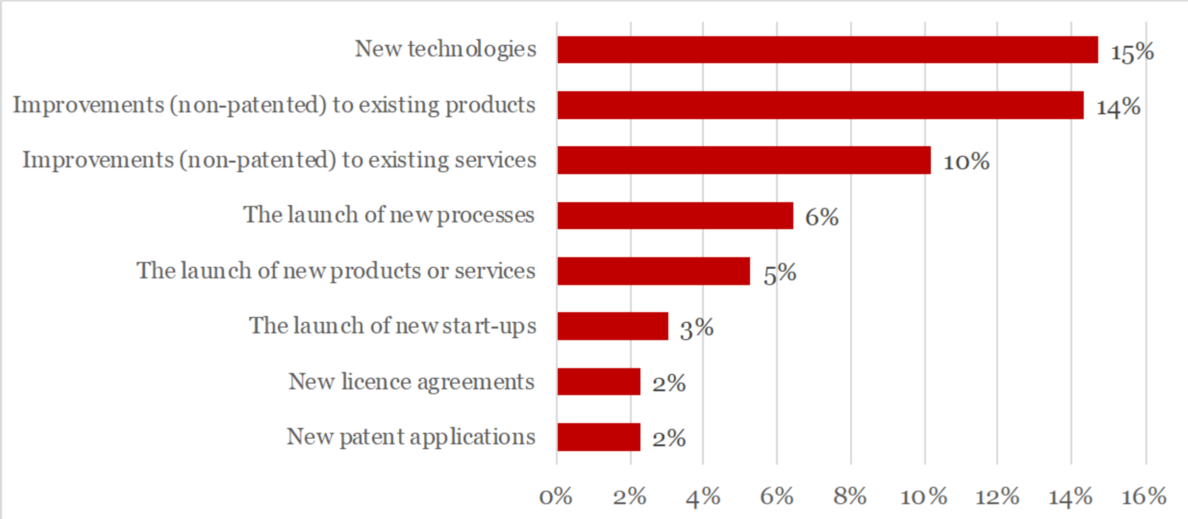
measurements (led by researchers at the University of Leeds) - using CLOUD-measured nucleation rates involving sulphuric acid, ammonia, ions and organic compounds.

These unique contributions to climate science thus allow climate models to be refined, based on experimental measurements rather than simplified theoretical models. CLOUD results are now being implemented in the global climate model of the UK Met Office, which is one of the major models that inform the Intergovernmental Panel on Climate Change. This is helping to clarify the role of aerosols and clouds in partially offsetting global warming from greenhouse gas emissions, thereby reducing the uncertainty in projected warming during this century.

A sound understanding of how the system of inorganic and organic molecules responds to changes in gas emissions and environmental factors will help to more accurately predict how these affect future climate – providing crucial information for the public and policy-makers to take appropriate action. The potential value of such improvements is vast. For example, the Met Office recently estimated that its climate change information would bring £2.95bn in value to the UK over the next 10 years.[58]

UK survey respondents were also asked whether their involvement with CERN (in CERN projects or using experimental data) had led to any of a series of **innovation-related outputs** (listed in the figure below). More than one-third (37%) of respondents reported at least one of these suggested outputs, with new technologies most often cited (15% of respondents), followed by improvements to existing products and services (14% and 10% respectively). A minority (2-6% in each case) also reported the launch of new products or services, processes, or start-ups, as well as new licence agreements or patents.

Figure 16 Extent to which CERN projects and experimental data have led to innovation outputs (n=265)



Source: Questionnaire survey of UK scientists and engineers

A small number of specific examples were then given, illustrating some of the **innovation outputs emerging from the UK's involvement in CERN research**:

New patent applications

"We started bunched-ion-beam experiments at ISOLDE, building the ISCOOL ion beam cooler-buncher with an EPSRC grant. This has made possible many laser spectroscopy measurements on radioisotopes and enabled a greatly-improved

[58] London Economics (2016) Met Office General Review 2016. Available online: https://londoneconomics.co.uk/blog/publication/met-office-general-review-march-2016/

technique of Collinear Resonance Ionization Spectroscopy. A member of my group has a number of patents arising from this development."

New technologies

"Worked with UK companies to develop radiation resilient ultrasound technologies for application in the nuclear power industry."

"The manufacture and sale of Medipix detectors, integrated into a retractable mount, for use on a range of commercially available electron microscopes from several manufacturers. Medipix is now used on the I06 beamline at Diamond Light Source, to name a single application."

New products and services

"Improvements to client support in the retail sector, using machine learning techniques and processes developed using CERN".

The launch of new start-ups

"I recently received funding to start consultancy services based on knowledge gained from CERN."

"Several of my PhD students, trained at CERN have gone on to found start-ups."

"Our group leads work on modelling the radiation environment in the ATLAS detector, which has led to a spin-off with the nuclear industry involving testing of ultrasonic sensors for high radiation environments."

"We have filed 3 patents and launched a start-up company (Artemis Analytical Ltd.) based on techniques developed at CERN".

"I was involved in a start-up to use photon detection to do quality assurance of silicon wafers using ideas gained from my particle physics research from CERN."

Measurements of **patenting activity** are commonly used to capture the extent to which research streams or programmes foster innovation and economic development. Obtaining intellectual property through the filing of a patent application is often an important milestone in the process of developing a new technology product or service and citations by patents indicate the usefulness of research (results contained in the cited article) for subsequent technological development activities. Technometrics - methods used to capture patenting activity - cannot measure all dimensions of the innovation process and innovation outcomes, and firms and inventors use a variety of strategies to protect innovations. However, it provides a robust means of measuring the dimensions it is able to track.

Patents where CERN held intellectual property (for which it is the assignee), as well as all patents making mention of CERN in their description, were captured from the European Patent Office (EPO) database, PATSTAT, as part of the bibliometric analysis (see Appendix D). In total **331 such patents** (in fractional counting) were identified, including 51 that were assigned to CERN and 280 that mentioned CERN in their description. These patents related to computer technology (62), electrical machinery (43), environmental technology (35), chemical engineering (33) and measurement (25), among others.

For comparison, the European Space Agency has approximately 450 patents and patent applications relating to inventions made by its staff. This suggests a higher level of patenting activity than at CERN, but it is important to note that CERN generally seeks to allow the widest possible use and tends to only use patents to protect this goal (i.e. stopping others from patenting and thereby restricting use).

The 331 CERN-related patents found in the analysis were broken out by country, based on country of origin for patent inventors (inventorship), and by country of origin for patent assignees (intellectual property). Of patent applications making mention of CERN research, **10 had UK inventors** and **13 UK assignees**. The USA obtained the largest measurements here, with 101 patent applications including a US inventor and making mention of CERN innovations, and 96 applications with a US assignee and making mention of CERN innovations. France held the second rank when considering inventorship (81 applications) but was third when considering intellectual property (37 applications).

These results suggest that CERN has contributed in some small degree to innovation practices and systems in the UK. In turn, patent counts act as partial evidence that UK industries, consumers, patients and society more broadly benefit from the UK's participation in CERN.

7.3 Improved performance amongst UK suppliers

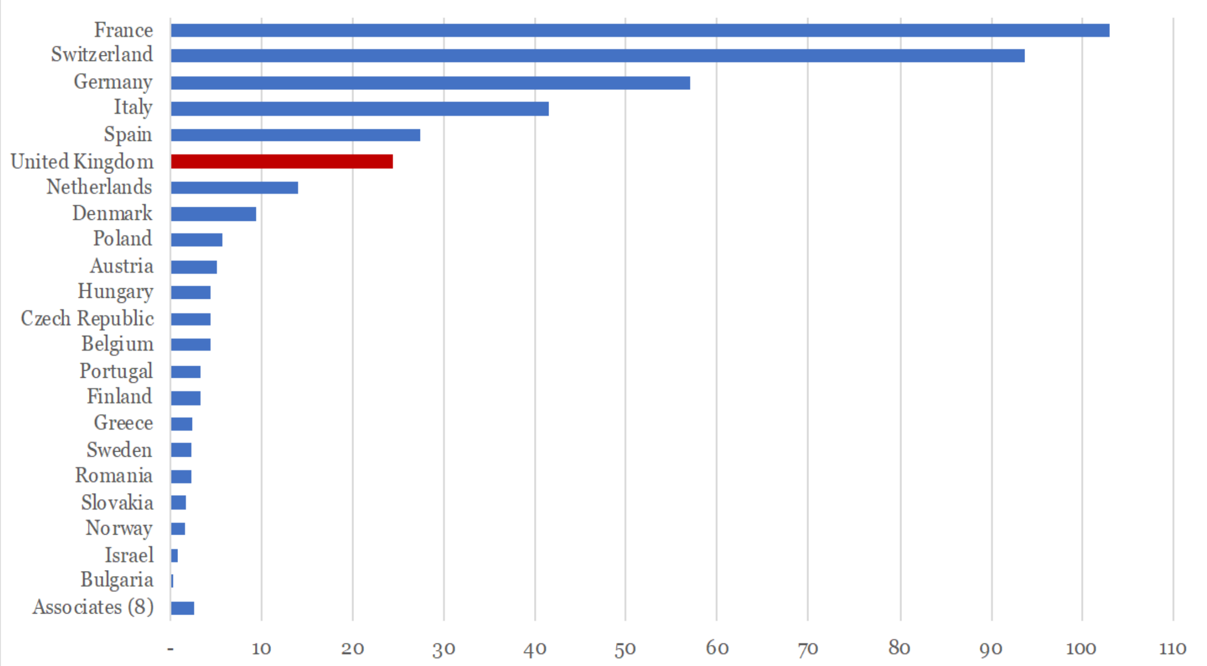
Membership gives UK companies access to CERN contract opportunities (addition revenue) → This can also bring benefits to: understanding, networks, reputation, innovation → Supporting increased productivity, market share, profitability, etc.

CERN membership gives UK companies access to contract opportunities with CERN

CERN membership gives UK companies access to contract opportunities with CERN for the supply of goods or services to the facility. Individual research groups working on technology development for CERN may also partner with or contract companies as part of their projects. Awarded contracts bring **direct additional revenue to UK organisations and support employment** (industrial return).

Products and services are procured for the building, maintenance and operations of the facilities (not for the experiments – which are discussed below). From the latest CERN procurement reports we see that **UK companies won £18.7m in contracts from CERN in 2018** (CHF 24.35m, see Figure 17). This equates to 5.9% of total CERN expenditure in Member and Associate States and is higher than most countries (but below Spain, Italy, Germany and the two host countries, France and Switzerland).

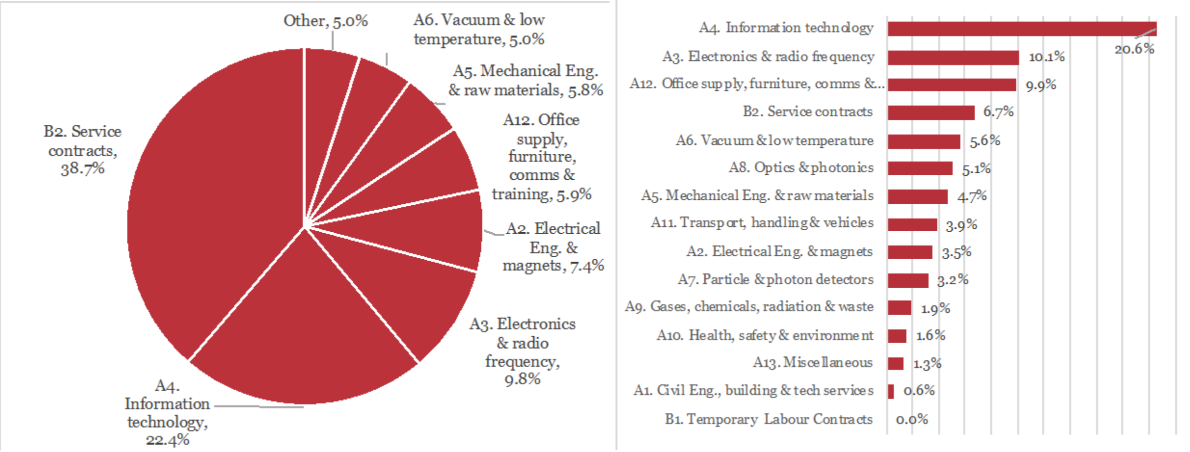
Figure 17 Value of CERN contracts (supplies + services) awarded, by country (Million CHF, 2018)



Source: CERN Procurement Report 2018

The following figures show how these contracts are split between different service and supply codes. The chart on the left presents the division of 2018 UK contract values between codes. It shows, for example, that the majority relates to service contracts and information technology. The chart on the right presents the proportion of the total value of contracts to all member states that is awarded to the UK across the different codes. This shows, for example, that the UK does relatively well in information technology, electronics and office supply, as well as service contracts (all above the UK's 5.9% share of total contract value overall in 2018).

Figure 18 CERN contracts (supplies + services) awarded to the UK, distribution of total value by code (left) and as a proportion of total awards to all member states (right).



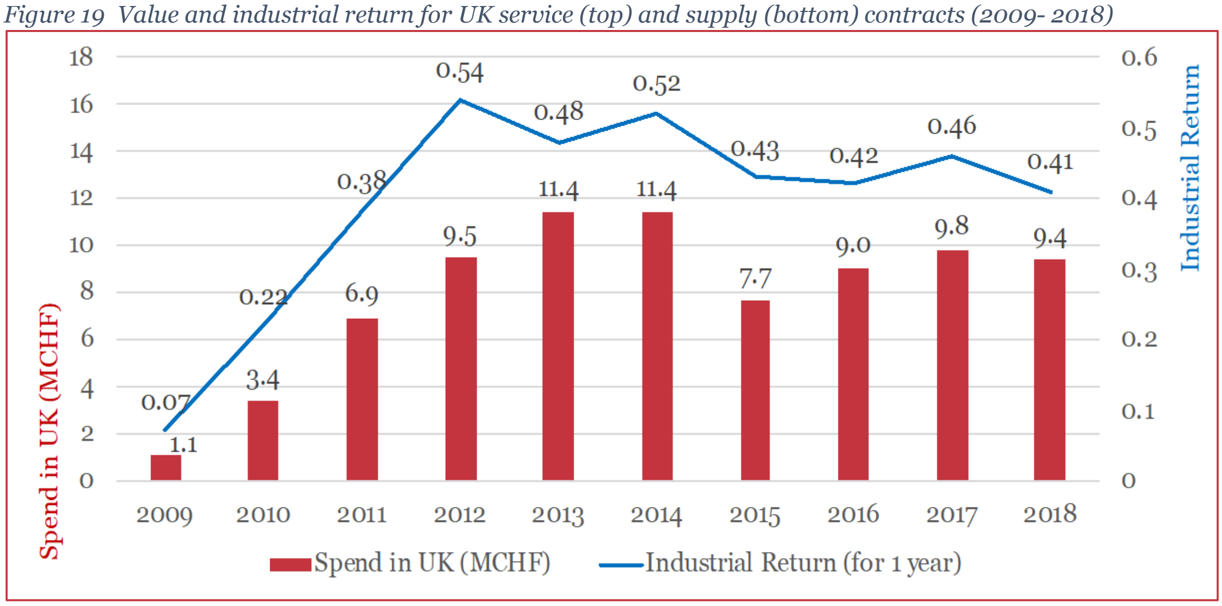
Source: CERN Procurement Report 2018. 'A' codes are supplies, 'B' codes are services.

UK companies have been awarded **£168.5m[59] (CHF 240.4m) in CERN contracts over the past 10 years** (2009-2018, in nominal prices). This is 5.9% of the total value of contracts awarded during this period. Accounting for inflation, this equates to £183.3m in real (2018) prices.

CERN provided the study team with additional details of UK contracts exceeding 10K CHF (>£7.5k) between 2009 and 2018, which includes information on contractors. This suggests that **~500 companies** were awarded contracts during the period [individual firms and values are confidential].

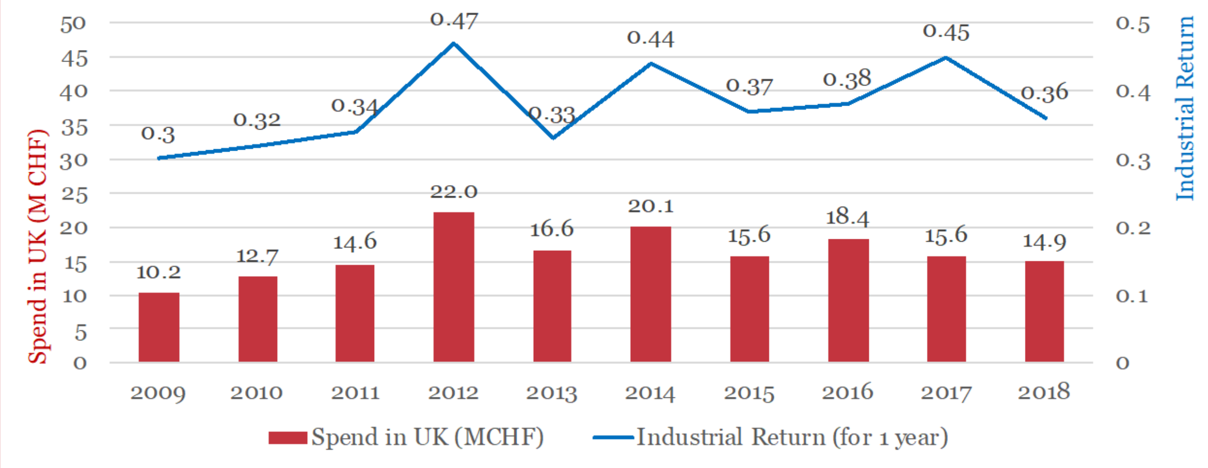
The following figures plot the total value of UK contracts and (1 year) industrial return rates for each year, 2009 to 2018. The first shows service contracts, the second supply. Both show rapid improvement in the UK's return from 2009 to 2012, followed (in the case of services) by a slight downward trend since. The return from supply contracts over the past five years has been more variable, with no clear trend[60].

Figure 19 Value and industrial return for UK service (top) and supply (bottom) contracts (2009- 2018)



[59] Converted from CHF based on average exchange rates each year, which varied between 0.59 and 0.79 during the period.

[60] The calculation of supply contracts changed in 2017, it used to include utilities (electricity, water, insurance, etc.) and this accounts for the uptick in industrial return for supply contracts in 2017

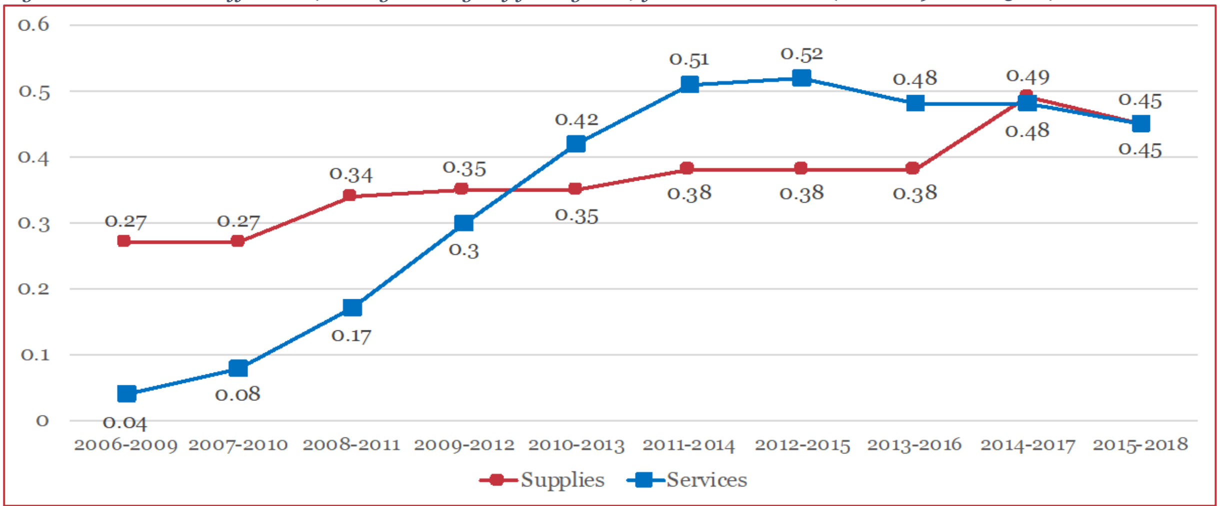


Source: CERN Procurement Reports 2009 – 2018. Nominal prices.

The **return coefficient** provides an indicator for a country's (direct industrial) return on investment, based on a rolling average of four years. The following figure shows the UK coefficients for supplies and services for the past ten years. (There are various potential issues and caveats to be aware of[61]). In recent years the UK has had a return coefficient above 0.4 for services contracts and so is classified as well balanced. This coefficient has tended to increase over time, peaking at 0.52 for the 2012-15 average. By comparison, the UK has in recent years had a return coefficient above 0.3 (but below 1) for supplies and so is considered poorly balanced for these contracts.

It is beyond the scope of this study to explore methods to improve the UK's return coefficient. STFC itself regularly undertakes analysis of UK industrial engagement and works with CERN to increase the return to the UK.

Figure 20 Return coefficient (rolling average of four years) for UK contracts (2006-09 to 2015-18)



Source: CERN Procurement Reports 2009 – 2018

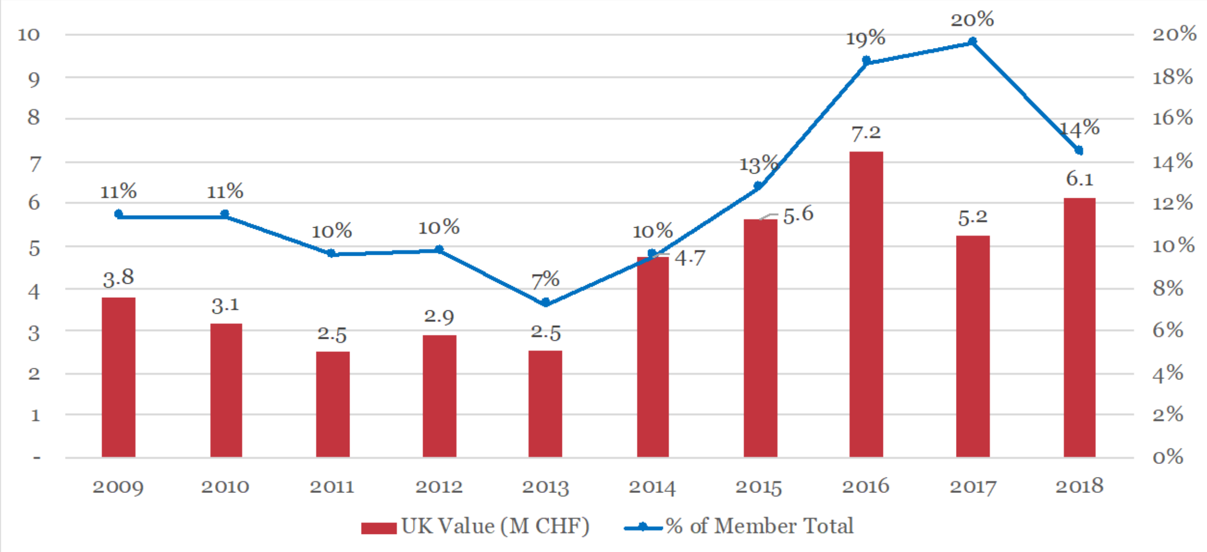
[61] For example: The procurement process does not include any contracting for R&D; The calculation of supply contracts changed in 2017, it used to include utilities (electricity, water, insurance, etc.) and this accounts for the jump in return coefficients for supply contracts for 2017; The return coefficient is only calculated based on contracts at the CERN facility, not the other work strands such as those for visiting research groups, those for the international experiments or those universities may place on behalf of experiments; It excludes single orders <1kCHF and spend in non-member states; The coefficient is subject to fluctuations in exchange rates (e.g. the GBP:CHF exchange rate decreased from ~1.7 in 2010 to ~1.3 in 2018); Increases in the value of contracts awarded do not necessarily mean increases in the return coefficient, if a country's investment in CERN has also increased; Contracts placed by the CERN pension fund are not included; Services are recorded against where a company is established, while supplies are based on the country of manufacture (or last major transformation).

Procurement for each experiment is organised within the countries that are members of that experiment. This is largely conducted locally, coordinated through universities and national labs, and so is very difficult to centrally track. However, a small proportion (some £36m per year on average over the past decade) now goes through CERN's procurement process and is therefore recorded centrally (CERN procurement report Table 4 – procurement by visiting research teams and collaborations). .

The following figure shows data for the past decade for the value of contracts awarded to the UK through this route. In 2018, for example, 6.1m CHF (£4.7m) was awarded to the UK, which is 14% of the value going to all member states. This is a substantially higher proportion than the UK achieves through CERN's procurement, although it is likely that the UK is also one of the main users (i.e. procurers) of this central procurement route (which may overly benefit local – i.e. UK – contractors, in the same way that Switzerland and France benefit from proximity for CERN's central procurement). Importantly, procurement undertaken by the CERN Pension Fund is also included in these statistics (see below).

Over the full ten-year period (2009-18, nominal prices), **£30.9m** (CHF 43.8m)[62] has been awarded to UK contractors. Accounting for inflation, this equates to £33.4m in real (2018) prices.

Figure 21 Procurement on behalf of visiting research teams & collaborations - value of UK contracts (2009-18)



Source: CERN Procurement Reports 2010 – 2018. Orders and contracts placed by CERN, but paid for by the Visiting Research Teams and Collaborations. Nominal prices.

The **CERN Pension Fund** is more or less autonomous. Although it uses CERN procurement to manage contracts, these are not included in the main services/supplies statistics, but instead are included in the 'other experiments' figures (those in the figure above). Several sizeable contracts have been awarded to UK organisations through this route and we sought to investigate this activity further, approaching the Pension Fund for further information on the number/value of contracts awarded.

Unfortunately, there is no centralised record or system which can provide analysis of the number / value of UK contracts awarded by the Pension Fund over any period of time. However, a note has been kept of some of the bigger contracts awarded in the last few years. There are 16 such contracts for UK organisations that are known, mostly awarded in 2017 or 2018 (plus one further contract each for 2016 and 2019). Individual contracts range in value from £10k to £3.7m, with most lasting for a period of one or two years. The total value of these contracts to the UK is £7.1m.

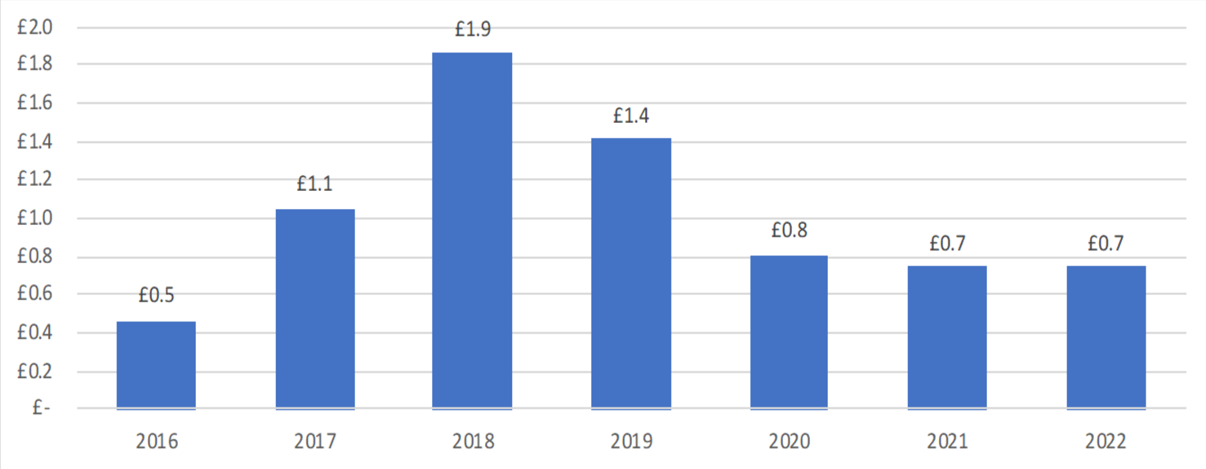
[62] Converted from CHF based on average exchange rates each year, which varied between 0.59 and 0.79 during the period.

The majority of the income is accounted for by three UK companies:

- Northern Trust is the Global Custodian for the pension fund. In 2018 it was awarded a multimillion-pound contract for 5 years.
- Buck is the pension fund actuary. It was awarded a two-year contract extension in 2016 (worth nearly £1m), and a follow-up contract in 2018 for a similar figure
- PwC is the pension fund auditor. In 2017 it was awarded a three-year contract worth several hundred thousand pounds.

The following figure plots income to the UK from the 16 large contracts known about, with the value of multi-year contracts dispersed evenly over the relevant period (i.e. a £200k two-year contract starting in 2017 is plotted as £100k in 2017 and £100k in 2018). The 2018 total is likely to be most complete, given the time period of the contracts that have been made available (although this will still be an underestimate – as there may be other earlier contracts that extend in to this year, in addition to smaller contracts that are not being picked up). Therefore the £1.9m attributable to this year could be taken as a broad indication of the (minimum) value of contracts being awarded by the Pension Fund to UK suppliers in a typical year.

Figure 22 Value of CERN Pension Fund contracts (where known) issued to UK suppliers (2016-18) – with total contract values distributed evenly across contract periods (in £m)



Source: CERN Pension Fund

UK suppliers realise wider benefits beyond the value of the contract itself

CERN contracts and involvement in CERN-related research projects can also bring additional benefits to these businesses. For example, it can lead to the development of new skills and knowledge or can provide new opportunities through additional contacts and international networks. Contracts relating to CERN may also increase the reputation and prestige of the suppliers concerned, or may result in new and improved products / services that open up new markets and opportunities. These benefits may in turn support increased market share, turnover, employment, and profitability of UK companies. This may be through further contracts with CERN, or sales to other third parties.

For example, in a 2003 survey of CERN suppliers[63] more than half of respondents indicated that they would have had poorer sales performance without CERN. Other benefits mentioned by respondents included the development of new products and services as a direct result of supplying CERN, new R&D activity, increased international exposure, and opening of a new market.

[63] Autio, E., Streit-Bianchi, M., & Hameri, A.-P. "Technology Transfer and Technological Learning Through CERN's Procurement Activity", (2003), http://cds.cern.ch/record/680242?ln=en, Sep 2013

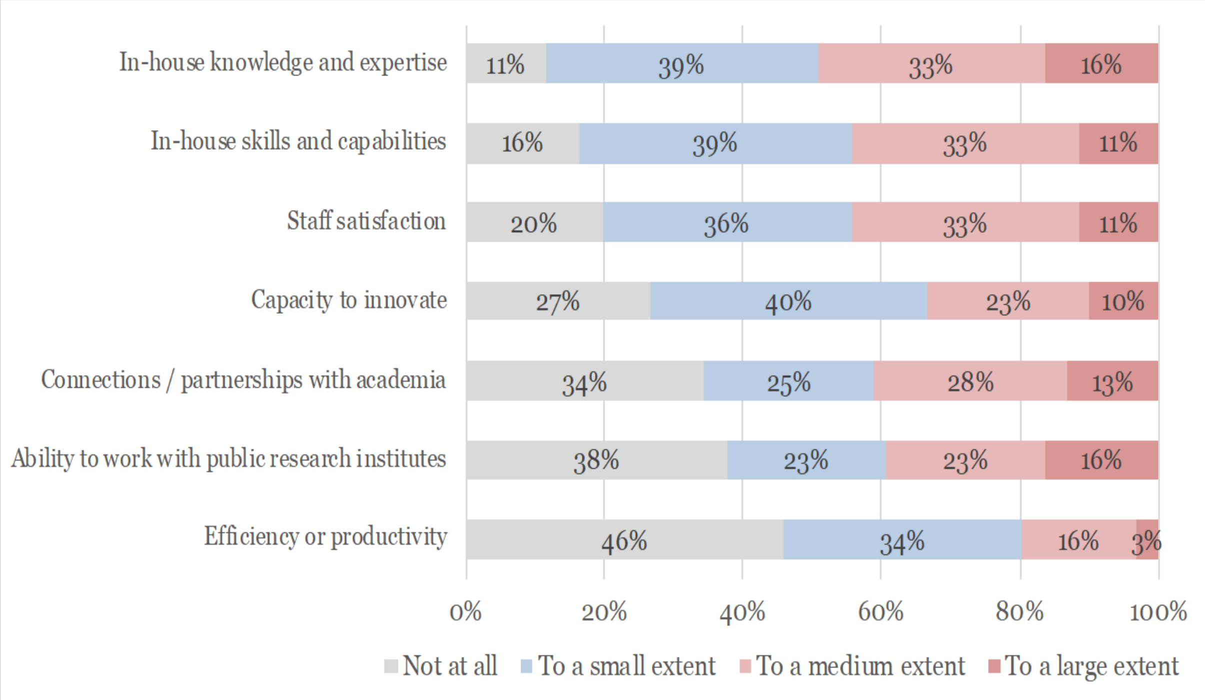
We have conducted our own survey, focused only on UK suppliers that have provided goods/services for CERN (either directly to CERN, or through supplying research groups/institutions on CERN-related activities). This sought to capture information on the benefits that have been achieved through contracts relating to CERN. The results provide both quantitative data (e.g. self-reported value of benefit beyond contract value) and qualitative information, along with illustrative examples of how CERN procurement has benefitted UK companies. A full analysis of the survey is presented in Appendix C.

Amongst the responding population (n=65, 10-15% of all UK CERN suppliers) we have captured input from a range of companies. They range in size between one-person businesses and multi-nationals with thousands of employees, while their annual turnover ranges between £45k and £62m. Most are involved in some form of manufacturing, although the sample also includes other sectors (e.g. ICT, consultancy).

A majority (97%) had been awarded contracts by CERN directly, while fewer (37%) had been awarded CERN-related contracts by research groups and institutions. Many had done both. Between them, the respondent companies had been awarded (across all years) over 2,300 CERN contracts worth over £78m – most often relating to the supply of electronics, mechanical and electrical engineering.

Beyond the value of the contracts themselves, suppliers were asked about the extent of other benefits and improvements within their organisation that had resulted from being involved in CERN contracts. As the following figure shows, all seven of the aspects asked about were felt to some degree by most suppliers. The most widespread benefits included staff satisfaction, knowledge and skills. Around three quarters of suppliers have seen some increase in their capacity to innovate, as a result of CERN contracts, while over half have seen some improvement in their efficiency or productivity.

Figure 23 Extent to which past CERN contracts have led to improvements within the organisation (n=61)



Source: Questionnaire survey of UK suppliers

Some suppliers provided further insight that illustrate the specific improvements seen within their organisation in each of these areas:

In house knowledge / expertise: *"The knowledge and expertise gained has allowed us to develop products for other larger markets"*

In house skills and capabilities: *"The increased skills in the machining of new metals (for the manufacture of CERN components) has enhanced capabilities across all internal sectors of our business"*

Staff satisfaction: *"The CERN name encourages recruitment candidates to want to work with us"*

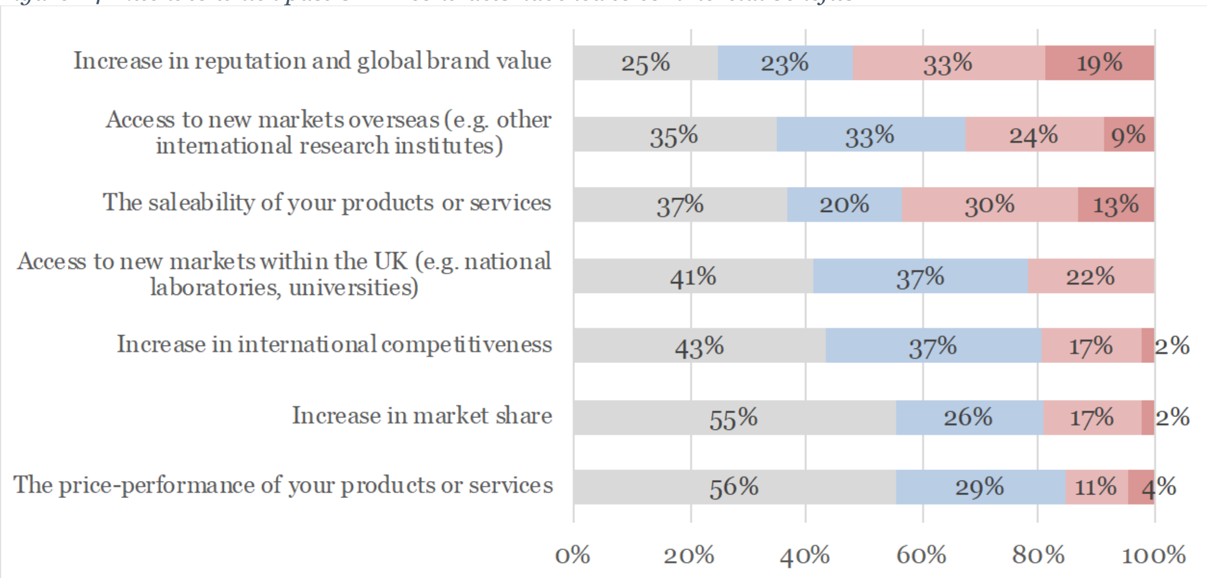
Ability to work with public research institutes: *"Having worked for CERN reflects well on the status of our company as a competent, reliable and stable organisation to work with"*

Capacity to innovate: *"We have innovated to meet ever-increasing demands on our manufacturing technology"*

Around a third of respondents had seen improvements to existing products and / or services, as a direct result of their CERN contracts, while several reported the launch of new products, services and process, as well as patent applications, flowing from their past work with CERN.

There was also widespread reporting of an increase in **opportunities and competitiveness**. In most cases (75%) there has been some benefit for the suppliers' reputation and global brand value. In addition, between half and two-thirds of respondents reported an impact on their access to new markets (in the UK or overseas), on their international competitiveness and on the overall saleability of their products or services. Just under half reported benefits in terms of market share or price performance.

Figure 24 Extent to which past CERN contracts have led to commercial benefits



Source: Questionnaire survey of UK suppliers

A series of **case study** examples have been developed, demonstrating wider benefits to specific UK suppliers. These are summarised below and presented in full in Appendix E.

Case Studies of Suppliers - Summary

Supplier benefits – Reputational benefits

- **Arcade Ltd** have held CERN contracts valued at over £1.7m to supply heating, ventilation and air-conditioning systems and components to a number of the experiments. These projects have supported the expansion of the company's engineering team and allowed them to demonstrate a wide range of systems for a high-profile customer. Their work for CERN has provided assurance of the quality of the products, supporting Arcade UK to successfully secure contracts in the defence sector, such as a large contract for BAE Systems to work on their submarines. (Case Study 21 in the Appendix)
- **TG Engineering** is a supplier of precision machined components and engineering solutions to leading industries, including the supply of vacuum chambers (following the acquisition of NTE Vacuum Technology). The working history with CERN has benefits for the reputation of the company and its products. Indeed, representatives from the firm noted that much of their business came through word of mouth recommendations and that the association with the CERN brand had had a positive impact on the perception of the company and its products. (Case Study 22)

Supplier benefits – Access to new markets

- **HV Wooding** have supplied CERN with a range of manufactured products including yoke and collar magnet parts, busbars, and machine parts, delivering over 28 contracts for CERN worth approximately £1.4m in total. Working with experts at CERN, HV Wooding developed a new manufacturing method using laser cutting and wire erosion, a process the company had not extensively used before, but has now applied with other clients. Their work with CERN was the first with large scale scientific facilities and being associated with the CERN brand opened the door to subsequent contracts with other facilities in the UK (e.g. RAL) and abroad (e.g. Brookhaven National Laboratory in the US), helping further consolidate their export activity. Based on the knowledge gained, the reputational benefits for the company and the support these contracts provided for accessing new markets, company representatives estimated these benefits were worth £600k to the company. (Case Study 23)

Supplier benefits – Development of new products

- **UHV Design Ltd.** is a manufacturing firm specialising in the design and manufacture of products to manipulate beamlines and samples under ultra-high vacuum conditions. Over the past decade its involvement with CERN has been relatively modest, with most orders received being for standard products or variants thereof. In 2017, however, CERN approached UHV Design with a particular request for a customised version of their magnetically coupled Linear PowerProbe that could also operate remotely in vacuum. The resulting solution brings together creative design, smart materials selection and precision operation. Having successfully passed the prototype testing phase at CERN, UHV Design has recently received a confirmed order for a quantity of these devices and orders for further quantities are expected over the coming years. Furthermore, it is envisaged that this new design could improve the operability of beamlines around the world and reduce unscheduled downtime due to loss of ultra-high vacuum conditions. While their exposure to this particular market segment is still developing, this piece of development work has further widened the product range which UHV Design can offer this market in the future. (Case Study 24)

Supplier benefits – Innovative capacity building

- **Micron Semiconductor** is a world leading manufacturer of silicon detectors with a strong relationship with ATLAS UK research groups. This relationship has involved the iterative and collaborative design of pixel detectors, with university groups providing their design requirements and empirical observations and Micron Semiconductor providing manufacturing expertise. This paid research and development has been beneficial for the company as it removes some of the risks and the time that would be required under other circumstances. Such projects have been beneficial in pushing the design and processing limits of the company and their products and this early development work is expected to come to fruition soon, with the company currently tendering to supply large quantities of detectors. Micron are now considered to be one the world's best in this area due to their work with CERN experiments. (Case Study 25)
- **Exception PCB** manufactures printed circuit boards and has delivered over 700 contracts with CERN valued at £900k. This has included both standard products and those that are technically more challenging. For example, a joint funded development project involved the development of a printed circuit board with challenging physical geometrics and tight margins due in part to the less common materials used. The project required a degree of upskilling and adaptation on behalf of the company, increasing their experience and expertise of the process and characteristics of the less common material. This knowledge has since been applied to other projects within the company. Off the back of this type of work, Exception PCB have established an internal group, Integrated Design Support, to provide support to CERN and other customers to trial and explore new ideas and push the boundaries of what is possible. This allows the company to explore new opportunities, undertake reciprocal learning with CERN, as well as positioning them to deliver contracts in the future. In this way CERN has provided Exception PBC with steering to find their niche market and competitive edge. (Case Study 26)

UK suppliers realise additional sales as a result of past CERN contracts

Over half (52%) of suppliers surveyed reported that their past CERN contracts had resulted in an increase in sales income (beyond the value of any additional contracts with CERN), while a similar proportion (45%) reported an increase in profitability. Around one-third had also experienced some increase in employment that was attributable to their past CERN contracts. Below, we quote some of the comments provided explaining the wider commercial benefits of being a CERN supplier:

> *Our company would not have grown as much if we had not made our CERN-related sales [electro-magnets supplier]*
>
> *We are now in discussion with other universities about providing similar support [printed circuit board supplier]*
>
> *We are an SME and want to publicise the fact that we were chosen by CERN for such a prestigious contract award. [electronics supplier]*
>
> *CERN provided an introduction to others requiring our products and technical skills [machined component supplier]*
>
> *The reputational benefit (and seeing our product in use by CERN) has allowed us to make sales to commercial and other academic customers. The experience with CERN also enables us to do a better job with subsequent customers. There are years when supplying to CERN has lost us money, but we believe the benefit outweighs the cost [software supplier]*
>
> *Improvements in in-house knowledge and expertise has allowed us to develop products for other larger markets. We now manufacture 1,000 units per year and generate around £20m annual revenue supporting 100 jobs [magnet supplier].*
>
> *Without CERN, we would have had to chase smaller value sales in riskier areas [manufacturer].*

The opportunity has helped us to develop new materials and processes, and we have been able to showcase our expertise, which has resulted in additional sales [precision engineering supplier]

CERN has increased our visibility in the market place, improved our sales revenue and contributed to annual growth of the business [manipulation product suppliers]

The CERN name impresses our clients and potential clients in the STEM sectors. Without our past contracts, it would have taken us longer to get where we are today [communications supplier].

In the 1990s in particular, CERN work allowed the company to establish itself. The company might not have survived in the early years. Now we are sustainable without CERN work. [manufacturer of meters and probes]

As a result of CERN contracts, we have been able to successfully offer services to ITER – so far worth £80k [design consultancy]

Many of the respondents (n=33) attempted to estimate specifically what their current turnover and employment levels would be, hypothetically, if they had never been a CERN supplier.

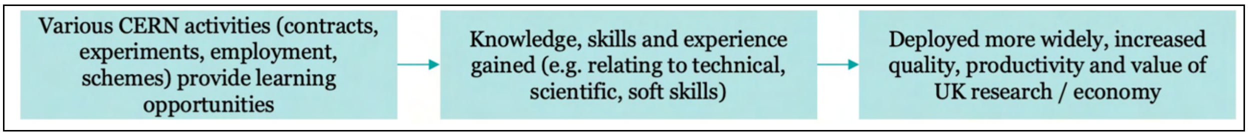
Just over half (59%) felt that it would not have made any difference (i.e. the CERN contracts had not had any wider impact on sales, beyond the value of the contract itself). In the remaining cases, respondents believed that their current annual turnover (from non-CERN contracts) had been boosted by anywhere between 2% and 28%, as a result of their past work for CERN. The largest estimated increase (+28%) was from a company that had been a supplier to CERN for several decades and had received millions of pounds worth of CERN contracts in total over this period. **Across the sample (n=33), the average impact on turnover (self-estimated) was thought to be around +4%.**

The current turnover of respondents to the supplier survey averaged £7.8m in 2018. If this were to hold across the full 500 UK suppliers of CERN, then an average +4% CERN-related boost to their collective turnover would equate to around £157m in 2018 in additional income for UK businesses. We estimate that a further £1bn in turnover and an additional £110m in profit (2018 prices) has been supported amongst UK suppliers in the past decade overall, on top of the direct income received through contracts. Approaches to monetising the value of CERN to the UK supplier base are explored further in Section 10.

Reflecting the various positive benefits of working on CERN contracts (e.g. improved capabilities, international opportunities, or new markets and sales), the vast majority (92%) of respondents to our survey anticipate tendering again in future, including two-thirds who “definitely” will.

8 Impacts relating to world-class skills

8.1 Increased skills and capabilities of the UK workforce



CERN offers various learning & development opportunities for the UK workforce

The cutting-edge technology and international setting of CERN can be an inspiring training ground for the STEM workforce. CERN employees and researchers, as well as staff within contracted suppliers, can acquire skills and knowledge on the job and in informal exchange with team members. CERN also offers dedicated training schemes for students and for those more advanced in their careers (e.g. Fellowships and LTAs), while large numbers of students earn their PhDs based on work carried out at CERN.

The **training schemes** offered by CERN include:

- The CERN Summer Student Programme – which has run since 1962[64] and offers undergraduate students of physics, computing and engineering an on-site programme of activities over 8-13 weeks. Students are given the opportunity to join in the day-to-day work of research teams, usually working on a specific supervised project within an experiment. They also attend lectures on a range of topics, visit the accelerators and experimental areas and take part in discussion session and workshops. Students are also required to prepare a short report, which is submitted at the end of their stay. The UK has the largest number of student applicants each year (2007-16), although differences in success rates mean the UK's eventual participation numbers are second to that of Germany.
- The Openlab Summer Students Programme – is a public-private initiative (between CERN, research institutes and ICT companies) that was founded in 2002. It is offered to students who have completed at least three years of full-time studies at university. Over nine weeks, students work with some of the latest hardware and software technologies and see how advanced ICT solutions are used in high-energy physics. The students initially attend the main lecture series for CERN summer students, and later a series of lectures prepared by ICT experts. Visits to the accelerators and experimental areas are also included, as well as trips to other research laboratories and companies. Of the 17 organisations currently collaborating on the programme, four are UK-based (King's College London, Newcastle University, EMBL-EBI, and European Society of Preventive Medicine).
- The Doctoral Programme – was established in 1985 and aims to provide an environment for the preparation of a PhD thesis in applied science or technology[65]. Through the programme, students can spend between 6 to 36 months at CERN, making use of the facilities, as well as obtaining supervision from both a scientific staff member from CERN and from their university.
- The Technical Programme – is for undergraduate students in Applied Physics, Engineering or Computing who are looking for a practical training period or a place to complete their final project. Students can spend between 4 and 12 months at CERN, assisting staff in their various projects.
- The Administrative Student Programme – is aimed at Bachelor or Master degree students specialising in administration. They spend 2-12 months training at CERN during their studies.

[64] Originally the 'vacation students programme'

[65] In one of: applied physics, IT, mathematics, electrical, electronic, mechanical or civil engineering, instrumentation for accelerators and particle physics experiments, materials science, radiation protection, safety and environmental protection, science communication, surveying, ultra-high vacuum

CERN also offers a range of **other opportunities for students and researchers**, which include:

- Short Term Internships – for undergraduate students in the technical or administrative field, who get a practical training programme of 1 to 6 months geared towards their particular field of study.
- The Fellowship Programme – offers different categories of fellowship in line with different levels of education and experience: the Junior Fellowship (those with a BSc or MSc degree); the Senior Fellowship (a PhD or four years' experience post-MSc); the Senior Research Theoretical and Experimental Fellowships (a PhD and up to ten years' experience in your field); and the Post Career Break Fellowship (Junior or Senior Fellows). Depending on the type and subject of the fellowship, candidates are given opportunities to e.g. participate in a research group of their choice, gain experience in science journalism, or develop new IT tools to use in case of software limitations.
- The Technician Training Experience programme - aimed at those looking to get a first, professional experience to further their career, or before they embark on advanced study. It is specifically for newly qualified apprentices and is intended to address the shortage of highly skilled technicians.
- The Entrepreneurship Student Programme - is for Masters-level students who undertake 5-weeks intensive training to use CERN technologies as case studies for exploring their knowledge and business ideas and to facilitate entrepreneurial learning. The scheme launched in 2017.

More experienced professionals can also apply to the Scientific Associates and Corresponding Associates programmes to make use of the research facilities and participate in its programmes and activities.

Specifically in the UK, the (STFC and EPSRC) **Long-Term Attachments (LTA) programmes** provide students with the opportunity to continue their PhD at CERN whilst receiving training. (Postdocs and faculty who have significant roles on experiments also spend periods of time on LTA). Students work as part of an international team of experts and are trained in preparing apparatus, data-taking, data analysis, hypothesis testing, critical thinking, project management, statistical techniques, communication, report writing and presentations. The Centres for Doctoral Training in Data Intensive Science, established by STFC in 2017, also provide opportunities for PhD students to undertake research projects and placements at data intensive experiments including CERN (further detail in section 8.1).

There is significant uptake of CERN training opportunities in the UK

CERN data suggests that in the past decade around 1,000 individuals from the UK have participated across the various programmes and schemes set out above. Table 5 shows a breakdown of UK participants by programme over certain periods (based on data availability), from which we have estimated total attendance across the programmes for a full 10-year period.

In the final two columns we present the cost of commercially available programmes and courses that may offer similar skills and use this to estimate the total value of training received across many of the programmes offered (for free) by CERN. Following this methodology, we estimate that the value of student, doctoral and technical programmes for 380 UK participants over a ten-year period (2009-18) has been £4.9m (once one takes account of inflation). This approach (including limitations and assumptions) is explored further in the summary of monetised benefits (see section 10).

Table 5 UK participants in training programmes (various years)

Programme	Avg. duration	Data coverage	Total UK participants	Annual avg.	Est. total (2009-18)	Cost of equivalent training	Total value
Summer Student	8-13 weeks	2007-17	186	17	170	£10k	£1,700k
Openlab Student	8-13 weeks	2013-16	3	1	10	£10k	£100K
Doctoral & Technical	3 years 1 year	2007-17	198	18	180	£16.1k	£2,898k
Administrative Student	1 year	2010-17	13	2	20	£52k	£1,040k
Fellowship Programmes		2007-17	176	16	160		
Long Term Attachments		2010-16	305	44	440		
Total			**881**		**980**		

In addition to students, there are many other personnel from the UK interacting with CERN and acquiring skills and knowledge 'on the job', and in informal exchange with team members. For example:

- 1,042 CERN researchers from UK institutions (January 2019) – 13% of the total from member states
- 215 UK members of CERN personnel (2017) – 8% of the total from member states
- 44 UK fellows employed directly by CERN (2017) – 6% of the total from member states
- 94 associated members of personnel (2017) – 5% of the total from member states

In the previous section we estimated that some 500 UK companies are also likely to have interacted with CERN through procurement contracts over the past decade. The number of individual staff members benefiting within these companies is unknown, but the overall total will be in the thousands.

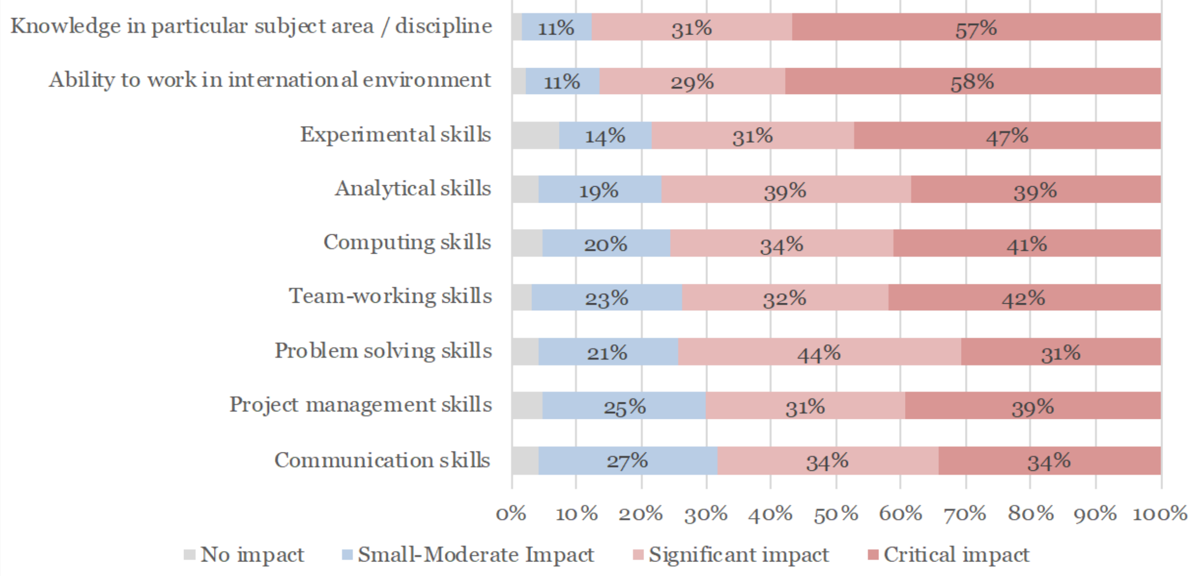
The UK workforce has gained knowledge, skills and experience through CERN

The acquired knowledge and skills, gained through these different forms of interaction with CERN can relate to various domains, e.g. technical, scientific, digital, project management, multi-lateral / international team working, cultural awareness, problem solving, process improvements, etc.

Scientists and engineers responding to our survey were asked about the impact of involvement in CERN on their skills and capabilities, and those of the wider group or department. Nearly all respondents (90%+) reported some degree of impact in all of the nine areas listed (see Figure 25), with a majority in each case reporting that the impact was 'significant' or 'critical'. These greatest impacts were most widespread in relation to subject area knowledge and working in an international environment.

In addition to the various skills and capabilities rated below, respondents pointed to other areas where there had been skills benefits from their involvement with CERN. These included skills and capabilities relating to presenting and public speaking, communication, writing, languages, design, outreach, teaching, time management, international diplomacy, networking, and collaboration.

Figure 25 Extent to which involvement in CERN has had a positive impact on skills and capabilities (n=176-194)



Source: Questionnaire survey of UK scientists and engineers

When asked to provide further details of an area in which CERN had had a particularly significant impact on their activities, many focused on their ability to pursue their research, and on the progression of their career. Several illustrative quotes from respondents are provided below.

> *"State of the art computing techniques. This is a fast-moving area and it is vital that advances are appreciated and employed quickly to improve the performance of both data taking and analysis. The techniques the students learn are often very important for those leaving particle physics for their future careers"*
>
> *"Contact with the best experimentalists has injected realism into my phenomenology research"*
>
> *"I have applied my computational analysis skills to projects outside of my particle physics research, regularly helping to solve problems"*
>
> *"I received an education in principles of data analysis which is unsurpassed in any other field in which I have been associated, including medical imaging, computer vision and machine learning."*
>
> *"Working at CERN gave me a good grounding in how to undertake research and work in international collaborations. These experiences stood me in good stead."*
>
> *"Improvement in data analysis skills, including machine learning."*
>
> *"My time at CERN (three months in 2017) made me much more aware of the skills needed and operations required to successfully run a research facility"*

Other comments suggest that what distinguishes the experience at CERN from that obtained in a university or national centre, is the level of expertise available, the scale of the projects, the interdisciplinary nature of the work and exposure to tools and techniques at the technological frontier. We have previously (see Section 6.2) presented a longer list of unique or special features of CERN that were put forward by the UK science and engineering community.

Knowledge & skills gained via CERN are deployed more widely in the UK economy

The acquired knowledge and skills, gained through interaction with CERN can also be deployed and applied in a variety of fields – both relating to science and engineering, but also beyond, supporting an increase in the quality, productivity, and value of UK research and the economy more broadly.

When our survey respondents were asked whether their involvement with CERN had contributed to tangible impacts on the UK economy or society, most providing a response pointed to the experience and skills developed by those engaging with CERN, which have then been transferred into other walks of life. A number of more specific examples were given, including:

> *"Those trained at CERN have had leading roles in other technology-led areas having left the field. They seem to be the only ones who understand fundamental principles involved in quantitative analysis of scientific data."*
>
> *"I have worked with students who have now left particle physics and moved into areas that include financial services, proton therapy, and software development. In all cases the students used transferable skills they picked up working at CERN."*
>
> *"The PhD students I have trained have all gone on to take important roles. Examples include one in the commercial cyber defence sector, another works on R&D for our navy's submarines and another has gone on to pioneer data analytics work at consulting companies in London."*
>
> *"The impact on training literally hundreds of engineers and scientists that then move to other sectors is hugely important."*

Various efforts have been made to obtain more concrete information about the careers of students and others who have been involved in CERN experiments, which we summarise below.

For example, at the end of 2016 STFC collected information on the **first destinations of STFC-funded PhD students** who had completed their doctorate in the previous four years (2012-15). The majority of these 941 students were funded in the area of astronomy, particle astrophysics, cosmology and solar system science (n=521), however the data also includes students from experimental particle physics (186), theoretical particle physics (126) and nuclear physics (73). There is no information on the extent to which these students had interacted with CERN.

The results nevertheless provide some insight into the breadth of next destinations of STFC-funded students. For instance, 28% went into the private sector, with majority of these working in software engineering / development (35%) and data analysis (24%) roles, and the remainder were spread across management, IT-related, consultancy, engineering, finance, patenting and other roles. The dominant role varies by the PhD subject area: software development for theoretical particle physicists; data analysis for experimental particle physicists; and engineering for nuclear physicists. Around 5% of students went into the public or charity sector, most commonly into the civil service and the health sector. The other two-thirds remained within academia (a postdoc position or other university post).

In a more specific sub-exercise, STFC assessed the next destinations of 86 **UK students that had returned from Long Term Attachments at CERN** and submitted their thesis in 2014 or 2015. This analysis found that (where known), nearly all of these students (96%) were in work – mostly (79%) within the UK. Of these 53 individuals employed within the UK:

- A majority (57%) were employed by universities (as a PDRA/Fellow), research institutes or schools
- A third (34%) were employed elsewhere in the private sector. This includes in the finance industry (4), consultancy (4), manufacturing (4), IT/Software (3), and other sectors (3), where their roles were usually recorded as either data analyst/scientist or software engineer/developer.
- A small proportion (9%) were employed elsewhere in the public sector – often by the NHS

Recently CERN commissioned a larger scale **polling of nearly 2,700 past and current CERN researchers** (mainly experimentalists), and over 160 theorists who had collaborated with the CERN theory department. A snapshot of the findings was published in the CERN Courier[66]. This highlighted that the majority of participants (63%) who had left high energy physics were now working in the private sector, often in information technology, advanced technologies and finance domains, where they occupy a range of positions and responsibilities. Those in the public sector were mainly in academia or education. In addition, for those who had left the field, many skills developed during their experience at CERN were highlighted as important in their current work. Most frequently they cited: programming, data analysis, working internationally, logical thinking, communication, working under pressure and adaptability.

A **CERN Alumni Programme** has also recently been established which should improve upon these statistics – and indeed, already provides some interesting insights. It was designed and implemented during 2016/17 as a project of the Director General, before the network ("the High Energy Network") was formally launched in June 2017, and is run by a newly created Office of Alumni Relations. All previous and current members of CERN personnel may request to join, including anyone employed as members (staff / fellows) or associated members of personnel (students / associates / researchers).

The scheme is not only about obtaining statistics; the alumni network has been designed to provide those who have left CERN with a means of keeping in touch (both with CERN and with each other). It seeks to establish a global, inclusive and cohesive community, which strongly interacts with CERN, and from which research at CERN may leverage increased support. It has three main objectives:

- Demonstrate to member states the impact of CERN on society via the people that it has engaged
- Help colleagues, and in particular younger ones, with their future career development
- Foster ambassadorship for the mission and values of CERN and leverage support from the network

Specific activities of the network so far include: a first "CERN Alumni Collisions" reunion event (2018); "Moving out of Academia To…" seminars (three so far targeting different sectors and involving alumni in the sector); a "Beyond the Lab- Particle Physics and Astronomy in business" event (with STFC and University of Edinburgh, 2019); and a range of others (15 so far, including 3 in the UK). There are also several regional groups, including in London (with 81 members) that organise events. The alumni website includes material to support the ambassadorial role of the network, while 250 job opportunities have also been shared through the network, supporting the career development of members.

The network started with no existing data on past employees. Already (at the start of 2019) there were 4,229 members, with one-third with a current contract with CERN and two-thirds having have left (the Alumni). Around half are currently working in the research sector, while the rest are spread across a range of professional sectors (higher education, software, IT and services, financial services, etc.).

There are currently 349 Alumni that are either British nationals and / or located in the UK (13% of the total). Just under half of the British alumni are based in the UK (while 16% are in Switzerland, 8% in France, 5% the US, 2% Canada, etc.), and of the alumni located in the UK, a third are working in research, while 5%-20% (respectively) are working in computer software, financial services, higher education, information technology and services and internet sectors.

This is likely to represent only a fraction of the true UK alumni numbers. For example, LinkedIn statistics currently show that there are 1,304 individuals located in the UK that have (in the past) worked at CERN. This includes 82 who are currently in the finance sector, 158 in computer science, 126 in information technology and services, 304 in research and 85 in higher education.

The Alumni website publishes **"alumni stories"** of individual members[67], including some in the UK:

- A member of the CMS collaboration (2003-16), who took part in the construction of the tracker and then dealt with data reconstruction and analysis. A few months after taking the radical decision to quit the research field he was hired by a private company to work with big data

[66] Assessing CERN's impact on careers. CERN Courier Volume 59, Number 2 March / April 2019.
[67] https://alumni.cern/news?category_id=852

- A supporting scientist to the Beamline for Schools competition (2017) as part of a three-month STFC graduate scheme placement (but at CERN). The opportunity provided knowledge and experience that he then put to use in his role at the ISIS Neutron and Muon source
- A former physicist from the LHCb collaboration (2012-16) who is now part of an industry team undertaking data engineering with the UK Home Office to remove extremist material from the Web. The project uses machine learning and artificial intelligence to stem opportunities for extremist organisations to post content on smaller platforms
- An individual who, after working with Montecarlo simulations in the ATLAS collaboration (2006-10), is now a marine ecosystem modeler at the Plymouth Marine Laboratory. In this role he develops complex computational models that are then used to support research and policy making
- A developer of software and electronics as part of the construction of the LEP machine (1984-88), first as a Summer Student and then as a Fellow. She returned to the UK to work for a technology consultancy firm in Cambridge and is now CEO at a private finance company

Another well-publicised case is that of Harry Cutts, a Computer Science graduate from the University of Southampton, who took part in the 2014 CERN openlab Summer Student programme. He is now working as a software engineer at Google, specialising in front-end development. Quotes from Harry have highlighted the technical skills learnt at CERN, which could be directly transferred into industry, but also the benefits of non-technical skills (e.g. networking opportunities, adapting to working environments) to his future career. He also claims that working at CERN got his CV noticed by Google.

A final relevant example comes from the UK firm Axomic Ltd (now OpenAsset), which was set up in 2002 by two CERN scientists working on IT projects. The company offers software for architects, civil engineers and construction companies to store and search for images and 3D plans on the internet. The company has quickly grown to 30 staff, with a global client base of 600 leading architectural practices[68].

Finally, in 2017, STFC also established eight **Centres for Doctoral Training** in Data Intensive Science, with an initial intake of around 100 PhD students. These Centres seek to produce highly trained and employable PhD graduates with advanced and widely applicable skills in DIS, who will ultimately become the future leaders of this field in both academia and industry. During their first year students get advanced training in data intensive science techniques, including Machine Learning. This is then followed by the main thesis research project on a world-leading data intensive science experiment, such as CERN, with many students able to undertake a year-long placement at their experiment.

The Director of one of these Centres for Doctoral training (UCL) commented:

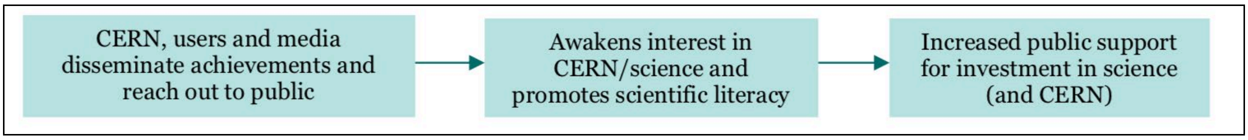
> *It is clear the skills young researchers are getting through their connection with CERN (especially their experience with large data volumes from the LHC) is in high demand and makes these graduates very desirable on the job market. Having gained experience at CERN and developed a huge skillset, they go on to get very good jobs in a range of areas that contribute to the UK economy (including media, retail, banking and online services). The need for this talent is only going to grow.*

Such highly trained and experienced personnel are in great demand within the UK economy. Shortages of STEM skills (equating to some 173,000 workers) have been estimated to be costing UK businesses £1.5bn a year in recruitment, temporary staging, inflated salaries and additional training costs[69].

We have attempted to monetise the value of these skills by considering the additional wage that can be commanded by young researchers that have engaged with CERN. The results suggest that young CERN researchers from the UK (over the past 50 years) will have enjoyed **an extra £489m "wage premia" during the last decade** (2018 prices). This approach is discussed further in section 10.

[68] Details of the company's income have been withheld from its reporting to Companies House. However, the unaudited financial statements for the year ended 31st January 2018 show the firm has total equity above £500k.
[69] https://www.stem.org.uk/news-and-views/news/skills-shortage-costing-stem-sector-15bn

8.2 Increased UK public appreciation of science



As has been set out in previous sections, CERN addresses fundamental questions of the Universe, at a facility of unprecedented scale, while CERN technologies have underpinned the development of a wide range of innovations and everyday products. CERN, its researchers, and the media undertake various dissemination activities and public outreach work to celebrate and share these achievements.

Unusually amongst CERN member states, the UK's STFC also employs a dedicated communications professional based at CERN to champion examples of UK involvement. Building on this, STFC also supports scientists with public engagement fellowships and grants, encouraging them to work across schools and universities e.g. to create research projects via the CERN@school initiative (next section).

CERN, researchers and the media disseminate and reach out to the UK public

In our survey of UK scientists and engineers, the great majority (78%) felt that CERN had communicated with the UK public 'to a large extent'. A similar response was given in relation to the referencing of CERN by other organisations (including UK public bodies, the media) in communicating with the public.

CERN itself has worked hard to increase its profile and engagement with the public. For example, it takes more than 120,000 visitors (members of the public) on **guided tours** each year. This is in addition to visitors who only visit the **permanent exhibitions** on site. Around 10% of public visitors each year are from the UK, and over the past six years (2013 – 2018) there have been 3,192 groups of UK visitors who have gone on organised tours at CERN, with 72,108 individuals visiting in total (mostly from schools and universities, but also other members of the public and VIPs). The next section of the report includes more detailed statistics on UK **school visits** to CERN.

CERN also utilises **social media** outlets to disseminate information via an authoritative source, to gain public interest, to enhance learning and to influence the global scientific agenda. It is active on Twitter, Facebook, YouTube, Instagram and LinkedIn, and recorded over 40,000 UK social media interactions in 2018 (followers, likes and interaction engaging with 'CERN' or 'LHC'). CERN began using Twitter in 2008 and by 2013 was the most effective international organisation on the platform[70]. It now has more than 2.55 million Twitter followers, 670,000 followers on Facebook and a rising number of Instagram followers (global figures)[71]. Whilst there are few figures available for the UK alone, CERN's press office report that UK residents are amongst the top five countries using its Facebook, Twitter English, Google+ and Instagram accounts. Over 220,000 UK users also visit CERN's **website** each year, with each spending on average 3-4 minutes on the site (2017[72]). UK users account for nearly 7% of total traffic.

CERN's **media monitoring** shows 2,000 mentions of CERN in the UK media each year (2,200 in 2015, 2,000 in 2017, 1,500 in 2018). Examples of key outlets (below) show the reach of each piece of coverage.

Table 6 Top UK media outlets (by reach) disseminating CERN related content, 2017

Outlet	Number of Clips	Reach		Outlet	Number of Clips	Reach
MailOnline UK	35	627,000,115		theguardian.com	25	362,419,186
BBC News Online	29	473,507,766		Phys.org	39	246,455,306

Source: CERN National Media Monitoring 2017

[70] https://twiplomacy.com/blog/twiplomacy-study-2013/

[71] https://twitter.com/cern?lang=en; https://www.facebook.com/cern/ accessed 5 September 2018

[72] CERN regularly re-tenders for media monitoring services and so data is only available for limited time periods. CERN also transferred to a new website towards the end of 2018 and so consistent statistics are not available for this year.

Those consulted during the study have also pointed to a number of other examples of CERN-related broadcasts on **UK TV and Radio** in recent years. For example:

- BBC Two Horizon – "Inside CERN" (2016)
- VEGA Science Trust/STFC short films about CERN (2008)
- Mega Structures Atom Smasher: Detecting Cosmic Particles – National Geographic Channel (2008)
- BBC TWO Horizon - Hunt for Higgs (2012, 2015)
- BBC Radio Wales broadcast live from CERN (2019) to 90,000 listeners, with a show featuring students from Ysgol y Preseli comprehensive school and members of the Wales at CERN community
- BBC Radio Lancashire (2017) followed St Christopher's Sixth Form students (Accrington) to CERN and presented their show there.
- Naked scientist podcast "analysing antimatter" (2011) – "We talk to researchers at CERN who are capturing anti-hydrogen so scientists can study it properly for the first time".
- BBC Radio 4 – Big Bang Day Schedule (2010)

Other **public exhibitions, events and activities** in the UK that were mentioned include:

- LHC on Tour (an STFC travelling exhibition), including a life-size, walk-through section of the LHC tunnel and accelerator alongside interactive exhibits, informative artwork and digital media. This delivered 24 events at 20 venues (2012-2017), capturing the attention of around 380,000 people.
- Science Museum "Collider" exhibit (2013/14), curated by an STFC/science museum supported postdoc (Harry Cliff, Cambridge) in collaboration with CERN. This award-winning exhibition originally received 54,000 visitors.[73] It then became the first to tour outside of the Science Museum Group and between 2014 and 2017 drew an audience of 600,00 people.[74]
- Mosquitoes in the LHC – a play at the National Theatre featuring the LHC
- 'A world, a Particle' exhibition at the Victoria Gallery and Museum in Liverpool (arranged and curated by the University of Liverpool physics department). There were over 70,000 visitors to the museum during the period of the exhibition.
- Arts@CERN programme. The COLLIDE international award enables internationally renowned artists to have a 2-month residency at CERN. The outcome of the 3-year programme in partnership with FACT in Liverpool (the '*Broken Symmetries'* exhibition) then showcased the works generated between November 2018-March 2019.
- The Physics Pavilion (organised by CERN, STFC and IoP) at the WOMAD international arts festival. The space provides a platform for adults and children to engage with CERN physics in different ways. This has included UK scientists and engineers, including representatives from the CLOUD experiment (see CLOUD case study) as well as Tactile Collider (an interactive workshop to allow participants to engage with the LCH through tactile objects). The Pavilion attracted 4,000 visitors in its first year (2016) and 6,400 visitors in 2017 (2018 data not yet available).

Nearly all respondents (94%) to the survey of **UK scientists and engineers** reported that they also (personally) had referenced CERN (its facilities, experiments and discoveries) to communicate with the UK public over the past 10 years – including two-thirds who said that they had done so 'to a large extent'. Some specific examples were given, which are shown below.

> *"Last year we e.g. visited the Orkney Science Festival with ten scientists. During that stay we also visited small schools on very remote islands like Sanday, Stronsay and Westray, which were probably never before visited by scientists working in fundamental research. In all our activities we present research results, that are based on the experimental measurements performed at CERN."*

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[73] https://group.sciencemuseum.org.uk/wp-content/uploads/2017/06/annual-review-2013-2014.pdf
[74] https://group.sciencemuseum.org.uk/wp-content/uploads/2018/07/SMG-Annual-Report-Accounts-2017-2018.pdf

"I have initiated several public engagement projects, which have, for example provided CERN data to UK school pupils. This has directly inspired students to continue with physics at university level."

"Each person who visits, studies or works there becomes an ambassador. This has a knock-on effect that is seldom measured."

Among the general public, CERN is well-known for its research into elementary particle physics at the LHC, and its 'celebrity status' was boosted by the **discovery of the Higgs boson in July 2012**[75]. This work not only led to one of the most highly-cited publications in particle physics (more than 8,000 citations to date[76]) and the award of the Nobel Prize in Physics in 2013[77], it also received broad (and likely unprecedented for particle physics research) attention in the media. Around 1 billion people are estimated to have viewed rebroadcasts of two technical presentations announcing the discovery of a new boson[78]. In the UK, an STFC-funded series of short films ("Colliding Particles") were viewed nearly 100,000 times on YouTube and Vimeo between December 2012 and July 2013[79].

When we asked UK scientists and engineers through survey to give examples of specific CERN-related announcements that had had a significant impact on the UK public's understanding, interest or support for science and engineering, the majority pointed to the discovery of the Higgs boson (and associated Nobel Prize, given the UK role in its theorisation), while others mentioned the operation of the LHC (the first collision and each restart). Several also pointed to the recent (January 2019) publication of the Future Circular Collider study Design Report, which was picked up by mainstream media in the UK.

"The first collisions at LHC sparked wide public interest, so much so that media web-sites (BBC, Telegraph, CNN) were overwhelmed by the demand for information (given the capacity of the Internet/broadband at the time)."

"The discovery of the Higgs boson brought ideas about fundamental physics to the public like nothing else I've known in my lifetime."

"Although the media may not have communicated the facts as well as the scientists working on these experiments may have liked, it is hard to deny that the public was flooded with buzz about the 'God particle'"

"The FCC plans were on the front page of the Times"

CERN increases UK public appreciation of science

The British Science Association sets out **four categories of general public** in relation to science: scientists; enthusiasts; the receptive; and the apathetic. CERN's mission, history, scale, and cutting-edge technology offers opportunities to inspire and help the public within the UK to move up this scale, to the point where they might become science enthusiasts, or at least engaged friends, as well as more supportive of public (financial) support for science (and in this case, CERN specifically).

The various dissemination and outreach activities set out above will have helped to support this by exciting the UK general public and by awakening interest in CERN, the science that it supports and the

[75] Chatrchyan, S. et al. (2012). Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Physics Letters B, 716(1), pp.30-61 and Aad, G. (2012) Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Letters B, 716(1), pp.1-29

[76] http://inspirehep.net/record/1124338#

[77] https://www.nobelprize.org/nobel_prizes/physics/laureates/2013/ ; awarded to François Englert and Peter W. Higgs

[78] http://avc-dashboard.web.cern.ch/node/3

[79] http://impact.ref.ac.uk/CaseStudies/CaseStudy.aspx?Id=34170

outcomes and benefits of this work. The UK public's engagement with CERN's activities and findings should also help promote scientific literacy and foster the development of a culture valuing science, helping to increase interest in and engagement with science in general, as well as inspiring more young people to take up and pursue STEM-related studies and careers (see next section).

Enhanced scientific literacy and a culture valuing scientific investigation should also lead to wider cultural and societal impact by enabling the public to become active citizens within a scientifically advanced contemporary society, able to engage in socio-scientific debate and to make better personal choices, as well as critically assess claims and evidence (e.g. consumer, healthcare or political choices).

The UK government's periodical surveys of **Public Attitudes to Science** address some issues of relevance here (e.g. value of a scientific career). Their most recent research was undertaken in 2014[80]. This shows a positive improvement in the public's attitudes towards and perception of science and scientists. Notably, more now agree that "it is important to know about science in my daily life" (72% agreed, versus 57% in 1988). Also, people are now more comfortable about the pace of change, with fewer (34%, versus 49% in 1988) now agreeing that "science makes people's lives change too fast".

However, this and other public engagement surveys (e.g. Eurobarometer Special Report 419) tend to work at a rather generic level and do not invite respondents to comment on particular institutions. Nor do they allow analysis of the results by scientists from a particular discipline. The surveys do explore attitudes towards priority topics, but those covered tend to be quite broad and highly topical (vaccination of people attracts a hugely positive response while nuclear power and GM crops attract the opposite). There is also no reference to CERN or particle physics. CERN does not carry out such studies.

We have been able to identify just one smaller-scale public survey, in France, which explored the public's **awareness of CERN** in very narrow terms.[81] This report found that around 46% of the general public was aware of CERN, which was significantly higher than for ESA and the ESRF, but significantly lower than other international organisations like UNESCO, WHO and NASA.

The same author also polled the public (1,027 university students across four countries, including approximately 200 in the UK in 2015) on their **willingness to pay** for LHC research activities (offering options of €0, €0.5, €1 or €2 per year, for 30 years)[82]. A minority (27%) was unwilling to pay anything. A grossing up of the balance arrived at a figure of €3.2bn (for 30 years). A separate analysis of just French respondents[83] computed a figure of €4 per person per annum as the maximum amount taxpayers would be willing to pay for the construction of a new particle accelerator at CERN. (This compares with the actual national payments, which amount to around €2.7 / person per year).[84]. **An estimate of €4 per person per annum (for 10 years) would equate to £1.2bn in the UK** (2018 prices). This approach to monetising the value of CERN is explored in Section 10 (summary of monetised benefits).

Our own survey asked UK scientists and engineers for their perspective on the extent to which CERN (the facility, its activities and achievements) has an **impact on understanding and perspectives of the wider public**. Nearly everyone thought that CERN had some influence on all of the areas listed (that CERN has become well known and of interest to the UK public, that it has helped inform, engage and enthuse about science and engineering, and that it has increased support for investment in science and engineering in the UK). In each case, the majority claimed CERN's impact was "large".

We also asked respondents to put this in the context of wider efforts to increase UK public understanding of and support for science and engineering. Even making this comparison, 75% said that CERN's contribution was particularly significant (a large or very large contribution) within the mix.

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[80] https://www.ipsos.com/ipsos-mori/en-uk/public-attitudes-science-2014

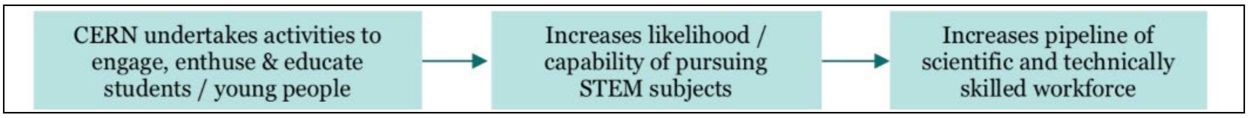
[81] Scientific Research at CERN as a Public Good: A Survey to French Citizens, 22 August 2018, Massimo Florio (University of Milan) and Francesco Giffoni (CSIL – Centre for Industrial Studies and University of Milan)

[82] Forecasting the socio-economic impact of the LHC: a cost-benefit analysis to 2025 and beyond

[83] Scientific Research at CERN as a Public Good: A Survey to French Citizens, 22 August 2018, Massimo Florio (University of Milan) and Francesco Giffoni (CSIL – Centre for Industrial Studies and University of Milan)

[84] https://cerncourier.com/lhc-upgrade-brings-benefits-beyond-physics/

8.3 Increased UK STEM uptake



In this section, we examine the importance of engaging young people in science and engineering, and how the UK's involvement in CERN can help encourage and support that engagement. This includes through programmes delivered by CERN directly, as well as initiatives delivered by UK organisations and individuals - leveraging the expertise and capabilities made available through CERN.

CERN inspires young people through its scale, the types of 'universal' questions it addresses and its international nature. It also undertakes various activities to directly engage, enthuse and educate students and to support the teaching of CERN-related subjects. As a result, young people will be more likely to, and capable of, pursuing STEM subjects in school, helping to nurture the pipeline of future talent and contributing to ensuring that the UK has access to a scientific and technically skilled workforce. This will help to sustain the UK as one of the world's leading research and innovation nations and support the further growth of its high technology economy.

The importance of engaging young people in STEM

A recent Wellcome Trust survey by King's College London found that public interest in science is high, with 63% of people interested in hearing from scientists about their research.[85] Ipsos MORI also found in the latest Public Attitudes to Science survey that 91% of people (and 84% of 16-24 year olds) agree that young people's interest in science is essential for the UK's future prosperity.[86]

A 2015 report by the UK Commission for Employment and Skills[87] asserts that the UK's economic future lies in high value, innovative and knowledge-intensive activities. The Government's industrial strategy sectors, for example, are identified on the basis of their potential to contribute to future economic growth and employment – and the majority are characterised by a strong reliance on high level STEM skills (and therefore a highly skilled UK STEM workforce). The report points to several pieces of evidence:

- There is an association between hourly pay and the use of STEM skills in the workplace, suggesting these skills are a factor in increased earnings and productivity
- International benchmarking suggests that the UK's science and innovation system is hampered by weaknesses in its STEM talent base
- There is insufficient domestic human capital to exploit science and innovation, including deficits of domestic talent and of Masters/PhD graduates working in research
- 43% of vacancies for professionals in science, research, engineering and technology are hard to fill due to skills shortages - twice the average for all occupations.

It is difficult to measure precisely the economic impact of STEM skills, but research in STEM-reliant sectors helps illustrate their value. EngineeringUK, for example, has calculated that around 5.7 million people, or 19% of the UK workforce, work in engineering organisations and that engineering contributes around 26% of the UK's gross domestic product[88]. At the same time (as mentioned earlier), shortages of STEM skills in the economy (some 173,000 skilled workers) are estimated to be costing UK businesses £1.5bn a year in recruitment, temporary staging, inflated salaries and additional training costs[89].

Below we set out how the UK's participation in CERN has had a direct influence on the physics curriculum in UK schools, on scientific activities undertaken and on students' enthusiasm for science.

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[85] Monitor and Culture Tracking Survey. https://wellcome.ac.uk/sites/default/files/monitor-wave3-full-wellcome-apr16.pdf
[86] https://www.ipsos.com/sites/default/files/migrations/en-uk/files/Assets/Docs/Polls/pas-2014-main-report.pdf
[87] Reviewing the requirements for high level STEM Skills, UKCES, July 2015
[88] Engineering UK 2017: The State of Engineering, February 2017
[89] https://www.stem.org.uk/news-and-views/news/skills-shortage-costing-stem-sector-15bn

CERN initiatives and activities for schools and students

CERN runs on-site programmes for teachers and students, while also providing additional resources to support further work in the classroom, in order to engage with young people and inspire the next generation of STEM professionals. Details of these programmes and UK involvement are set out below.

CERN offers several **programmes for teachers**, to encourage them to engage and interact with the facility, to support their development and to facilitate the exchange of knowledge and experience.

The CERN National Teacher Programme is a one-week scheme available to teachers from Member and non-member countries. Its objective is to encourage participants to act as ambassadors and pass on the subject to the next generation of e.g. physicists, engineers, IT specialists. The programme supports teachers' development and facilitates the exchange of knowledge and experience by encouraging teachers to network with staff based at CERN. It can also help CERN establish closer links with schools.

In the UK, the programme is organised by the national STEM Centre, which provides a bursary towards the costs of the trip, as well as supply-teacher coverage. The programme started in 1998 and consists of a series of workshops and lectures that explain the main work taking place at CERN and provides advice on how teachers can bring physics and CERN's expertise into the classroom. To follow up after each teacher programme, the lecture material and video recordings are archived to act as resources for teachers introducing particle physics into the classroom. Through the programme, teachers understand how to integrate the tools and resources provided by CERN into their teaching.

The UK has the highest number of teachers attending the programme, which is tailored to fit with the UK curriculum. An average of 125 UK teachers per year attended in the period 2010 to 2016 (see Table 7), compared to e.g. 99 per year for Germany, 85 for Italy, 49 for Spain and 34 for France.

Table 7 Number of UK teachers attending the CERN National Teacher Programme

2010	2011	2012	2013	2014	2015	2016	Average
321	143	77	101	79	82	74	125

Statistics provided by STFC

In addition, CERN offers two 2-week international teacher programmes: which are both open to teachers from around the world. CERN has been holding these since 1998, with the aim of teaching about the physics and engineering projects taking place at CERN, with the idea that school physics teachers are curious about this kind of work and the most suitable to transfer the knowledge of what is produced at CERN to students.[90] Through lectures, workshops and networking activities, teachers are able to engage in the exchange of knowledge and experiences between teachers of different nationalities, and learn more tools to help popularise physics both in and outside the classroom.[91] Over the period 2010-2016, 16 teachers from the UK attended the International Teachers Programmes.

Table 8 Number of UK teachers attending the CERN International Teacher Programmes

2010	2011	2012	2013	2014	2015	2016	Total
3	3	2	2	2	2	2	16

Statistics provided by STFC

These programmes support teachers' development and facilitate the exchange of knowledge and experience. Benefits to UK schools flow from these visits, as teachers have action plans, feed the outputs from their visits into their continuing professional development (CPD) and are required to demonstrate how they are sharing the knowledge and best practice gained from their visit more widely.

[90] Hst-archive.web.cern.ch. (2018). Available at: http://hst-archive.web.cern.ch/hst/1998/1998.htm [6 Aug. 2018].

[91] Voisins.cern. (2018). *High School Teachers Programme | CERN and its neighbours*. [online] Available at: https://voisins.cern/en/offre/high-school-teachers-programme [Accessed 6 Aug. 2018].

The STEM Centre followed up one trip to CERN that involved 78 UK teachers, and found that more than 11,000 students had been taught directly with context from CERN within just three months of the visit.[92] This was not just in physics; material had been included within maths, biology, chemistry, engineering and computing lessons as well. If such outcomes were to hold more generally (i.e. for all 125 UK teachers in the programme each year on average), then over 175,000 UK students will have been taught with context from CERN as a result of the teacher programme over the course of a decade.

Not only do teachers improve their skills in terms of subject matter, they also gain an improved understanding of the breadth and depth of STEM careers. The same STEM Centre survey found that teachers are also more confident in talking to students about careers in science and engineering. Teachers are often the main source of careers advice for their students and having this experience of real-world contexts can support them to give more effective, targeted advice.

Pupils can also engage through **on-site school visits**. These are free of charge and allow students to "discover the mysteries of the Universe" and the work of the laboratory through guided tours, exhibitions, talks, films and a visit to ground-level visit points. STFC also undertakes activities with each visiting school, providing information before and after the visit, as well as writing to inform the local MP and inviting them to also visit CERN.

Nearly 2,300 UK school groups visited CERN in the past five years (459 per year on average, 2014 - 2018), with nearly 54,500 teachers and students visiting in total (10,898 per year on average). The majority of these students (~85%) are at A-level, whilst the remainder are at GCSE level. A few UK primary schools have also recently started visiting CERN. The number of school teachers and students visiting CERN from the UK has been higher than from any other country, despite the relative distance to the UK).

Table 9 Number of UK school groups, teachers and students visiting CERN, 2014-18

	2014	2015	2016	2017	2018
Number of UK school groups visiting CERN	418	427	499	466	484
Number of UK school teachers and students visiting CERN	9,349	9,985	11,918	11,486	11,753

CERN Visits Service database

After visiting CERN, schools also have the possibility to further participate in a visit to **S'Cool LAB**, a Physics Education Research facility at CERN which gives students the opportunity to participate in experiment sessions and physics in education research. Working in small groups of 2-4, students manipulate equipment and associated software to explore particle physics phenomena connected to CERN's research and technologies. They make predictions, observe their experiments, and discuss their results. Each session is delivered by a S'Cool LAB Tutor - a specially-trained volunteer from CERN.

CERN offers support to schools in both the planning and the follow up of their CERN visits. Before a visit, schools have access to resource and planning material which is made available from both CERN and the STFC. In addition, there is an online symposium to which teachers can refer in planning their visit and additionally, follow up materials, including continuing professional development (CPD) sessions for teachers are also made available for school and teacher use.

Based on a CERN survey of participants, all (100%) of teachers who participated in school visits reported that they would bring another group to CERN, with 89% rating their visit to CERN as either 4 or 5 out of 5.[93] Teachers also rated these visits highly (average score above 4) in terms of the relevance to the

[92] http://www.sec-ed.co.uk/best-practice/the-power-of-stem-study-visits/

[93] CERN data

curriculum, the usefulness of the visit for themselves as teachers, being inspired, helping to highlight career options to students and being motivated to follow up with CPD.[94]

CERN also provides **educational materials for teachers to use in all schools** via the internet (whether they have visited or not). These materials range from presentation slides to videos and from simple word documents to interactive tours. All are aimed at allowing teachers to provide excellent classes to their students, increasing their knowledge and encouraging them into science.

Providing useful clear material makes it easier for students to learn new complex information and instils a belief that they can achieve a good grade. Schools report that students often fear that achieving a good grade in maths or science is harder than for other subjects and that this is one of the reasons students move away from science. The materials also make students aware of the range of opportunities that studying physics will bring outside of education (many believe that studying maths or physics can only mean a life in the lab or as a teacher, rather than creating apps or going into data science) [95].

Finally, each year CERN runs the **Beamline for Schools (BL4S) competition**, which invites teams of high-school students from anywhere in the world to propose a scientific experiment that they want to perform. Short-listed teams win a cosmic-ray detector for their school and often the chance to visit a nearby physics laboratory. The winning team is invited to CERN to carry out their experiment.

UK initiatives and activities for schools and students

For those students or schools not able to take part in a visit, the **CERN@school** initiative brings technology from CERN into the classroom to aid with the teaching of particle physics. It also aims to inspire the next generation of physicists and engineers by giving participants the opportunity to be part of a national collaboration of students, teachers and academics, analysing data obtained from detectors based on the ground and in space to make new, curiosity-driven discoveries at school.

We have developed a detailed case study of the UK-based CERN@School programme (as well as the Institute for Research in Schools, which was established as a result of the programme). The full text of the case can be found in Appendix C, while a brief summary is presented below.

CASE STUDY 28 – CERN@School programme and IRIS

The **CERN@School** initiative is a prime example of how CERN and CERN-developed technologies have had an impact on skills development and engagement of young people. The programme, initially inspired by a school visit to CERN, builds upon the Medipix collaboration and helps to engage students with physics through hands-on research activities. The programme has been able to source 40 Medipix detectors and has used these to support engagement with over 460 schools and 20,000 students to date.

As set out in the 2017 Education Endowment Fund (EEF) report[96] examining the size of the attainment gap in science, good evidence was found that the ability to reason scientifically – by testing hypotheses through well-controlled experiments – is a strong predictor of later success in the sciences and that this skill can be developed through programmes that allow pupils to design experiments that require them to control variables. This active learning approach created by CERN@school has enabled students to develop a range of those skills, including research design, critical and independent thinking and the ability to analyse results critically. Such skills are difficult to develop in standard A-level laboratory work where there is usually a pre-determined answer on a marking scheme.

The success of CERN@school has also led to the formation of the **Institute of Research in Schools** (IRIS). This charitable trust aims to develop an extended range of research fields, within which schools and teachers can participate in authentic research. IRIS has found that this type of in-school research increases the attainment of students, while also enhancing teacher job satisfaction and retention. IRIS

[94] https://indico.cern.ch/event/622184/contributions/2524932/subcontributions/226499/attachments/1448102/2231825/IPPOGReport_elizabeth_apr2017.pdf

[95] CERN Impact Evaluation

[96] https://educationendowmentfoundation.org.uk/school-themes/science/

has developed research projects across a variety of areas within STEM, including space science, particle physics, material science, biomedical science and climate science. This has helped develop an education system where there is less distinction between research and learning, and between theory and genuine scientific experiments. It has also offered students the exciting experience where no-one, not even the teachers, know the answers in advance, and all have to follow the process of science and learn together.

IRIS has undertaken a research study[97], looking at the attainment data for A-level students in one of the schools in which it works in order to explore the impact of participation in one of its programmes. During the four years of one intervention, 53 A-level students participated and 201 did not (control group). This study showed that participating students made almost three times the progress of the whole A-level cohort and six times the progress of students who did not participate in the IRIS-led research.

Finally, one day **Particle Physics Masterclasses** are hosted by universities and laboratories across the UK each year. These are aimed at students taking particle physics modules at AS- or A-Level, but are open to anyone with an interest in studying particle physics. There are 20+ Masterclass events held each year, with many of them oversubscribed. One of those consulted for the study highlighted the value of these masterclasses (and the CERN data upon which they rely):

> *"We use data from CERN as part of our "masterclass" for A-level students in the School of Physics. This is one of the key events to try to encourage students to pursue physics (and other science) degrees, which is critical for providing the highly skilled graduates needed for the future UK economy. CERN particle physics data allows students to have hands-on experience and is a key part of the masterclass."*

[97] https://impact.chartered.college/article/parker-iris-stem-students-teachers-participation-research/

Evidence of increases in UK STEM uptake

There has been a clear increase in the number of students studying STEM subjects at UK universities in the past decade (2007/08 – 2015/16), with a 32% increase in full time undergraduate STEM entrants and a 17% increase in post graduate STEM entrants. Subjects with the largest relative increases include physics and astronomy, chemistry and materials science and mathematical sciences[98].

While there are many factors at play, there is evidence that CERN has also played a role. For instance, a survey of 673 physics undergraduates in eight UK universities found that 95% were attracted to study science because of activities in particle physics (such as CERN), with half saying specifically that they were inspired by the discovery of the Higgs.[99]

The upward trend in university STEM uptake could continue, as the number of students taking A-level physics in the UK is also rising (an increase of 3% between 2014 and 2018). This is against a declining overall trend in the number of students taking A-levels. Furthermore, the attainment level for those undertaking physics A-level is also higher. Across the UK, a greater proportion of students achieved A*-A grades in physics (30%) in 2018 than in all A-Level subjects (26%).[100]

Respondents to our own survey of UK scientists and engineers also asked for their views on the impact of CERN on young people in the UK, and specifically on their involvement in STEM subjects. The great majority (82%) of respondents felt that CERN had 'to a large extent' inspired young people in the UK to take up and pursue STEM subjects and careers. A majority (58%) also felt CERN had, to a large extent, better enabled and prepared them to pursue these routes.

We also asked respondents to put this in the context of wider efforts to increase uptake of STEM subjects in the UK. Even making this comparison, 72% said that CERN's contribution was particularly significant (large or very large) within this mix. By comparison, only 1% claimed it was 'negligible'.

One respondent provided anecdotal evidence of the impact of CERN on university applications:

> *"Analysis of UCAS forms of students applying for physics at Oxford strongly suggests that CERN-based science is one of the primary drivers of bringing school students into physics at university. (The other major driver being astronomy/astrophysics.)"*

[98] https://webarchive.nationalarchives.gov.uk/20180319123059/http://www.hefce.ac.uk/analysis/HEinEngland/subjects/stem

[99] Survey undertaken by the Ireland for CERN Campaign. Quoted in the IOP Case for Irish membership

[100] FFT Education Data Lab, Results data analysis 2018. Physics, A-level. Accessed December 2019, https://results.ffteducationdatalab.org.uk/a-level/physics.php?v=20180904

9 Impacts relating to science diplomacy

This section explores the benefits of CERN to the UK from the perspective of science diplomacy. This aspect of CERN's activities has been widely documented over very many years in a wide-range of papers and book chapters. Sir Christopher Llewellyn-Smith's recent paper recounting the background to the creation of SESAME, the middle east synchrotron, is typical and an excellent introductory text to CERN's international relations work more generally[101]. It notes that CERN was conceived with two aims: to enable the construction of expensive facilities beyond the means of any individual European country; and to foster collaboration between countries that had very recently been in conflict. Over the years, CERN has built bridges between peoples in many ways, and Llewellyn-Smith lists a series of points where CERN has been instrumental across the 60 years it has been in operation. For example:

- It was the first intergovernmental organisation that Germany joined after the war; the first post-war meetings between German and Israeli scientists took place at CERN
- Collaboration between CERN and Russia continued throughout the Cold War, and provided a model for later USA-Russia collaboration
- In the 1970s, scientific contacts between Europe and China were pioneered at DESY and later at CERN, in collaborations led by Nobel Laureate Sam Ting (MIT), with the backing of Deng Xiaoping
- In 1985, when USSR-USA arms negotiations in Geneva were stalled, the US delegation asked the DG of CERN to arrange a dinner at CERN for Russian and US advisors, which facilitated a breakthrough
- CERN had an open-door policy for Eastern European scientists during the cold war, allowing them to quickly join CERN (an expression of their European identity) following the fall of the Berlin wall

CERN has found that, although they can initially be mutually suspicious, scientists and engineers with very different political or religious views who work together quickly develop technical respect. This then leads to greater understanding and tolerance of their respective views. Today over 13,000 scientists carry out research at CERN (some 7,900 from the 23 member states, the rest from 55 other countries). The collaborative work that these (mainly young) scientists carry out at CERN undoubtedly creates better understanding across and within their respective societies.

By nature, the benefit to the UK of its central involvement in these global communities cannot be measured easily; rather, the evidence of the benefits is in the form of examples and narrative. CERN itself has not conducted any formal evaluation of its role in science diplomacy and simply points to its various documented successes, including having been granted observer status on the UN General Assembly in 2012, in recognition of the critical potential of science for peace and the centre's many decades of experience in creating "open spaces". To that end, this exercise has similarly had to be content with a largely qualitative assessment of the literature, complemented by our surveys and interviews with CERN's international relations team and selected discussion partners. This element of our work has also included a short case study of the SESAME synchrotron (appended to this report).

Our analysis has underlined the central role of CERN, working in concert with individual scientists, within this realm of science diplomacy. It suggests that CERN member states have tended to be part of the ensemble rather than the main actors, selectively providing support and encouragement to the initiatives of others. UK scientists have been prominent in many of these international initiatives.

Following the theory of change developed for the study, we have explored three aspects of the UK and CERN's involvement in the international scientific landscape: (i) UK influence in the international S&T landscape; (ii) the UK's image as a 'great' science nation; (iii) UK involvement in CERN's international diplomacy and in supporting the development of the global physics community.

[101] 'Science Beyond Boundaries: SESAME and the International Cooperation,' Chris Llewellyn Smith, Ch 26 in International Cooperation for Enhancing Nuclear Safety, Security, Safeguards and Non-proliferation–60 Years of IAEA and EURATOM: Proceedings of the XX Edoardo Amaldi Conference, Accademia Nazionale dei Lincei, Rome, Italy, October 9-10, 2017.

9.1 UK influence in the international S&T landscape

Membership allows UK involvement / influence in CERN governance and wider agenda setting fora	→	Offering opportunity to influence decision making (funding & priorities) within and beyond CERN	→	Increased UK-relevance and 'fit' of opportunities, activities and outcomes

CERN is based on international co-operation, with 23 member states and 105 countries participating in experiments. Its international dimension is anchored in its Convention: "CERN shall organise and sponsor international co-operation in research, promoting contacts between scientists and interchange with other laboratories and institutes." Membership and participation in CERN experiments therefore ensures that the UK science policy and research community has a 'seat at the table,' with the opportunity to be at the centre of many of the largest and most fundamental global projects in high energy physics and related fields. Participation in CERN projects provides a platform for UK scientists and engineers to engage more widely in many other global initiatives and international networks.

Membership of CERN allows **greater UK involvement in various levels of CERN governance** (decision making bodies, staff, researchers and the collaborations). For example, UK scientists, engineers and administrative staff have held / still hold various influential positions at CERN (see box), while both BEIS and STFC are represented on CERN Council[102] alongside 60 other high-level representatives of national governments, funding bodies and research institutions from 30+ countries.

Current UK personnel in key positions include:

- Chris Parkes - deputy spokesperson for the LHCb experiment, 1 of the 4 biggest experiments
- Keith Ellis - Chairperson of Scientific Policy Committee (SPC), 1 of 2 subsidiary bodies to Council
- James Purvis and Paul Collier - heads of departments for Human Resources and Beams respectively

Past UK personnel in key positions included:

- Directors-General: Chris Llewellyn Smith (1994-98) and John Adams (1960-61, 1971-80). 2 of 15
- Presidents of Council: Alec Merrison (1982-4), Ben Lockspeiser (1954-7), William Mitchel (1991-3)
- VP of Council: H. Melville (1964-65), G. Stafford (1973-75), W. Mitchel (1990), R. Wade (2011-12)
- Chairs of the SPC: Cecil Powell (1961–63), Godfrey Stafford (1978-80), Donald Perkins (1984-86), Chris Llewellyn Smith (1990-92), George Kalmus (1999-01), Ken Peach (2005-07)
- Chairs of the finance committee: Janet Seed 2004-06, Charlotte Jamieson (2014–16)
- Spokespersons: Dave Charlton (ATLAS), Guy Wilkinson (LHCb), Jim Virdee (CMS), Peter Dornan (ALEPH), Phil Burrows (CLIC), David Plane (OPAL), Wilbur Venus (DELPHI)
- Other: Erwin Gabathuler (Head of the Experimental Physics, 1978-82), John J. Thresher (Director for Research, 1986-91), John Ellis (Division leader Theory, 1988-94), Lyn Evans (LHC Project Manager, 1994-2010), John Walsh (Chair of Tripartite Employment conditions forum, 1994-95), Roger Cashmore (Deputy DG, 1999-03), Steve Myers (Director. of Accelerators and Technology 2009-13), Vince Hatton (Head of HR), Andre Naudi (Chief financial officer), Terry Wyatt (Chair of LHC experiments committee), Ian Butterworth (Director of Research, 1983-1986).

Involvement in CERN and its governance provides UK ministries and funding agencies, as well as the wider UK science base with a platform for international S&T engagement, leadership and agenda-setting. Benefits include some **ability to influence CERN decision making** (e.g. with regard to scientific priorities, funding levels and new experiments)[103], thereby enhancing the alignment of CERN activities with UK capabilities and priorities. As a result, the UK may benefit from a better than average 'fit' for its research community as regards to the relevance of CERN experiments and projects to UK

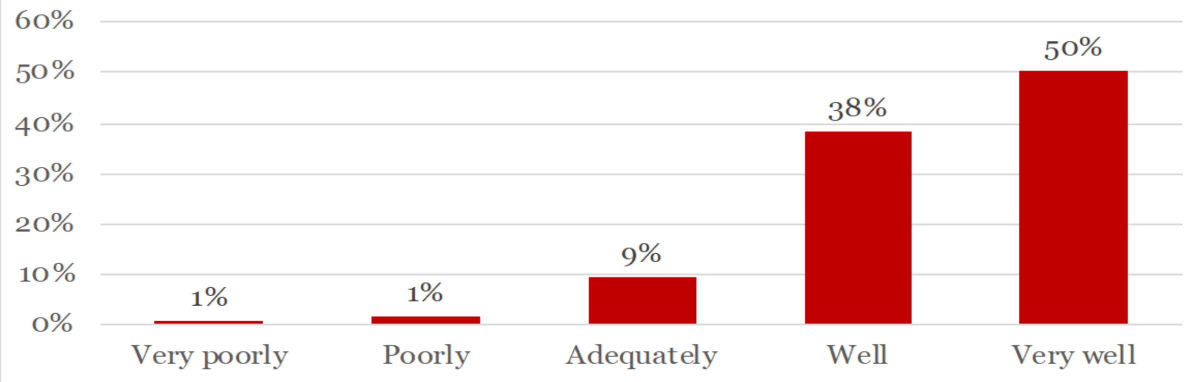
[102] Currently Tom Child, Deputy Director for Global Science and Innovation (BEIS) and Mark Thomson, Executive Chair (STFC).

[103] Indeed, when we asked UK scientists and engineers through survey how they judged the UK's central role within CERN's governance, 96% said the UK had been as or more influential than other leading countries.

interests and capabilities. This currently applies to a lesser extent for UK industry (e.g. supplier contracts), but STFC is working hard to improve matters here.

When we asked about this in our survey of the UK community, the great majority confirmed that CERN's priorities and activities align 'well' / 'very well' with UK research interests and capabilities (see below).

Figure 26 Alignment of CERN's priorities/activities with UK research interests/capabilities (n=151)



Source: Questionnaire survey of UK scientists and engineers

CERN activities/priorities, and the UK's input to these, may also **influence the decisions of other bodies** (e.g. national funders). For example, the European Strategy for Particle Physics is prepared under the auspices of CERN, but with the participation of other major stakeholders. UK membership of CERN also enables building of coherent relationships with the international research community that is broader than the confines of individual partnerships, and represents efficiencies in terms of time and effort required. Hence, going beyond CERN, the UK's membership contributes to its international presence and visibility, and enhances its network of high-level connections in S&T.

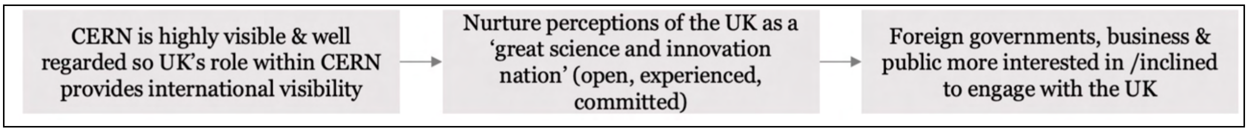
As an example, the Deep Underground Neutrino Experiment (DUNE) is an international flagship project hosted by the U.S. Department of Energy's Fermilab, which will push the state-of-the art in neutrino science: The South Dakota detector will be the largest of its type ever built and will use 70,000 tons of liquid argon and advanced technology to record neutrino interactions with unprecedented precision.[104]

Professor Mark Thomson, now STFC Executive Chair, and Professor Stefan Soldner-Rembold (University of Manchester) were elected co-spokespersons of the international DUNE collaboration. This international collaboration includes more than 1,000 scientists and engineers from over 175 research institutions in more than 30 countries, and together will deliver up to 40% of the total investment and scientific capacity of the experiment. Many of those scientists met first through the collaborations on CERN experiments. CERN itself is the single largest international sponsor and research partner: prototypes of the DUNE far detectors are under construction at CERN, while the full detectors and their computing systems are being designed and built by a collaboration of scientists from more than 30 countries. The UK is heavily involved in this new initiative, having made a £65m commitment to contribute to the detectors and computing systems.

Such international connections lend 'weight' to the UK's views on science and policy and increase the UK's ability to shape international priorities. Respondents to our survey reported that these effects were, for example, visible in CERN Council discussions, in EU strategies (through ESFRI), in the European Particle Physics Strategy Group, through the number of UK scientists invited to speak at major conferences or quoted in the media, and in the number of UK representatives on panels and committees.

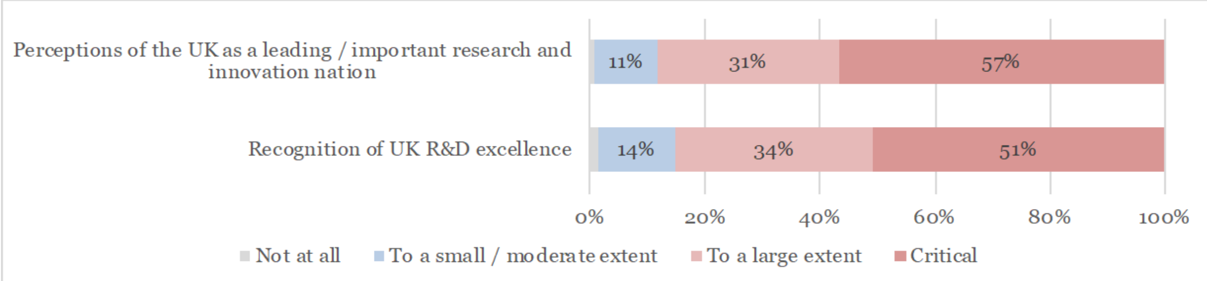
[104] http://www.fnal.gov/pub/science/particle-physics/experiments/neutrinos.html

9.2 The UK's image as a 'great science and innovation nation'



CERN is highly visible internationally and widely acknowledged as one of the most advanced scientific endeavours in the world. Its global reputation for cutting-edge research brings spillover benefits to its members and contributes to the UK's status as a 'great science and innovation nation', extending beyond CERN's research remit, and a favourable perception of the UK as a country to engage with. This has been confirmed by the UK community, the majority of whom claimed through survey (below) that the UK's involvement in CERN has a significant ('large' or 'critical') positive impact on international partners' perceptions and recognition of the UK as a leading research and innovation nation.

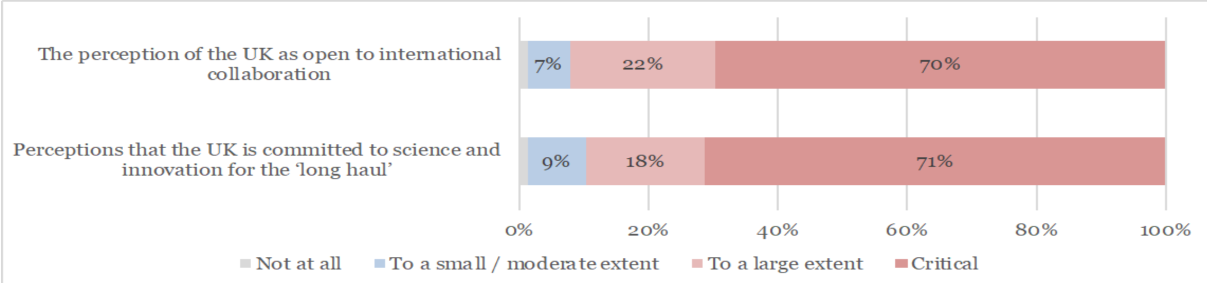
Figure 27 The impact of UK membership / involvement in CERN on UK science and engineering (n=171-1181)



Source: Questionnaire survey of UK scientists and engineers

The UK's membership of CERN (and the central role it plays within the organisation), provides the UK with international visibility at the highest level, nurtures its perception as a great science and innovation nation, signals that the UK is open to, and experienced in, international collaboration and business, and demonstrates that it is committed to science and innovation for the 'long haul'. Again, this has been confirmed by the UK science and engineering community, the majority of whom (72%) reported that the UK's involvement in CERN has a 'large' impact on the UK's international presence and visibility. Most also believed (see below) that CERN plays a critical role in perceptions of the UK as both open to international collaboration and committed to science and innovation.

Figure 28 The impact of UK membership / involvement in CERN on UK science and engineering (n=171-181)



Source: Questionnaire survey of UK scientists and engineers

The image of an internationally-engaged science nation may also have wider implications, i.e. beyond the S&T community. By fostering a positive attitude towards the UK, foreign governments, businesses, and the general public may be more interested in and inclined to engage with the UK, with positive effects on diplomatic and economic relationships, and tourism. Since 2014, CERN has welcomed three new member states (Israel, Romania and Serbia) and five Associate Members (Turkey, Pakistan, Ukraine, India and Lithuania), while a further three countries are currently in the pre-stage to membership (Cyprus, Slovenia and Croatia). It could be argued that these countries see CERN membership as an important step in establishing themselves internationally, both in the field of particle physics and more widely, as "scientific" nations.

9.3 International diplomacy and engagement

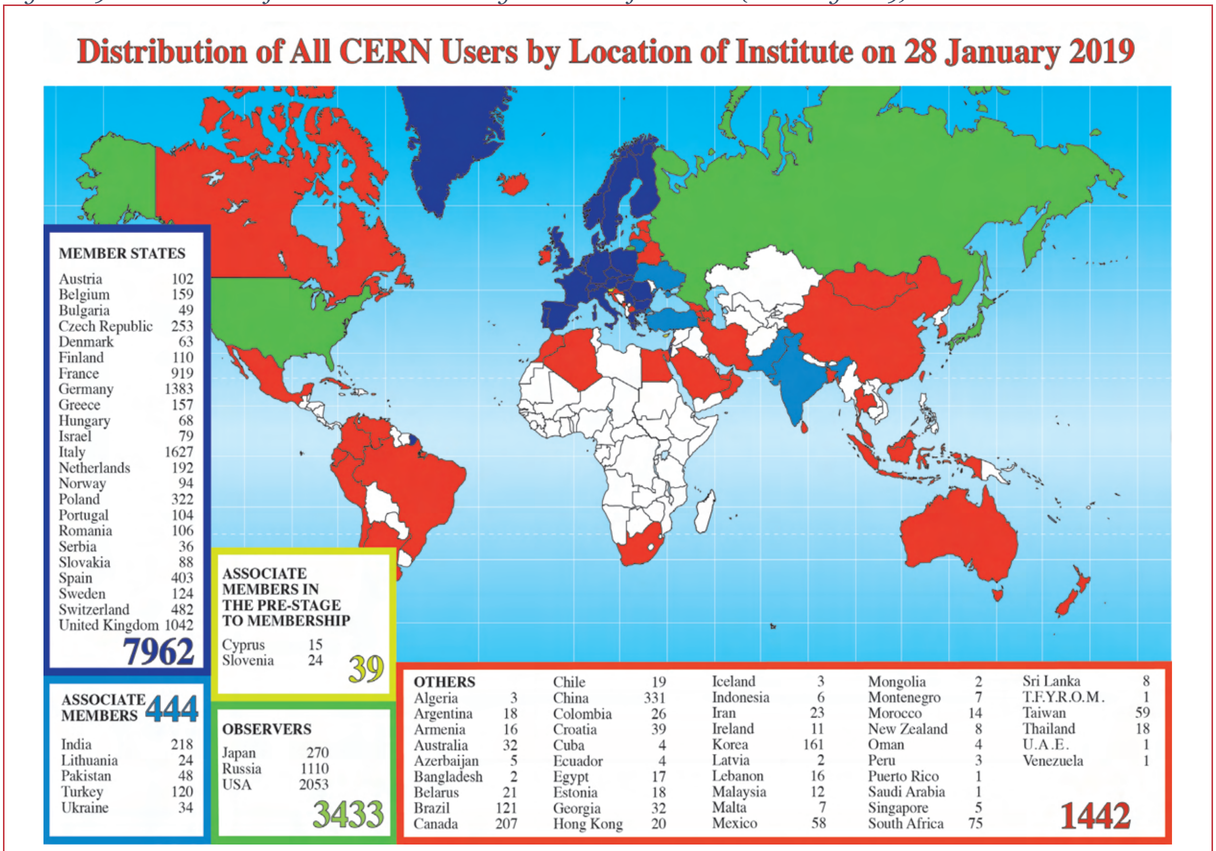
Membership gives UK companies access to CERN contract opportunities (addition revenue)	→	This can also bring benefits to: understanding, networks, reputation, innovation	→	Supporting increased productivity, market share, profitability, etc.

CERN's origins can be traced back to the late 1940s. In the aftermath of the Second World War, a small group of scientists and public administrators identified fundamental research as a potential vehicle to rebuild the European continent and to foster peace in a troubled region. It was from these ideas that CERN was born in 1954, with a dual mandate to provide excellent science, and to bring nations together. ("A peace project, mobilising European competitiveness in science, and strengthening the ties to the United States"[105]). This vision of rapprochement through science engagement was continued in the following decades, as research links with Russia were upheld throughout the cold war era. During this time, CERN served as a bridge between East and West: the 1968 agreement between CERN and the Soviet IHEP laboratory later became a model for an agreement between the USA and the Soviet Union.

To this day, CERN provides an important platform for international collaboration and exchange. This occurs through various means, and at different levels. For example:

- Joint investment and decision making (i.e. CERN governance)
- Joint experiments (multi-country teams of researchers, scientists and businesses) (e.g. see Figure 29 which shows how current CERN researchers are based in institutions across ~80 countries)
- Provision of a 'neutral' space for wider diplomacy, interaction or discussion (beyond CERN issues)

Figure 29 Distribution of CERN researchers by Location of Institute (January 2019)



Source: STFC

[105] O. Hallonsten. The politics of European Collaboration in Big Science. The Global Politics of Science and Technology - Vol. 2.

CERN's international relations strategy revolves around a commitment to secure sustained political and financial support for its scientific and societal missions:

- Stakeholder relations
  - Strengthen cooperation between CERN and its member states
  - Enhance links with associate and non-member states, as part of geographical enlargement policy
  - Build partnerships with international stakeholders (e.g. ESA, UN, EC) to serve as a voice for fundamental research in global policy debates
- CERN's Education, Communications and Outreach programmes
- Strategic planning and evaluation
- Protocol service for visiting dignitaries

While it is not part of CERN's mandate to pursue international diplomacy as an end in itself, the laboratory has continued its policy of openness and transparency in all of its activities and has if anything become even more important over time as a neutral space for mutually beneficial collaboration among the world's scientists and engineers.[106] Successive Directors-General and individual scientists have shown a deep commitment to this wider international cooperation agenda and CERN's exemplary contributions in the realm of science for peace were formally recognised in December 2012, when CERN was granted **observer status at the UN**, serving as a leading voice for global science with a right to participate in the work of the General Assembly and to attend its sessions as an observer.[107] Professor Fabiola Gianotti, CERN DG is a Member of the Scientific Advisory Board to the UN Secretary-General.

CERN has also been helping the UN in an operational capacity, providing the IT infrastructure that allows the UNOSAT programme to be at the forefront of satellite-analysis technology, e.g. for disaster-risk reduction or regional capacity development.

The resolution to grant observer status to CERN was submitted by Switzerland and France, and was supported by all other member states including the UK. The origins of this decision had several starting points, but the visit to CERN by Ban Ki-Moon UN Secretary General and his senior officials was a major factor, with the delegation reportedly having been deeply impressed with its global village quality. His predecessor, the late Kofi Annan, had also been a great champion of CERN, whose activities cover areas of considerable interest to the UN General Assembly. CERN and the United Nations are both actively involved in disseminating knowledge in the fields of science and technology, particularly with a view to development. Through its projects, which bring together scientists from all over the world, CERN also promotes dialogue between nations and has become a model for international cooperation.

> *"Science has the potential to significantly impact all three dimensions of sustainable development – economic, social and environmental," said Mr Martin Sajdik, President of the United Nations Economic and Social Council (ECOSOC). "The international community must consciously and deliberately work to ensure that advances in science and technology have positive effects towards that end."*
>
> *"CERN is delighted to celebrate its 60th anniversary at and with the United Nations," said CERN Director-General Rolf Heuer. "With this event we wish to promote a more effective dialogue between science and international affairs, and to openly exchange views on how science can be more integrated into global and national decision-making processes for the benefit of all."*[108]

[106] In 2016, the Commission published the document Open Innovation, Open Science, Open to the World, where it defines science diplomacy as "the use of science to prevent conflicts and crises, underpin policy making, and improve international relations in conflict areas where the universal language of science can open new channels of communication and build trust."
[107] https://press.cern/press-releases/2012/12/cern-granted-status-observer-united-nations-general-assembly
[108] https://home.cern/news/press-release/cern/un-and-cern-celebrate-science-peace-and-development-and-cerns-60th

One of CERN's most notable recent achievements is the **SESAME light source** in Jordan, which opened officially in May 2017 and follows the CERN model, promoting scientific collaboration in the Middle East (members are Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority, and Turkey).[109] Leading UK scientists have played an important role in the realisation of this new world-class research facility, and none more so than Sir Christopher Llewellyn Smith FRS, former CERN Director General and past president of the SESAME Council (2008 to 2017). Indeed, Llewellyn Smith is one of the five people named personally in the AAAS 2019 Award for Science Diplomacy for his contribution to this major project.[110] We have prepared a short case study of the origins and development of SESAME, as an illustration of the critical role CERN and its member states have played in creating this new facility, which is included in the appendices to this report.

The AAAS press release underlines the exceptional nature of the SESAME achievements:

> *"SESAME is a remarkable example of how scientists can unify in the pursuit of knowledge, even among nations with longstanding political tensions," said AAAS CEO Rush Holt. "The scientific enterprise in and of itself can promote peace and foster international collaboration."*
>
> *"In recent years, there is hardly a more shining example of science diplomacy than SESAME, which demonstrates the power of science to build bridges in the face of geopolitical tensions," said Mahlet Mesfin, deputy director of the AAAS Center for Science Diplomacy.*

The success of SESAME in bringing together regional actors may be replicated in other areas too, including a new regional research institute in the Balkans. As with SESAME, its development owes much to the efforts of Professor Herwig Schopper, former CERN DG.[111]

> *The Balkan states are joining forces to set up a South-East Europe International Institute for Sustainable Technologies (SEEIIST) with the primary goal of promoting 'science for peace' and the development of science and technology.[112] This research infrastructure will be based on the CERN model and is intended to further mitigate tensions between the countries in the region by encouraging scientists and engineers to work together on one common goal.*
>
> *Two scientific options are being discussed: the first is a fourth-generation synchrotron light source with intense beams from infrared to X-ray wavelengths; and the second is a state-of-the-art cancer therapy machine using protons and heavy ions for patient treatment with a strong research programme. Both options will be based on innovative cutting-edge science and technology. This international collaboration platform is also being designed to educate young scientists and engineers in the region to help reverse the brain drain. Studies are currently*

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[109] SESAME was singled out as a particularly good example of one of three classes of science diplomacy, using science cooperation as a precursor to improved international relations among countries, see page 20 of 'New Frontiers in Science Diplomacy,' Royal Society, 2010.

[110] Christopher Llewellyn Smith, Eliezer Rabinovici, Zehra Sayers, Herwig Schopper and Khaled Toukan received the 2019 AAAS Award for Science Diplomacy. https://www.aaas.org/news/architects-cooperative-middle-eastern-research-center-receive-2019-aaas-award-science

[111] The concept of setting up a science institute promoting 'science for peace' in South-East Europe was first proposed by Herwig Schopper in autumn 2016 at a meeting of the World Academy of Art and Science in Dubrovnik, Croatia. At around the same time, the setting up of a regional synchrotron light source or cancer therapy machine was also being discussed in Montenegro by the Minister of Science Sanja Damjanović and her two international advisors Hans Specht (Heidelberg University & Former DG GSI) and Nicholas Sammut (University of Malta). This was the perfect opportunity to join both ideas together and to propose the setting up of such an institute for the benefit of all the Balkan states.

[112] http://seeiist.eu/about-us/

underway to ensure the facility's sustainability and a layer of technology transfer is also being included for the technology to be exploited by industry.

A Declaration of Intent to establish SEEIIST, was signed at CERN on the 25th of October 2017 by ministers of science or their representatives, independent of where the final location would be. The initial signatories were Albania, Bosnia and Herzegovina, Bulgaria, Kosovo, The Former Yugoslav Republic of Macedonia, Montenegro, Serbia and Slovenia. Croatia also agreed in principle and Greece participated as an observer.

Just a few months later, in January 2018, a scientific forum was organised at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy where the concept studies worked out by two groups of distinguished international specialists were presented and discussed.[113] *Two UK-based scientists were involved in these working groups. At the Forum, representatives from the IAEA declared an interest in supporting the initiative through training programmes and the European Union representatives also showed favourable support of the project potentially providing resources to support the preparation of the detailed conceptual design.*

Just one week after the Trieste forum, the first SEEIIST steering committee meeting took place in Bulgaria. The committee consisted of representatives from each of the signatory countries, chaired by the Minister of Science of Montenegro. The meeting was introduced by the Bulgarian president Rumen Radew who showed strong interest and promised support of the initiative. With the initiative gaining momentum, the next step is to take a decision on which of the two scientific options to choose and to set up the executive team to move matters forward

CERN continues to place high importance on international collaboration, and actively seeks to establish links with and promote research by countries across the globe. For example, 2017 saw the first Africa-led experiment[114] by Western Cape University in South Africa (facilitated by the UK); 'retired' but still operational CERN servers were donated to facilities in Bulgaria, Algeria and SESAME in Jordan[115]; and undergraduate students from LMICs participate in CERN's summer programme, of which around 40 per year are supported by UK Global Challenges Research Fund (2017-21).

The UK may benefit *directly* from improved interaction / relations with other countries, e.g. through enhanced international influence. It may also benefit *indirectly* from improved interaction between countries, e.g. countries discussing global socio-political challenges, with global (including UK) benefits, or certain other countries improving their 'relationship' that may e.g. increase peace and security.

In our survey, the UK science and engineering community have been clear about their strongly positive views about the importance of CERN as a platform for international diplomacy, engagement and trust/relationship building. Nearly three-quarters of the respondents (73%) believed that it served this role 'to a large extent', while a further quarter said that it did so either to a small or moderate extent.

Some respondents provided additional comments regarding the role of CERN in international diplomacy and relations that bring benefits to the UK.

[113] The forum was supported by the United Nations Educational, Scientific and Cultural Organisation (UNESCO), the International Atomic Energy Agency (IAEA) and the European Physical Society (EPS). Over 100 participants including scientists, engineers and policy makers from universities, industry, government and regional or international organisations attended the meeting. Amongst others, the event was also attended by the European Strategic Forum on Research Infrastructures (ESFRI) and by the European Commission, which was represented by Robert-Jan Smits (DG Research and Innovation, European Commission).

[114] https://home.cern/about/updates/2017/07/ubuntu-powerful-motto-important-experiment

[115] https://home.cern/cern-people/updates/2017/10/servers-sesame

"The UK has benefited from CERN contributions to the establishment of peaceful scientific cooperation"

"CERN brings together people and students, from different environments with different cultures to work together to a common goal, advancing human knowledge. This is precious and very valuable for young UK scientists. Where else do Iranians and Americans, Indians and Pakistanis collaborate on common goals."

"CERN's role (with a significant internationally agreed/approved mission) is even more important in the context of Brexit, a rise of nationalism and an emerging breakdown of international cooperation."

"An intangible benefit, easily overlooked, is the model of open collaboration which is very hard to quantify and very likely not easily appreciated. I think that similar collaborations in important areas, e.g. climate science, would be hugely beneficial but difficult to establish for commercial reasons, i.e. exploitation of IP, and political motives. I would favour attempts to do so, using CERN as a model."

CERN's activities have established processes for engagement and contribute to **building relationships and trust between its members**. CERN's international platform has also enabled engagement between countries that traditionally have limited interaction. This is something we have explored through the bibliometric analyses undertaken specifically for this study (see Appendix D). This analysis shows that almost 62% of CERN **NPP** papers are written as part of international co-publications, and from the perspective of national publication sets, CERN papers are much more likely to be written as international co-publications than non-CERN papers.

Science-Metrix has developed indicators that make it possible to capture, quantify and measure the relative intensity of collaborations between researchers of different countries.

The resulting **collaboration affinity** (CA) score provides an asymmetric view on the propensity (affinity) of countries to collaborate with each other. In other words, it can serve to measure the propensity of the UK to partner with France (affinity of UK toward France) as well as measure the propensity of France to partner with the UK (affinity of France toward the UK). The collaboration affinity index is the ratio of observed to expected co-publications from either of the above perspectives. It equals 1 in case of neutral relationships, it is higher than 1 in case of positive affinities, and it is below 1 in case of a negative affinities. These affinities can be computed in NPP with and without CERN papers to help disentangle the potential contributions of CERN in shaping the international collaboration landscape in NPP as well as in alleviating tense relationships. In other words, this indicator helps to capture the Centre's contribution to international rapprochement between UK and foreign physicists (or between any other pair of countries), either from the perspective of the UK or the partnering country.

The findings highlight that CERN facilitates a shift in the UK's collaboration landscape toward partner countries with which there is comparatively less interaction otherwise. CERN papers help to shift collaborations away from an obvious partner such as the US toward others such as Malaysia and Turkey.

Where feasible (i.e., the NPP publication data made it possible to reliably compute CA scores), CA indexes were also computed to explore the affinities between other **sets of countries that are otherwise involved in tense diplomatic relationships**. This found that India and Japan enjoyed higher co-publication activity with China through CERN papers, greatly increasing the relative weight of that partner in their co-publication landscape (with the CA of India toward China going up from 0.45 to 1.00, and from 0.34 to 1.17 for the CA of Japan toward China). India had nearly twice as many CERN co-publications with China (2,458) between 1996 and 2017, than it had non-CERN co-publications (1,291). The collaboration affinity of Pakistan toward India was also greatly increased by CERN-related activities. In the 1996-2017 period, Pakistan had 797 co-publications overall in the NPP field with India, of which only 94 were not identified as CERN papers. Therefore, intentionally or not, CERN appears to have made contributions to science diplomacy objectives in the specific context of rapprochement between countries with tense political relations.

An assessment of how CERN papers shape the "centrality"[116] of countries in international co-publication practices also found that the CERN provided opportunities for less-established national science systems. Most smaller science systems that gained in centrality through CERN did so relative to other such national systems, rather than by competing directly with the established players. Indeed, the top 15 most central collaborators in NPP co-publications remained mostly unchanged whether CERN papers were included or not in the publication set analysed.

9.3.1 Developing the global physics community

The other benefit of CERN's international work, which comes through especially strongly in our interviews, is its contribution to the expansion and extension of the global physics, engineering and computing community around the world. CERN has consciously supported the inspiration and development of young researchers around the globe, through its educational outreach programmes.

Specialised CERN schools provide training on particle physics, accelerators and computing to several hundred young researchers each year, many of which are run internationally as part of a commitment to improve access and participation of smaller or less well-endowed scientific communities. This is not entirely selfless, of course, as those young researchers expand the pool of brilliant postdoctoral fellows CERN can recruit to work on its research and applied physics, engineering and IT. Moreover, as those national research groups expand, new countries will often agree to join CERN's experiments helping to finance ever more ambitious research collaborations and experimental programmes.

We see this capability and community development activity at work in Asia, Latin America and Africa.

UK scientists have been at the centre of many of these outreach activities, making important contributions to the setting up of regional schools such as the CERN Latin-American School of High-Energy Physics (CLASHEP), which has helped inspire many young physicists, expand national HEP communities in Argentina, Brazil, Chile, Colombia and Mexico as well as facilitating the emergence of regional scientific cooperation. Discussion partners tell us that their involvement with CERN has given them a lifelong passion for science and international research cooperation, with people devoting their careers to building local research communities, with individual fellowships providing an anchor point for new research groups that may expand in time into new departments in the first instance and then several universities or national research institutes. This evolution has also persuaded governments of the importance of science nationally – not just technology or applied research – and has led to countries joining CERN collaborations (e.g. ATLAS in 2008). CERN has also provided a portal to other scientific programmes, with new collaborations in other countries such as the US and with researchers taking up positions as visiting academics or getting involved in international collaborative projects with partners in other countries (whom they first met at CERN). This can in time also lead to the investment in new national research facilities as well as to important technological spill overs too.

The following three mini-case studies illustrate how CERN has developed global physics communities around the world, prepared through discussions with international physicists.

[116] i.e. the extent to which a country appears in co-publications, and the extent to which these co-publications are authored with other countries that are also themselves highly collaborative.

Professor Maria Tere Dova, is Professor of Physics at the Universidad Nacional de La Plata, IFLP (CONICET/UNLP) in Argentina She won a CERN post-doctoral fellowship in the 1980s to work on the new L3 experiment, one of four large detectors on the Large Electron–Positron (LEP) collider at CERN. This would have been impossible in Argentina at the time without the support of CERN, and affected Professor Dova profoundly and created in her a total conviction to build a high-energy physics group nationally. That research experience on L3 led to her being identified as an important young scientist and she was invited to join the ATLAS team by Peter Jenni (former ATLAS project leader), where she worked with Fabiola Gianotti (the subsequent ATLAS Leader and future CERN Director General). The experience set in motion a number of other events, which over a 10-year period led to the creation of a high-energy physics research group within the Universidad Nacional de La Plata and Argentina joining the ATLAS international partnership (2008). The Argentinian government's commitment to CERN has held firm over time and the current government had agreed to support Instituto de Física La Plata (IFLP) in collaborating on the global trigger system for the High Luminosity Atlas Phase II upgrade (MoU is to be signed by Minister of Science in spring 2019). Argentina will work on the electronic design of the trigger with the UK and the US. The government has given them the green light (and financial support) to build some of the Global modules in Argentina, and will also invest in the construction of a new lab / building and some specific hardware for signal distribution. This will be the first time that Argentina will contribute with hardware, which is seen as an important progression in the level of engagement of Latin America in the global project. It is also worth noting the role played by CERN's international schools. Specifically, Nick Ellis also organised a CERN Latin American School of High Energy Physics (CLASHEP) which was run in Argentina in 2005 (and Chile in 2007), and other countries in other years which helped expand LATAM involvement in CERN and continues to this day[117]
Professor Marta Losada Falk is a Colombian high-energy physicist, a pioneer of physics in Colombia, and the president of Antonio Nariño University (UAN) in Bogota. She completed her PhD at Rutgers University in the US and was a postdoctoral researcher at CERN from 1997 to 1999, while the Large Electron-Positron collider (LEP) was running. She is one of the collaborators on the ATLAS experiment at the Large Hadron Collider, which provided the inspiration and the platform from which to build a new ATLAS research group at UAN as well as to expand the presence of high-energy physics in Colombia. The UAN group has worked on the trigger system for ATLAS since 2007, using a combination of hardware and software to detect significant particle collision events in the detector.[118] CERN provides a unique experience for young researchers; to go to CERN and be part of a global pool of talented and committed individuals; the environment also encourages an openness and appreciation of other cultures; people from around the world with different academic traditions and different religions and ideological reference points[119]

[117] CLASHEP was established in 2001 as a way of engaging young Latin American scientists in the field of particle physics - particularly in the experimental aspects of research. It has played an important role in encouraging Latin American institutes to collaborate with CERN and showing how non-Member-State physicists can work as equals with Member-State nationals. "CLASHEP reflects some of CERN's guiding policies: enlarging its membership and involving new nations in its programmes," says Nick Ellis, director of the CERN Schools of High-Energy Physics. "After the School was held in Argentina in 2005 and in Chile in 2007, these countries expanded their involvement with the Organization."

[118] Professor Losada is one of several people that were case studied by Hannah Louise Openshaw in a review of the ATLAS experiment's contributions to global physics: www.atlas.cern/updates/atlas-news/atlas-around-world-faces-behind-physics

[119] Professor Losada also noted the importance of the EU in its provision of funding to support the ambitions of CERN globally and the creation of sustained networks of physicists across Latin America. The collaboration of Latin American groups with ATLAS was supported through HELEN, the High Energy Physics Latin-American-European Network. After it was launched in 2002 (under EU programme FP6), the programme provided economic and logistic resources to students and researchers from Latin America to join research projects at prestigious physics laboratories in Europe. Support continued within the EU FP7-funded project, EPLANET (European Particle physics Latin American NETwork, 2011-2016; €3.25m in EU funding), which was coordinated by Luciano Maiani (former CERN director) at the Universita Degli Studi di Roma la Sapienza (https://cordis.europa.eu/project/rcn/97759/factsheet/en) and has been renewed in Horizon 2020. The EPLANET Latin

Professor Zeblon Zenzele Vilakazi is the Deputy Vice-Chancellor Research and Postgraduate Affairs at the University of Witwatersrand (Wits) in South Africa.

Professor Vilakazi completed his PhD at Wits on the Investigation of coherent correlated effects due to incidence of ultra-relativistic leptons on oriented crystalline matter, which included spending time at CERN. This was followed by a post-doctoral fellowship at CERN, which was funded by the Swiss National Science Foundation. He returned to Cape Town to take up an academic post at the University of Cape Town (UCT) in 1999 where he was instrumental in establishing South Africa's first experimental high-energy physics research group focusing on development of the high-level Trigger for the ALICE experiment at the Large Hadron Collider.

Professor Vilakazi was subsequently appointed as the director of iThemba LABS (2007) and Group Executive for Research and Development at the Nuclear Energy Corporation of South Africa (NECSA) in 2011. In addition to these notable achievements within South Africa, Professor Vilakazi has also served as a chairman of the International Atomic Energy Agency's Standing Advisory Committee on Nuclear Applications from 2009 to 2011 and was nominated by the World Economic Forum in 2010 as a Young Global Leader.[120]

Professor Vilakazi explains that CERN was instrumental in persuading the South African government of the importance of basic research, and 20-years later the government routinely uses its involvement with CERN as an exemplar and an attestation of its commitment to international science. The country's involvement in the Square Kilometre Array (SKA) might in some small way be linked to this earlier engagement. The country has also used CERN as a portal to build links with other countries internationally, such as the Brookhaven National Laboratory in the US and the Joint Institute for Nuclear Research in Russia. It has also helped to form stronger academic collaborations with neighbour countries too, as well as helping South Africa play a fuller role within the wider continental commitment to science and innovation.

American HEP community is composed of about 1000 physicists and engineers, more than a half young physicists, graduates and PhD's. On the EU side, we see predominantly Spanish and Italian partners, with a small role for the University of Leeds.

[120] He is a member of the Academy of Sciences of South Africa. He is a member of the Programme Advisory Committee for Nuclear Physics at the Joint Institute for Nuclear Research in Russia and a member of the International Union of Pure and Applied Physics Working Group for Nuclear Physics.

10 Summary of monetised benefits

In this section we summarise the monetisable benefits of the UK's involvement in CERN, as advised by Government guidelines on evaluation (HM Treasury Magenta and Green Books). This brings together evidence of monetised impact from previous parts of the report, alongside the results of additional approaches, to arrive at an overall (albeit partial) view of the *value* of benefits in monetary terms.

The section begins with an introduction to the purpose and scope of the analysis of monetised benefits, including the main challenges and limitations inherent in such an exercise (section 10.1). Section 10.2 then presents a summary of the estimated monetised benefits, covering a number of different areas of impact. Sections 10.3 to 10.5 then provide further details of the methodologies employed to arrive at these estimates, with additional explanation of parameters also provided in Appendix F.

In the monitoring and evaluation framework that then follows (section 11) we discuss opportunities for further development. This includes suggestions for strengthening monitoring systems so as to enable a more complete account of CERN-derived benefits, as well a recommendation that STFC commission a methodological study, specifically addressing large research infrastructure, which could critique different approaches to monetising impact and propose practical guidance for future assessment.

10.1 Introduction to (and limitations of) the analysis of monetised benefits

Estimating the monetised benefits of CERN entails giving a monetary value to relevant impacts *where possible*. It focuses on those impacts that it has been possible to monetise within the context of this study – and (importantly) **does not capture the full range of impacts emerging from CERN** (e.g. relating to wider technology spillovers or science diplomacy), which have been explored in previous sections. As such, this monetised assessment represents a lower bound estimate of overall impact.

The methods employed reflect the state-of-the-art with respect to the monetisation of the impact of research infrastructures (RIs), as per recommendations in peer reviewed journals and in Government guidelines. The OECD expert group on the socio-economic impact of RIs, for instance, has been identifying the best approaches to measuring the impact of RIs, including monetisation, and have recently concluded that estimating the multiplier effects on suppliers and willingness to pay approaches offer the best way forward[121]. The Treasury Green Book however advises against using multiplier effects when assessing economic impacts at the national level[122]. BEIS guidance on appraisal and evaluation for science capital also suggests using bibliometric data and average wages to value the production of scientific knowledge, as well as surveys to obtain self-reported estimates of additional income. All of these recommended techniques are applied here, alongside several other accepted methods. Where possible, we have also tested two methodologies to approach the same subject / impact.

Monetising the impact from RIs remains a challenge, however, for all evaluators and funding bodies. It is difficult, if not impossible, to attribute an economic value to research undertaken at CERN, since it contributes to the advancement of knowledge and flow of ideas, which may only materialise into socioeconomic benefits indirectly. As such, these benefits do not have 'market prices' that can be used to express them in monetary value. Furthermore, pushing the frontiers of human knowledge is an area where impacts could materialise in the much longer-term (15-25 years or more), with incremental progress being made over time (in a non-linear fashion) and with the support of various other efforts, investments, and knowledge beyond CERN. At the same time there are undeniable benefits of being a member and 'sitting at the table' where decisions are being made today about the future of particle physics 20-30 years from now, as this allows the UK to influence research agendas and be at the forefront of future developments. Again, these are important aspects, but nonetheless difficult to monetise. Finally, where individual examples of economic benefit to the UK can be traced and demonstrated to a reasonable extent (through a case-based approach), one cannot simply extrapolate to a global figure.

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[121] OECD (2019), "Reference framework for assessing the scientific and socio-economic impact of research infrastructures", OECD Science, Technology and Industry Policy Papers, No. 65, OECD Publishing, Paris, https://doi.org/10.1787/3ffee43b-en.
[122] HM Treasury (2018), "The Green Book: Central Government Guidance on Appraisal and Evaluation", para 6.6, p 39

This study faces an additional challenge. An analysis of monetised benefits that follows UK government guidelines needs to be concerned with **the net impact** (i.e. beyond what would have happened anyway, in the absence of CERN membership) **and attribution** (to what extent can impacts be attributed to CERN, taking account of the additional efforts and developments that have made them possible). There is no doubt that discoveries enabled by CERN, such as the World Wide Web or PET scanners for medical imaging, have had substantial (life altering) impacts on the way humanity operates, however it would be difficult to argue that the UK would not have been able to enjoy those benefits in the absence of its CERN membership (or that those discoveries would not have been created had the UK not been a member).

Finally, setting up an **impact window** (timeframe) for the analysis is not straightforward. Different impacts take different times to materialise. The impact of skills development opportunities (for contractors, researchers, employees, trainees, students) or of the knowledge arising from exposure to CERN related news and material could materialise almost immediately or in the short term. In some cases, those effects could last for a long period of time (e.g. in the form of a wage premia for those that work at CERN as employees or postdocs). Other effects could materialise in the short to medium term (3-10 years), such as the transfers of technology out of CERN (by UK research groups and companies) or the effects emerging from technologies that have been further developed for wider application, beyond CERN (with wider socioeconomic benefit), while pushing the frontiers of human knowledge and understanding could lead to impacts that materialise only in the much longer-term (15-25 years or more). Nevertheless, a time frame has to be set, so as to cover the same period across all benefits. We have therefore taken a practical approach and focused on the period suggested in our brief (2009-2018) and have conducted an analysis of the monetary value of UK benefits emerging during this period from CERN, with results adjusted for inflation and presented in real terms (2018 prices – see Appendix F.4).

10.2 Overall results

Table 10 summarises our estimates (using different approaches) across three dimensions (impact areas)[123]. Some of the key assumptions and limitations are also highlighted in the table. Further explanation of the approach used in each case, along with additional details of the assumptions made and the limitations of these methods, is then provided in the sub-sections that follow the table.

Where possible, we have tested two methodologies to estimate the same source of benefit. Often these different approaches are assessing the same impacts and so have to be treated separately (i.e. the results cannot be summed). We have used the largest results in each case to arrive at a total in the table. However, the ranges provided for some methodologies show that even within those areas in which it is has been possible to monetise benefits, the results can differ greatly depending on the approach used.

Using these different approaches, we have estimated **a total of £1.1bn in *monetised* benefits for the UK in the period 2009-2018** (2018 prices). We reiterate that this figure does not capture the full range of impacts emerging from CERN, which are explored (but not monetised) in the previous sections of the report. In particular, it does not include wider technology spillovers, which if monetised would be substantial (e.g. the World Wide Web – invented at CERN in the 1980s - is estimated to now contribute 2.9% to global GDP).

It is also worth noting that there is an alternative approach used by Florio et all (2018)[124] – not included within the table below - that entailed <u>asking wider society about their valuation of CERN</u> (using a willingness to pay approach). It is difficult to tell what people included in this valuation, but in theory it should take account of all benefits that flow from CERN (including some or all benefits that we have attempted to measure through other means). Based on information collected among students in France, a valuation was reached of €4 per person per annum to ensure the continued existence of the LHC in its current form (note the focus on just the LHC, rather than CERN). Applying this to the UK population provides an estimate of **£1.2bn in value for UK society** (based on a tax-payer population of 30.3m, an exchange rate of 0.85, and 10-year period of benefits). The approach is explained in Appendix F.5.

[123] We explored the possibility of monetising the impact of science diplomacy. Conversations with the UK FCO confirmed that the best way is to follow a case-based approach – which was not possible to carry out within the current study.

[124] Scientific Research at CERN as a Public Good: A Survey to French Citizens, 22 August 2018, Massimo Florio (University of Milan) and Francesco Giffoni (CSIL – Centre for Industrial Studies and University of Milan)

*Table 10 Summary of monetised benefits to the UK (2009-2018) in 2018 real prices**

	Approach	Method	Value	Key assumptions and limitations
Research	1. Willingness to pay of UK science & engineering community	Based on self-assessment of the UK scientific community's willingness to pay to ensure the continued existence of CERN in its current form (and the research benefits that flow from it to them).	£30.2m	• An accepted (economic) approach for assessing the value of goods or services that do not have a market price (commonly used to assess value of environmental services). • The question of 'willingness to pay' may be difficult to answer for a community that mostly accesses RIs as part of their funding and institutional arrangements. The scenario posed is by definition hypothetical, and consequently respondents may final it difficult to assess. • Respondents were advised that the CERN subscription fee equated to around £2.10 per UK taxpayer each year. This 'benchmark' may have influenced the responses given (although most gave a much higher value). • The mean average WTP response has been applied to academics working in UK Physics departments, while the (lower) median average has been applied to academics that work in other relevant departments. • The responses from a relatively small sample (176 individuals) have been grossed-up to provide a value for the full population (of around 25,000). The actual size of the full population is itself difficult to identify and has been approximated.
	2. Value of production of knowledge	Using salaries and time spent per paper published each year to assign a monetary value to papers produced through CERN (P0) and UK publications citing those publications (P1)	**£495.1m**	• An accepted (economic) approach for assigning a value to publications, using the value of time (measured by salaries) • Wages represent a narrow – although accepted-measure of the value of a person's time (which might e.g. not fully reflect the wider social value of what that unit of labour produces) • The criticality of CERN publications to the subsequent publications that cite them has been approximated by comparing: (i) the number of citations to CERN publications; with (ii) the number of citations to all publications. • The approach does not assess the value of advancements underpinned by the research contained in those publication and, as such, only captures the value of the *production* of knowledge (i.e. it is only a partial measure of research benefits)
Innovation	3. Additional profit (willingness to accept among UK suppliers)	Based on UK companies' willingness to accept to forgo CERN contracts, and secondary data on profit margins	£21.7m	• An accepted (economic) approach to the implicit valuation that companies place on having CERN contracts (going beyond the nominal values of the contracts, to include potential additional benefits, e.g. additional income streams, that would be lost). • The question of 'willingness to accept' may be difficult for suppliers to answer, given its hypothetical nature. • The approach relies on survey responses from a self-selected sample of respondents (30 out of the 500 suppliers invited to respond). The sample includes different sizes and sectors of companies, with differing lengths/scales of relationship with CERN, however similar information is not available on the full population and so it is not possible to test representativeness. • Additional income was converted to additional profit using the average (mean) profit margin of 176 (out of 500) suppliers that could be identified within Companies House data. Others may have ceased to exist or do not have the obligation to disclose their financial information given their size. As such the profit margin calculated for the 176 overestimate the profit margin of the ful population. • Does not include the value of contracts placed with UK firms by university groups and national laboratories, as part of CERN experimental programme

	Approach	Method	Value	Key assumptions and limitations
Innovation	4. Additional profit (Economic utility ratio)	Based on prior studies that estimate an 'economic utility ratio' (i.e. additional turnover generated by each £ of CERN contracts), and secondary data on profit margins	£32.5m	• An HMT Green Book recommended approach for measuring net economic gains emerging from additional turnover (due to additional income streams and/or learning effects) • Does not include the value of technological spillovers to the wider economy, which are expected to be substantial (examples are documented in our case studies and in Section 10.4.4) • Does not include the value of contracts placed with UK firms by university groups and national laboratories, as part of CERN experimental programme
	5. Additional profit (self-assessment from supplier survey)	Based on UK suppliers' estimates of turnover levels had they never been a CERN supplier, and secondary data on profit margins	**£109.7m**	• Similar to method (4), but based on assessment of additional turnover and grossed-up using the average turnover and number of suppliers (instead of the value of contracts) • Value of additional turnover relies on (un-validated) self-assessments made by companies • Respondents were asked about their turnover to date and a grossed-up figure is presented for the overall period of analysis, which means that estimates could be overestimated. • Does not include UK suppliers contracted by university groups and national laboratories, as part of CERN experimental programme
Skills	6. Wage premia and value of training	Using prior studies that estimate wage premia among CERN young researchers, and assumptions about salary and careers Value of training provided	**£493.6m** *£488.7m wage premia* + *£4.9m training*	• An accepted (economic) approach to measuring the value of skills gained (in terms of better salaries) and of training received (by assessing the value / price of commercial alternatives) • Based on self-estimation made by individuals that have worked or trained as (young) researchers at CERN. Average results from across 52 countries have been applied to the UK. • We have assumed that 30% of UK-based CERN researchers are young researchers (age data per country is not available) • Assumptions have been made about the destination of students and young researchers after CERN (we assume that 60% will work in academia or research centres, while 40% will work in industry, which is in line with the statistics collected by CERN on destination of PhD students). • Does not include CERN contribution to inspiring students to pursue STEM careers (briefly discussed in the Section 10.5.3)
	Total monetised benefit (2009-18)		**£1,098.4m** *(partial estimate)*	• Believed to underestimate the total benefit of CERN, given inability to estimate e.g. technology and skills spillovers

Source: Technopolis (2019). *Figures have been adjusted using an annual GDP deflator to arrive to 2018 values.

10.3 Approaches to monetising research-related benefits

It is difficult, if not impossible, to attribute an economic value to the impact of research undertaken at CERN, since it contributes to the advancement of knowledge and flow of ideas, which may only materialise into socioeconomic benefits indirectly, and in the longer term. As such, these benefits do not have 'market prices' that can be used to express them in monetary value.

We have however tested two approaches (recommended in the academic literature and government guidelines) that attempt to attach monetary values to some of the research-related benefits of CERN:

1. A willingness to pay (WTP) approach to measuring the scientific community's willingness to pay to ensure the continued existence of CERN in its current form (and the research benefits that flow from it to them)
2. Valuing the production of knowledge (VPK), which gives a monetary value to the production of publications that are emerging and enabled by CERN (though not to the advances that are then underpinned by this research).

Using these approaches, we estimate a monetised value of £30.2m (based on UK scientific community WTP) or £495.1m (based on valuing the production of knowledge), in 2018 prices. Note again, these measures do not capture the full extent of the impact of research.

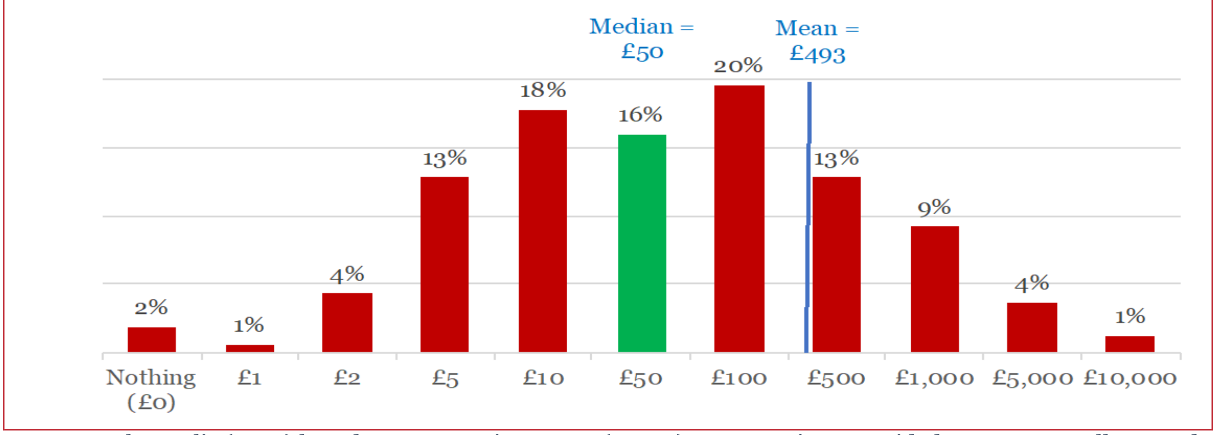
Both approaches and their caveats are explained in more detail below, while the breadth of impact emerging from research conducted at CERN has been documented in Section 6.

10.3.1 Approach 1: Willingness to pay of UK science & engineering community

As suggested by the HM Treasury Green Book, social benefits without a market price can be estimated using a range of techniques, including the so called 'stated preference' techniques (willingness to pay / willingness to accept). Stated preference techniques rely on asking people hypothetical questions and are classified into contingent valuation and choice modelling techniques. The former seeks measures of willingness to pay through direct questions such as 'What are you willing to pay?' or 'Are you willing to pay £X?' The latter seeks to secure rankings and ratings of alternatives from which WTP can be inferred.

We invited UK scientists and engineers through survey to provide a financial view as to the research benefits of CERN to them. Specifically, we asked what the maximum is that they would personally be willing to pay each year (for the next 20 years) to ensure the continued existence of CERN in its current form (and the benefits that flow from it). The spread of responses is shown below (Figure 30). While these range from £0 to £10,000 per year, the majority (53%) of respondents opted for a figure in the range £10 to £100, and indeed the median response was £50. The (mean) average is higher (driven by a relatively small number of multi-thousand-pound answers), at £493. These are high valuations if we note that the UK's subscription to CERN currently only costs the average UK taxpayer £2.10 each a year.

Figure 30 Willingness to pay of UK science & engineering community, distribution and value



Source: Technopolis (2019) based on community survey (n=176). Note: options provided were not equally spread.

We use this mean and median to calculate a total WTP for a ten-year period and then use the number of relevant academic staff in the UK to arrive to grossed up estimates for the UK science and engineering community overall.

There is no straightforward way to identify the size of the UK science and engineering community that benefits from CERN and the relative importance to their work (and consequent willingness to pay). We have assumed that the higher WTP estimate provided by survey respondents (the mean of £493) could be linked to academics working in UK Physics departments[125] (remembering that more than three-quarters of survey respondents indicated physics as their main field or discipline), while the lower WTP estimate (the median of £50) could be linked to those academics that work in other relevant departments (e.g. engineering) that are likely to benefit from the work being carried at CERN[126]. Appendix F.1 shows the HESA data used to estimate the number of academic staff in each of these groups.

Based on those parameters, we estimate that the total WTP over the period of analysis is £25.7m for academic staff in physics departments and £9.5m for those in other relevant departments (Figure 31).

*Figure 31 Total willingness to pay of UK science & engineering community (2019-2028) (nominal prices)**

Physics

Total value willingness to pay		(Mean) Annual willingness to pay		Scientific community (Physics)		Years
£25.7m	=	£493	x	5,203	x	10

Other relevant departments

Total value willingness to pay		(Median) Annual willingness to pay		Scientific community (other fields)		Years
£9.5m	=	£50	x	19,920	x	10

Source: Technopolis (2019). Average number of academic staff is based on HESA data for 2014/15 – 2017/18.
* The figures presented in the diagram are in nominal prices, i.e. do not account for inflation.

=> After adjusting for inflation, we get a total **willingness to pay of the UK science and engineering community** (for the continued existence of CERN in its current form and the benefits that flow from it) **of £30.2m for 2009-2018** (in 2018 prices).

Note that the willingness to pay approach is being used here to assess just the research benefits of CERN and only to the UK science and engineering community. It should not be confused with the *public* willingness to pay approach (mentioned at the end of Section 10.2) that is attempting to monetise CERN's benefits more widely (by asking the public to think about all of the benefits that flow from CERN when considering their willingness to pay for its continued existence).

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[125] Information on academic staff is only available at the cost centre level ('departments').

[126] We have included the following cost centres ('departments') to calculate this figure: General engineering; Electrical, electronic & computer engineering; IT, systems sciences & computer software engineering and Mathematics

10.3.2 Approach 2: Value of the production of knowledge

CERN provides researchers with the opportunity to access and process experimental data and contribute to the creation of new knowledge, with individuals being both researchers and producers of knowledge.

Florio et al (2015)[127] suggest that a valuation can be assigned to the *production* of scientific output by multiplying the average hourly wage of relevant UK scientists by the average number of hours that they spend producing a CERN paper. This 'value per paper' can then be multiplied by the number of CERN papers with UK-affiliated authors (which we call P0 publications in the figure below) to place a value on the UK's production of knowledge through CERN. The bibliometrics analysis for this study identified 4,600 UK-authored CERN papers (P0) in the period 2009-2018 (see data below).

Table 11 NPP publication output (full count) – CERN publications with UK author

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
164	287	393	527	503	524	489	591	561	561*

* Imputed from 2017 figure

Additionally, the knowledge produced in these CERN publications can then serve as the basis for the production of further knowledge. Specifically, they can be used as references in other papers published by UK-based authors, not only in Nuclear and Particle Physics, but also in other research fields such as Astronomy & Astrophysics and Materials (as shown through bibliometric analysis in Section 6.1). We estimate that there were 20,275 UK papers in the period 2009-2018 that made at least one reference to a CERN publication (any CERN publication produced between 1996-2018) (see data below). We call these P1 publications.

Table 12 UK publication output (full count) – UK publications citing CERN publications

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
1,496	1,534	1,699	1,927	2,038	2,289	2,268	2,356	2,334	2,334*

* Imputed from 2017 figure

It is difficult to measure the exact level of contribution of the original CERN publications to the P1 papers that then cite them (which will obviously be drawing on other sources as well). The 'criticality' of each CERN publication will depend on the relative importance of the findings contained in that paper to subsequent research, and that would have to be judged on a case by case basis (a task that is beyond the scope of this exercise). Florio et al (2015, 2016)[128] propose using the proportion of CERN-related citations over the total number of references made in a paper to approximate the weight or relative importance of the referenced CERN-related papers within that work. We have used this idea to apportion a percentage of the value of the production of P1 papers to the overall value of the knowledge produced within CERN (9%).

*Figure 32 Total value of knowledge produced (2009-2018) (nominal prices)**

Total value of knowledge produced	=	**Value of P0 publications**	+	**Value of P1 publications (that can be attributed to CERN publications)**
£546.4m		£394.4m		£152m

Source: Technopolis (2019) * The figures presented are in nominal prices, i.e. do not account for inflation.

[127] Florio el al (2015). Cost-Benefit Analysis of the LHC to 2025 and beyond. arXiv:1507.05638v1 [physics.soc-ph]

[128] Florio, M., Forte, S., Pancotti, C., Sirtori, E., Vignetti, S. (2016) "Exploring Cost-Benefit Analysis of Research, Development and Innovation Infrastructures: An Evaluation Framework". Working Paper N. 01/2016. Centre for Industrial Studies.

=> Based on those assumptions, and after then accounting for inflation, we have estimated that the **total value of the *production* of knowledge within CERN to the UK is £495.1m in the period 2009-2018[129].**

Further methodological explanation is provided in Appendix F.2.

Of course, the impact of P0 (and P1) papers goes beyond the *production* of those publications and is fully expressed by the further knowledge advances and innovations that they underpin. These **wider impacts are illustrated in previous sections of the report, but are not captured within the estimates presented above**.

[129] In terms of the counterfactual scenario, it is sensible to assume that PO and P1 papers would not have existed in the absence of the discoveries made possible by CERN.

10.4 Approaches to monetising innovation-related benefits

As mentioned in Section 7, CERN's scientific breakthroughs have often required major technological advances, both in terms of the core facility technologies (accelerators, detectors, etc.) and the supporting infrastructure (microelectronics, GRID computing, data analytics, machine learning, modelling, etc.). These technological advances may constitute new products or services for suppliers, which can be sold more widely to other research facilities and beyond. In several notable cases, the new solutions developed at CERN have provided the platform for a major new technology that has come into general use and had a transformative effect in all walks of life. Knowledge transfer occurs either:

- Directly, through researchers and companies involved in CERN technology development (which includes getting to 'preview' new ideas in the making), or through movement of staff trained at CERN
- Indirectly, supported by CERN/STFC KT activities (e.g. BIC, STFC Business Opportunities Team, STFC awards through CLASP and ISP), to individuals and organisations not part of the CERN community. There is also the wider impact that may emerge from the applications of those developments in e.g. manufacturing, health, ICT, finances, which are expected to be considerable.

In this sub-section, we focus first on the direct impact on the UK suppliers involved in CERN technology development, which we monetise using three different approaches. We then present some examples of the indirect impact emerging from the use of CERN technologies to the benefit of the wider society and from CERN's and the STFC's KT activities. Unfortunately, these effects cannot be aggregated into a single (monetised) figure. The effects realised through movement of staff trained at CERN is covered separately in Section 10.5.1.

Direct impact on UK suppliers

As explained in Section 7.3, CERN engages with UK suppliers through procurement contracts that in many cases entail the development of innovative products, services, and technologies (e.g. magnets, cooling systems, vacuum equipment, electronics). These can be quite specialised and require a degree of innovation (i.e. they are not just 'off the shelf' products), with further improvements and modifications needed to cater for the demanding requirements of cutting-edge research. These new or modified products and services could lead to further commercial gains if the suppliers are able to gain some temporary monopoly power (as they become the only agents that are able to sell these new or modified products and services)[130]. As such, the benefits that suppliers accrue from their relationship with CERN can be expressed using the *incremental profits* gained thanks to technology transfer and knowledge acquired in the development of those products, services, and technologies.

We have tested three approaches to measuring incremental/additional profit:

1. Willingness to accept among suppliers (captured via survey)
2. Economic utility ratio (as measured in a prior study)
3. Self-assessment of impact (also captured via our supplier survey).

These approaches entail looking at the value of procurement contracts of UK suppliers to CERN and estimating the additional turnover and profit generated due to the developments supported under those procurement contracts. Note that all three approaches have had to *exclude* the effects on UK firms contracted directly by university groups and national laboratories to conduct CERN related work, as this information does not exist in a centralised way.

We estimate that the impact for UK suppliers, emerging from procurement contracts with CERN, is £22m-£110m (depending on the approach used) and after accounting for inflation (i.e. in 2018 prices).

Each of the three approaches is explained in more detail below.

[130] There are also potential reputational effects for suppliers, which could allow them to make further sales (beyond CERN), given the same amount of resources. However, a reputational effect that allows a UK business to make additional sales will not necessarily represent a productivity gain. It *may* represent gaining market share at the expense of another supplier, with no net effect on UK or the sector's productivity.

10.4.1 Approach 3: Willingness to accept among suppliers

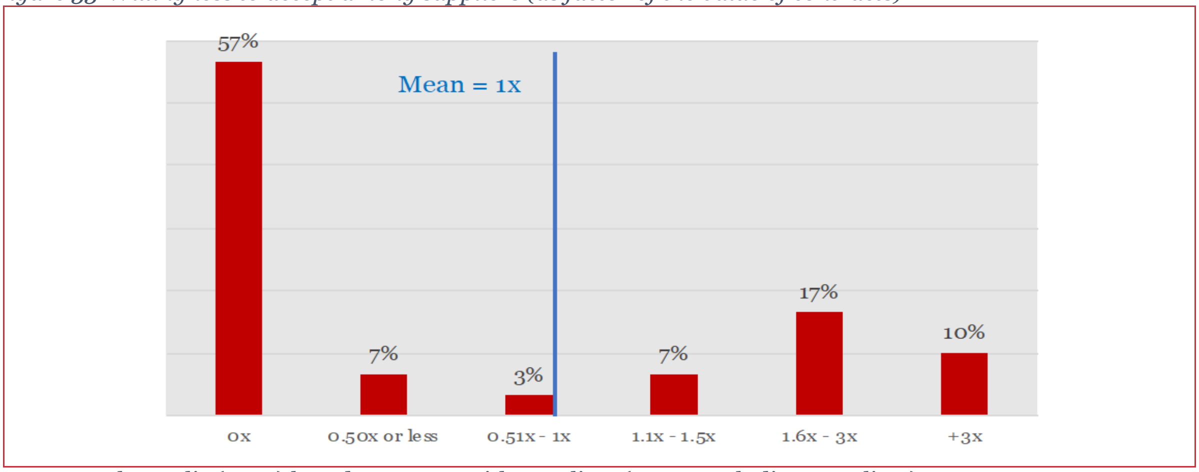
Similar to the exercise on WTP conducted with the UK research community, we also conducted an exercise on willingness to accept (WTA) compensation, with UK suppliers. As already mentioned above, under the 'stated preferences' techniques, the value attributed to a good or service can be studied from the perspective of WTP (the maximum amount a person would be willing to offer for a good), or by the WTA compensation (the minimum monetary amount required for an individual to forgo some good, or to bear some harm). We decided to adopt the willingness to accept (WTA) in the case of suppliers.

Surveyed suppliers were asked to put a financial value to the wider benefits of being a CERN contractor. Specifically, they were asked what the minimum amount would be that their organisation would accept (each year) as compensation for not being able to bid for any further CERN contracts. With this, the study attempted to capture the additional value to suppliers, above and beyond the value of the CERN contracts themselves (e.g. profit, additional sales elsewhere, improved knowledge, or other benefits).

Those suppliers who felt able to respond to this question (n=33) gave answers varying between £0 (i.e. where supplying CERN provides negligible additional benefit beyond the value of contracts) and £3m per annum (in this particular case, the organisation has received £1m-worth of contracts per year from CERN for many years). On average, the responding suppliers would be willing to accept £138k per year (although this average is skewed by one supplier – without whom the average falls to £48k).

The figures given represent between 0x and 7x the average annual contract value to the individual businesses concerned, with a multiple of 1x on average. The distribution of responses is shown in Figure 33 below. This suggests that (using this methodology) **the value of being a CERN supplier is considered, on average, to be double the annual direct income they receive from CERN contracts** (i.e. worth the direct income from the contract, plus the same value again).

Figure 33 Willingness to accept among suppliers (as factor of the value of contracts)



Source: Technopolis (2019) based on survey with suppliers (n=30, excluding 3 outliers)

Since this valuation is based on annual direct income, information on profit margins (earnings before interest, tax, depreciation and amortization, EDITBA) can then be used to estimate the value of profit associated with it. We have used FAME, a database of UK companies that provides financial information as presented in Companies House, to estimate profit margins of UK suppliers for the period 2009-2018. Using this database, we have identified information on the profit margins for 176 of the 500 UK suppliers of CERN[131]. We have used the median value of their profit margins (for 2009-2018) to calculate the value of profit associated with the valuation provided by suppliers (in terms of sales/turnover).

[131] Others may have ceased to exist or do not have the obligation to disclose their financial information given their size. As such the profit margin calculated for 176 is likely to be an over estimation of the profit margin of the 500 cohort.

*Figure 34 Innovation effects on suppliers (approach 3) (nominal prices)**

Total profit (by 2018)	=	Value of contracts (2004-2013)	x	Valuation (based on willingness to accept)	x	(Median) Profit margins
£25.6m		£133.1m		2		9.6%

Source: Technopolis (2019). Average yearly annual exchange rate has been applied to arrive to GBP figures for contracts. * The figures presented in the diagram are in nominal prices, i.e. do not account for inflation.

=> After accounting for inflation (i.e. in 2018 prices), this equates to **a grossed-up estimate of £21.7m, expressed in terms of additional profit** (based on willingness to accept).

10.4.2 Approach 4: Economic utility ratio

Florio et al (2015)[132] offer a method to estimate the impact of CERN on suppliers, using secondary data sources. This relies on prior studies to estimate an 'economic utility ratio', which is in simple terms a sales multiplier, that reflects the fact that procurement contracts with CERN are likely to generate learning-by-doing benefits in the form of increased turnover (or decreased costs), as discussed above. Bianchi-Streit et al. (1984), for instance, estimate that contracts over a period of 10 years lead to a multiplier of 3, five years down the line, for suppliers of CERN[133]. This indicates that, for every £1 in a procurement contract, a supplier company receives £3 in increased turnover or cost savings[134],[135].

We have assumed that this multiplier still stands and can therefore be applied to the value of procurement contracts, to estimate the (additional) increased turnover and (similarly to what is shown above) information on profit margins can then be used to estimate the associated value of profit. We have restricted the analysis to the value of contracts for the period 2004-2013, to estimate the value on additional profit by 2018 (following the time lags used in the Bianchi-Streit et al., 1984 study).

Figure 35 Innovation effects on suppliers (approach 4) (nominal prices)

Total profit (by 2018)	=	Value of contracts (2004-2013)	x	Economic utility ratio	x	(Median) Profit margins (EDITBA margin)
£38.3m		£133.1m		3		9.6%

Source: Technopolis (2019). Average yearly exchange rate has been applied to arrive to GBP figures for contracts.

=> After accounting for inflation, we estimate that **by 2018 UK suppliers to CERN will enjoy the additional profit of £32.5m** (2018 prices), due to contracts with CERN 2004-2013.

10.4.3 Approach 5: Self-assessment made by suppliers

As mentioned in Section 7.3, surveyed suppliers were invited to estimate what their current turnover and employment levels would be, if they had never been a CERN supplier. Based on their responses we found that the average impact on turnover (self-estimated) was thought to be around +4%. The turnover of respondents to the supplier survey averaged £7.8m in 2018. If this were to hold across the full 500 UK suppliers of CERN, then an average +4% CERN-related boost to their collective turnover would equate to around £157m per year in additional income for UK businesses in 2018. Similarly to the approach shown above, information on profit margins can then be used to estimate the associated value of profit.

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132 Florio el al (2015). Cost-Benefit Analysis of the LHC to 2025 and beyond. arXiv:1507.05638v1 [physics.soc-ph]

133 M. Bianchi-Streit et al. (1984). Economic Utility Resulting from CERN Contracts (Second Study)

134 The study included interviews with 160 European firms, who supplied estimates of increased sales and costs savings due to CERN contracts. It estimates that by 1987 CERN's high tech purchases in 1973-1982 will have generated Economic Utility of 3.

135 It is unclear if this estimate included a counterfactual estimation as this is not made explicit by the authors. To some extent one could argue it does since interviewees are asked to estimate the value of additional contracts that are directly linked to procurement contracts with CERN. They are not asked if those additional contracts could have happened anyway. However, the authors do discount the value of new contracts associated to developments that predated the contracts with CERN, which means that to some extent the estimated Economic utility ratio of 3 captures the net effect attributable to CERN.

We have assumed a growth rate of 10% to gross-up these estimates to 2009-2018 (as the average turnover corresponds to 2018). Based on this assumption we estimate that the total additional turnover for the period 2009-2018 is £1.05bn (=£2.1m x 500)[136] and the additional profit (based on assumptions about profit margins) is £101.2m (nominal prices).

Figure 36 Innovation effects on suppliers (approach 5) (nominal prices)

Total	=	Number of suppliers	x	Total value of additional turnover (2009-2018)	x	(Median) Profit margins (EDITBA margin)
£101.2m		500		£2.1m		9.6%

Source: Technopolis (2019). Average yearly exchange rate has been applied to arrive to GBP figures for contracts.

=> After accounting for inflation, we estimate via this approach that **UK suppliers to CERN enjoyed additional profit of £109.7m during 2009-2018** (2018 prices)**.**

10.4.4 Further technological spillovers (not included for monetisation)

Research/technology development conducted at CERN has a far greater reach than the effects that materialise through increased commercial gains among suppliers. These effects have been characterised in Section 7 and through our various case studies. The table below show some examples of monetised benefit that have emerged from companies' activities and from CERN and STFC KT efforts. However, these impacts (which go beyond the direct effects on suppliers) have not been included in the overall monetisation estimates as in many cases the monetary net effect to the UK is not possible to estimate in terms of productivity gains or social benefits. A much longer list of technologies that originated at CERN and that have had wider application and benefit can also be found in Section 7.1.

Table 13 Examples of further technology spillovers

Name	Type of impact	Short description
Medical imaging technology: PET imaging and scintillating crystals	New technology to address a growing global market	The combined PET-CT scanner combination has proven more accurate than either scanner independently and is one of the most effective imaging tools in oncology. In 2016, the global PET-CT scanner device market was valued at USD$1,454 million, and is estimated to reach USD$2,108m by 2023, growing at a CAGR of 5.0% (2017-2023). Furthermore, the combined PET-CT scanner has shown significant promise in reducing the cost of cancer treatment through earlier diagnosis and improved staging to determine the appropriate treatments, as well as improving patient quality of life.
Linear proton accelerators and next generation radiotherapy	Technology transfer and company growth	In 2013, Advanced Oncotherapy (AVO), a UK company, acquired ADAM, Application of Detectors and Accelerators to Medicine (a spin-off from CERN) to continue development of the LIGHT system for commercialisation. The company now has 129 staff across the UK, Switzerland and the US and a market capitalisation of £80m ($100m).
STFC-CERN-BIC alumni - Oxford nanoSystems	Supporting innovative companies	Support from the STFC-CERN BIC has enabled Oxford nanoSystems to go from a 2-person firm operating from a 300 sq ft lab to a 14-person company based in an 8,000 sq ft facility. Since graduating from the BIC in February 2016, the company has continued to grow and has secured financial backing from two major Oxfordshire investors. The technology will also continue to be applicable to a wide variety of applications. They are for instance working with fridge manufacturers to produce more compact refrigeration devices, which in turn will provide more space for food storage; they are investigating the technology's use on geothermal systems to enable more effective heat transfer; and believe that nanoFLUX has real potential in cooling data-processing hardware.

[136] The total value of £2.1m is derived by collecting information on annual turnover for each year of the period of analysis (2009-2018) and applying the +4% estimate. Differences with the total are due to rounding.

10.5 Approaches to monetising skills-related benefits

We tackle the monetisation of skills benefits via two routes:

1. An estimation of wage premia, to reflect the value of skills gained by young researchers due to their interaction with CERN
2. The value of UK individuals attending specific training programmes offered by CERN.

These are not alternatives methods to assessing the same impact, but rather two approaches to estimating two different impacts. As such the results, on this occasion, *can* be summed.

10.5.1 Approach 6a: Wage premia

We approximate the benefits of human capital formation by accounting for the wage premia (i.e. the additional pay) that young researchers at CERN enjoy (and will enjoy) for the rest of their careers as a consequence of their interaction with CERN. Florio et all (2015) already conducted a survey with 384 students and former students at CERN (from 52 different countries) to collect information on the perceived LHC premium on salary (either ex-ante or ex-post, depending on their current situation). Based on this, they estimated that an 11.8% premium can be attributed to each student over a career spanning 40 years (e.g. the cohort of 1969 students would enjoy the benefit up to 2009).

We have used this parameter to estimate the total value of the wage premia that will be realised amongst UK fellows, technical and doctoral students of CERN. We have also assumed that at least 30% of UK-based CERN researchers are young researchers (age data per country is not reported in CERN's published personnel statistics). Additional assumptions have been made about the destination of those students and young researchers after CERN (we assume that 60% will work in academia or research centres, while 40% will work in industry, which is in line with the statistics collected by CERN on destination of PhD students[137]).

We collected information on academic and industry salaries for both entry level positions and mid-career positions for 2019, and we have accounted for wage growth (using national statistics) to arrive to an estimate of the value of salaries for the period 2009-2018.

Our modelling includes all young UK researchers that have worked or trained at CERN at any time during the years 1969 - 2017 (5,677 young researchers) – as some of their 40 years of wage premia benefit will fall within our impact window of 2009-2018. It assumes that, for instance, a cohort of students and researchers will enter the labour market the following year and enjoy an entry level salary that year and for another 3 years, until they become more experienced and start enjoying a higher salary.

=> Based on those assumptions, we estimate that **the wage premia enjoyed by ex-young researchers at CERN amounts to £488.7m in the period 2009-2018.** This final figure accounts for inflation (2018 prices) and it includes the wage premia enjoyed by young UK researchers that have worked or trained at CERN for at least one year in the period 1969-2017.

10.5.2 Approach 6b: Value of training

As mentioned in Section 8.1, CERN offers various learning and development opportunities for the UK workforce. We approximate the value of those by looking at commercially available programme and courses that may offer similar skills, as their price provides an estimation of the valorisation individuals made of the importance of those courses for their career development. The table below shows the different programmes included in our calculations, as well as the estimated number of UK participants over our period of analysis (2009-18) and the value of similar training in the UK market.

[137] https://slideplayer.com/slide/3474468/

*Table 14 Value of training (2009-2018) (nominal prices)**

Programme	Data coverage	Average duration	Total UK attendees	Annual average attendees	Est. total attendees (2009-18)	Cost of equivalent training	Total value
Summer Student	2007-17	8-13 weeks	186	17	170	£10k[1]	£1,700k
Openlab Summer Student	2013-16	8-13 weeks	3	1	10	£10k[1]	£100K
Doctoral & Technical	2007-17	3 years / 1 year	198	18	180	£16.1k[2]	£2,898k
Administrative Student	2010-17	1 year	13	2	20	£52k[3]	£1,040k
						Total	**£5,738k**

[1] Based on value of a 12-week course in Big Data (https://generalassemb.ly/education/data-science-immersive). [2] Based on the value of PhD at Imperial College; [3] Based on the value of a 1-year MBA at Imperial College. We have excluded the training that might be funded by STFC, such as the Fellowship Programmes, which also do not have a commercial alternative. * The figures presented are in nominal prices, i.e. do not account for inflation.

=> Following this methodology, and having accounted for inflation, **we estimate that the value of these four training programmes (for UK participants) is £4.9m** (2018 prices).

10.5.3 Other impacts on skills (not included for monetisation)

As mentioned above, our calculations do not include the contribution of CERN to inspire students to pursue STEM careers, which, in turn could help address UK STEM shortages. As shown in Section 8.3, CERN inspires students and young people through its scale, the types of questions it addresses, and its international nature. It also undertakes various activities to engage, enthuse and educate students and young people. As a result, teachers gain the confidence, capabilities, resources and enthusiasm to support (more/better) teaching of CERN-related subjects, while students increase their knowledge, understanding and interest (through visits, materials and teaching) in CERN-related subjects. Young people may be more likely to, and capable of, pursuing STEM subjects in school as a result.

This helps to nurture the pipeline of future talent and contributes to ensuring that the UK has access to a scientific and technically skilled workforce that will sustain it as one of the world's leading research nations and support the growth of a high technology economy. Furthermore, The STEM Skills Indicator reveals that nine in 10 STEM businesses (89%) have found it difficult to hire staff with the required skills in the last 12 months, leading to a current shortfall of over 173,000 workers - an average of 10 unfilled roles per business. The report estimates that the shortage is costing businesses £1.5bn a year (i.e. £8.6k per worker) in recruitment, temporary staffing, inflated salaries and additional training costs[138].

We estimate that an average of 17,600 UK students per year will have been taught with context from CERN as a result of the teacher programme, while around 11,000 UK students visit CERN in person each year. Every 100 students that decided to pursue a STEM career as a consequence of their interaction with CERN (and work in a STEM occupation after graduation) will contribute £8.6m a year to the economy. A survey of 673 physics undergraduates in eight universities in the UK showed 95% were attracted to study science because of activities in particle physics (such as CERN), with over 50% saying they were inspired by the discovery of the Higgs. Therefore, the impact of the teacher programme on the choices of UK students (and in the longer term on UK economic benefit) is likely to be significant.

[138] https://www.stem.org.uk/news-and-views/news/skills-shortage-costing-stem-sector-15bn

11 Future monitoring and evaluation framework

In this chapter of the report, we present our proposal for a monitoring and evaluation framework that STFC might use as the basis for tracking benefits flowing from the UK's engagement with CERN in future. The framework is also designed to support future independent evaluations by ensuring there is a more wide-ranging and complete record of achievements across each of the principal impact pathways.

11.1 Design assumptions

The framework draws heavily on the logic model developed for this study, which is presented in Section 5 (and summarised again below), with some level of simplification in the performance dimensions proposed and a clearer elaboration of the role for STFC in creating the various itemised benefit lists (e.g. innovations) and populating the basic performance figures (e.g. Highly Cited Papers).

Table 15 Overall structure for impact areas – benefits from UK investment in CERN

Area	Benefits to UK
1. World-class research	1.1 Pushing the frontiers of knowledge and enabling UK scientific progress 1.2 Access to facilities and opportunities for UK research excellence 1.3 Attracting investment and talent to the UK
2. World-class innovation	2.1 The wider application of CERN technologies 2.2 The wider application of CERN research findings 2.3 Improved performance amongst UK suppliers
3. World-class skills	3.1 Increased skills and capabilities of the UK workforce 3.2 Increased UK public appreciation of science 3.3 Increased UK STEM uptake
4. Science diplomacy	4.1 The UK's influence in the international S&T landscape 4.2 Improved diplomatic relations and engagement 4.3 The UK's image as a 'great science and innovation nation'

We have assumed the framework would support STFC in monitoring the full extent of UK involvement with CERN, to facilitate enhanced operations on the one hand and more extensive annual reporting on the other. It should also provide an improved platform for any future evaluations, allowing external evaluators to concentrate on analysing the quantum of additional wider benefits attributable to CERN membership, and less on basic data collection and compilation.

11.2 The Framework

The following tables present a list of possible indicators against the four impact areas and 12 pathways. The implementation column discusses where the data may be sourced and by whom. It also includes various suggestions for measures to strengthen the STFC-CERN monitoring system in order to provide future evaluations with a more comprehensive and robust evidence base. The list of performance dimensions is shorter and simpler than that addressed in the current study, reflecting lessons learned about what is most important for understanding CERN's key contributions and what is feasible within the context of a typical, broad-ranging evaluation (covering all impact pathways) such as this.

Table 16 CERN monitoring and evaluation framework: proposed indicators for World-Class Research

Impact pathway	Indicator	Implementation (who, what, how)
Pushing the frontiers of knowledge and enabling UK scientific progress	• Annual presentation of notable scientific and technological advances	STFC is already identifying and showcasing notable scientific advances realised through CERN and involving UK-based scientists or engineers (and is producing stories for newsletters on an ongoing basis). This is providing a long-list of interesting examples and should continue, but these individual items could also provide the basis for the development of longer and more structured 'scientific advances' case studies. This might be done periodically by the STFC team, perhaps every three months, with a view to creating 10-15 scientific case studies each year out of a longer list of promising items. This portfolio of cases should be developed to reflect the STFC's strategic commitment to both (i) frontier research and (ii) its underpinning technology (e.g. detectors, accelerators, engineering, e-infrastructure). They should also present not only the research result, but also say more about the significance of its implications for physics and ideally for the wider society and economy.
Access to facilities and opportunities for UK research excellence	• Number of researchers accessing CERN facilities	STFC should continue to collect the CERN HR statistics, though there are some indicators that could be collected more systematically. For example, there is value in recording the number of researchers from UK institutions, as well as those with UK nationality, given the higher proportion of international researchers within UK institutions. Similarly, CERN also collects data around the professional level and age of researchers and staff, which STFC could use to compare against selected other member states. STFC should coordinate with CERN to determine what additional information is collected and held on UK involvement in CERN research.
	• Bibliometrics – Annual number (and UK share) of publications on CERN research – Share of UK papers in the 10% most highly cited CERN NPP papers – Annual number of publications citing CERN papers, UK share	The engineering and physical sciences make extensive use of journal articles, and as such bibliometrics provides an efficient means by which to track the volume of UK-related CERN research outputs and assess its international standing. The analyses might be kept very simple, such that STFC could run the analytical exercise internally every year using an online platform and based on the list of CERN publications recorded centrally by CERN itself. Otherwise, there are a number of firms providing bibliometric analytical services reasonably economically. Such services could be contracted, perhaps alternating from one year to another between a simple computation of three or four standard citation metrics and a more wide ranging analysis of the UK's international standing in various disciplines in comparison with benchmark countries. The in-depth bibliometric analysis could also seek to capture references to CERN research in other disciplines, reflecting its influence in other areas of research.
	• List of UK-based scientists / engineers that have won major scientific prizes in recognition of CERN research	STFC is already tracking prizes, some of which are showcased in the STFC Annual Impact Report. This could provide the basis for a CERN-specific account of prestigious awards, which could be reported in a separate paper as well as being picked up as appropriate in corporate publications.
Attracting research investment and talent to the UK	• List of international researchers/organisations locating in the UK to take advantage of UK strengths relating to CERN	STFC may be able to orchestrate this monitoring activity, drawing on its pre-existing network of contacts in key institutions. This would involve STFC engaging annually with a shortlist of (~15) individuals from across the experiments and wider stakeholder community with a good view of the UK's involvement overall with CERN. This could take the form of an interview or feedback form, requesting examples of notable investments, inward movement of researchers, and the latest developments in their field. Indicative examples could then be pursued for further confirmation or detail as necessary.
	• Number / share of non-national UK scientists	The second indicator gives a sense of the international attractiveness of the UK. HESA collects data on the numbers of academics within physics departments according to their nationality (UK, EU, non-EU).

Table 17 CERN monitoring and evaluation framework: proposed indicators for World-Class Innovation

Impact pathway	Indicator	Implementation (who, what, how)
The wider application of CERN technologies	• List / case studies of technologies developed at or for CERN, which have come in to wider use	A list of relevant technologies (with wider application) should be produced and updated annually, with new additions in the past 12 months and a longer list of previous successes (the stock). This might be prepared based on several sources, including PATSTAT, Gateway to Research, a new survey of CERN suppliers and the work of STFC in tracking achievements more generally. It will also require interaction with the CERN Knowledge Transfer office, to prepare a complementary list of UK-based organisations that involved in licensing CERN technology, collaborating on R&D projects with CERN or even starting a company based on CERN technology. This is possibly a task that could be delegated to the CERN-BIC. STFC should also develop 5-10 examples into fuller impact case studies each year. This study has already identified many candidates that were beyond the scope of what the team could fully develop.
The wider application of CERN research	• List / case studies showcasing the application of CERN research, which has come in to wider use elsewhere	STFC should keep under review any news about the application of CERN research in other areas of relevance to the UK, such that it might develop 5-10 impact case studies annually. These cases may need to be prepared – or at least approved by the affected UK-based researchers and should therefore follow the structure of REF 2021 case studies to minimise any burden on the research community. A long list of candidate cases might best be prepared based on several sources, including a new researcher survey, as well as the work of STFC in tracking UK achievements at CERN more generally. Beneficiaries of STFC's Innovation Partnership Scheme Fellowships with links to CERN could also be good candidates. This qualitative research might be accompanied by an annual report detailing the wider use of UK-based CERN research in other fields and countries (using bibliometrics).
Improved performance of UK suppliers	• List/value of products / services brought to market by UK firms, dependent upon CERN	A new annual/biennial survey of UK-based suppliers - working with CERN (direct contractors) and UK universities (indirect suppliers) - to develop: (i) a list of new products / services launched by UK-based businesses in the previous year, which track back to work at CERN; (ii) a list of all (stock) new products and services launched in the period since the reporting was begun; and (iii) an estimate of annual turnover linked with innovative products and services brought to market in the last three years linked with CERN R&D.
	• International competitiveness of UK-based suppliers to CERN	STFC might carry out a biennial analysis of the competitiveness of UK-based suppliers, in order to test the extent to which some or all benefit from CERN contracts (depending on the findings, the research would also help in persuading other businesses to consider bidding). This exercise is more involved than simply tracking sales and employment and does need additional primary data on exports and profitability. It also requires some level of econometric analysis to take account of different contractual histories and also to allow for a comparison of CERN suppliers with the performance of matching groups of firms in order to estimate the size of any statistical differences.
	• UK industrial return in goods and services	The STFC collates and reports on these statistics already, and this should continue unchanged for both goods and services. It is helpful to see the annual and trend data for the value and number of contracts won (including comparisons with other member states), as well as more simply reporting the industrial return coefficients (which are less meaningful to most audiences). There would however be merit in doing more: a more disaggregated analysis in order to inform STFC as regards the effectiveness of its various promotional efforts (analysing bids too, if possible, as well as contract awards). STFC will no doubt want to continue its efforts to raise awareness among prospective bidders and may also want to trial new approaches, whether that is producing more success stories to show businesses that contracts are winnable and can deliver benefits even with low margins, or the kind of more active support provided by the National Contact Point network in its efforts to generate interest in Horizon 2020. A fuller, sector-specific analysis, would allow STFC to determine the relative effectiveness of its various business development efforts. A survey of suppliers could also provide feedback on company experience of the contracting process, STFC support and views on 'best practice' or 'lessons learnt' to share with organisations interested in bidding.

Table 18 CERN monitoring and evaluation framework: proposed indicators for World-Class Skills

Impact pathway	Indicator	Implementation (who, what, how)
Increased skills and capabilities of the UK workforce	• UK-based researchers and students' participation in CERN-related activities	An annual report should be produced, presenting an overview (count) of the populations involved with CERN. CERN HR statistics are a valuable source in this regard and there may be more STFC could extract from the data held. Determining the impact on skills will require additional work to systematically and routinely poll researchers on the skills and social capital they acquire through their work at/with CERN, e.g. looking at a range of domain, technical and management skills. This type of regular survey would also ideally be mirrored with a matching group of UK-based physicists and engineers that do not work with CERN. Group leaders could also be asked how many PhD theses have been delivered with CERN as a central focus/data source, and how many PhD students are working on CERN projects. It will also be useful to establish a career tracking capability to begin to follow the progress of CERN alumni through their future careers, across job titles, sectors and borders. This may be tackled best in collaboration with CERN. The Florio study should also be replicated for the UK, in order to try to determine the extent to which there is a wage premium for CERN alumni as compared with UK physicists and engineers more generally and how big that is.
Increased UK public appreciation of science	• Public engagement with CERN related media • Visits to CERN • Public view of CERN and science	STFC should present annual statistics on visits / web site visits / downloads, by location and demography. It may also be valuable to compare these data with other facilities (e.g. the ESO's Supernova Visitor Centre) and major science attractions (e.g. the Science Museum) to better gauge the scale and importance of the role played by CERN in this field. STFC should also move forward with a periodical study (3-yearly) to develop a view on the role of CERN (and maybe other major STFC investments) in shaping the public's view of science. This can borrow from the types of questions included in normal public attitude to science opinion polls, but with a link to specific scientific organisations. This could potentially be delivered in conjunction with other interested organisations such as the IOP.
Increase UK STEM uptake	• Engagement of students / teachers with CERN • Impact on student subject selection	STFC should compile and present an annual statistical review showcasing the numbers of schoolchildren and students (and teachers) visiting or using CERN. It should also develop a STEM uptake observatory, which would run periodical studies to follow up on the student participants to track their views on science and their choice of subjects, higher education decisions and careers. These should ideally be compared with matching cohorts of non-beneficiaries.

Table 19 CERN monitoring and evaluation framework: proposed indicators for Science Diplomacy

Impact pathway	Implementation (who, what, how)
UK influence in the international environment Improved diplomatic relations and engagement	A chapter in the annual report, detailing notable developments and more generally itemising all such highlights. The material would need to be identified internally within STFC, via researcher survey and through discussions with CERN and those UK individuals in key positions with CERN (e.g. representatives on CERN Council, Spokespersons for experiments). Occasional examples could be highlighted in an annual report, while the most promising could be prepared into fuller diplomacy case studies
The UK's image as a 'great science and innovation nation'	STFC might develop a tool for inviting its scientific partners to provide feedback on the experiences of collaborating with UK-based scientists as a learning / reflexive support for understanding what areas are strong or less good and where STFC could provide training or encourage different behaviour. In order to obtain a more rounded view of perceptions, STFC will need to commission international research to determine the views of scientists, scientific administrators, professionals and the public in 10-20 CERN partner countries. This is the type of work that could be done in concert with the science and innovation councillors in the UK embassies, however, it may be too burdensome for them to implement fully and so a consultant will need to be employed. The exercise might be run every two years, to spot any obvious trends. It will also need to be done at sufficient scale to allow the analysis to test for links between UK work at CERN and perceptions of UK science more generally, perhaps through selected critical incidents.

The framework presented above points to the need for several **additional data collection activities**, including new surveys (e.g. of UK-based CERN suppliers), bibliometric analyses and the collation of examples of technology development. These suggested additional activities, discussed further in Section 11.3, could constitute part of an enhanced monitoring system, run on a continuous basis by STFC or its contractors, with the results informing operational oversight and periodical external evaluations.

There are also several data and methodological challenges that need to be fixed or at least improved. To that end, we also suggest that STFC commission a **programme of methodological studies and targeted reviews** to run in parallel with the ongoing monitoring work in order to provide an enhanced evidentiary platform for future evaluations. These suggested studies are discussed in Section 11.4.

Section 11.5 then discusses arrangements for future evaluation efforts, including the **possible costs** of the additional monitoring activities and targeted studies suggested. Collectively, these are likely to go beyond the resources currently available within STFC. However, the various recommendations made in this section should provide a useful basis for further internal discussions and planning.

11.3 Monitoring arrangements

In addition to continuing with the current monitoring and reporting arrangements, we recommend STFC consider implementing **several additional data collection / analytical activities** in order to strengthen the monitoring system. This is in addition to the ad hoc studies listed in the next section, which may further inform the shape and evolution of some of these additional data collection activities.

- Researcher survey: Implement an annual or biennial survey of all UK-based CERN researchers and UK CERN staff, to obtain feedback on notable achievements in each of the four impact pathways.
- Supplier survey: Implement an annual or biennial survey of UK-based CERN suppliers to obtain feedback on their experience and capture information about specific capability benefits, innovations, wider sales and exports, plus competitive advantage. STFC should also work with universities to get a better grip on the contracting that takes place through experiments: how much is being procured, of what and who (and where) from? This would address a blind spot in the current system and provide STFC with a larger pool of contractors to survey (and no doubt more examples of success).
- CERN BIC: The STFC-CERN-BIC could prepare a more comprehensive annual report on the progress of tenants, and perhaps most importantly, conduct follow up interviews with all former tenants after they have 'graduated.' The reporting should provide a view of developments in the year (from graduating incubates to new licence agreements to company formations), as well as an overview of the growing stock of technologies of businesses. This should look to follow the core indicators and definitions of HESA's HEBCI survey to allow for some comparison with wider trends.
- Cataloguing individual achievements: There are numerous instances of individual successes in each of the four impact pathways, and STFC and CERN are capturing a good proportion of these currently. It would be helpful, however, if it could broaden its search for notable achievements. The current arrangements capture more information about scientific advances for example than they do about new appointments or international scientific missions; this reflects the balance of activities, and CERN's mission, however there is likely to be more to report on industry and skills and working systematically across all four impact pathways may be helpful. It would be good to record all of these items in a single repository or database, tagged with the relevant impact pathways and performance dimensions. This would produce a much longer list of interesting facts than can be presented in an annual report or newsletter, as well as support further analysis and feed into future evaluations.
- Case studies: STFC should then identify and develop a selection of examples from each impact area into fuller case studies, based on additional discussion and desk research. These cases could aim for two pages (500 words plus images) and follow a reasonably standard structure (from CERN-related activities, through the outputs and outcomes of this work, on to potential/realised wider socio-economic benefits. To give a sense of the resources that might be involved, the current study had a budget of 30 person days to develop the 29 cases shown in Appendix E (~1 day per case, to undertake

research, interviews and drafting). However, one could easily dedicate more time to developing a selection of the cases further, with additional detail and evidence brought in to strengthen the case (e.g. the average REF2014 impact case study took 30 days to produce).

The resulting cases could then be used in a number of different ways, to support STFC annual reporting and periodical external evaluation of UK participation in CERN:

- They could provide a source of persuasive evidence for a new STFC 'CERN annual report'
- They could enrich the presentation of CERN achievements within the Annual STFC Impact Report. CERN is cited already, but e.g. the 2018 report contains only a short paragraph in each main chapter and the presentation of benefits to the UK could usefully be strengthened. These 40-page reports must showcase all STFC achievements, however CERN is a major focus of investment and may warrant more coverage than it currently gets.
- The case studies could be added to the existing catalogue of CERN case studies, which sit on the web site. These could usefully be compiled in a single, searchable database to facilitate browsing. The compendium would also provide an excellent platform for any future external evaluations

- Biennial review of UK science at CERN: There would be benefit in carrying out regular bibliometric analyses to gauge the international standing of UK-based scientists on the one hand and the citation of their work on the other. This would also allow STFC to understand the changing geography of UK cooperation and selective international benchmarking with other leading scientific countries.
- Annual reporting of CERN derived KPIs: The surveys and case study database would also be a key reference for another suggestion we have made, which is to create an STFC-CERN annual report, which would include a chapter on each of the four impact pathways with a classical presentation of facts and figures, highlights and mini-case studies and any news of future developments. That annual report would provide a more considered reference point to feed into STFC's annual impact report and STFC's and UK scientists' involvement with CERN governance.

11.4 Ad hoc studies

Carrying out this study revealed a number of data and methodological challenges that proved difficult to overcome fully within the context of a single, broad-based evaluation. There are two or three areas where it would be worthwhile carrying out **separate targeted studies**, ahead of any subsequent impact assessment. This is because of the amount of work (and time) required to reach a more complete and robust view, which is likely to remain beyond the scope of a typical overarching evaluation.

Economic impact: As was discussed in the introduction to the previous section (summary of monetised benefits), monetising the impact from RIs remains a challenge. Our case studies have showcased the types of benefits industry suppliers derive from their involvement with CERN, however, there is a substantial body of codified knowledge being published annually that underpins other public research and shapes technology more widely. These wider knowledge spillovers are generally understood to be a major source of social benefit, however they are diffuse and not easily traced. Current micro-economic methodologies struggle to capture the full extent of the flow of benefits, and macro-economic techniques are just that, too macro. Florio's experimentation with contingent valuation methods and the valuing of citations to CERN publications are important developments, but may also require further consideration and re-use in order to learn more and to reflect on possible opportunities to fine tune the methods. We therefore recommend that STFC consider commissioning a major **methodological study**, specifically addressing large research infrastructure, which could critique different approaches to assessing (and monetising) economic impact and propose practical guidance for future assessment.

Skills: While our surveys found widespread agreement as to the strongly positive benefits of doing research at CERN for academics' technical training and careers and revealed several individual examples of high office, we were unable to get to a more complete and substantive view of CERN's impact on researcher skills. We did re-use Florio's wage-premia exercise, but had to do so using some of the parameters that CSIL had established, as there was no scope (time or budget) to do primary research in order to obtain more up-to-date and UK-specific figures. We were also unable to do any complementary research to detail and compare the rate of career progression – and number of scientific leadership roles taken – by particle physicists as compared with STEM researchers in general; are CERN physicists more successful than other scientists that simply don't have the benefit of a global centre of excellence. Equally, do particle physicists that have worked at CERN tend to earn more in any given national research system than other physicists working in other sub-fields and not involved directly with CERN?

Given that CERN has begun to establish an alumni programme, this may be an area where STFC – and maybe other research councils – could work with (even looking to co-fund) CERN on a more substantive **career-tracking programme** to follow the progress of CERN alumni through their future careers, tracing mobility across sectors and borders, as well as changes in seniority or occupation. A one-off UK study may be a helpful preparatory exercise, with some involvement of CERN within the project steering group; there would also be merit in looking to encourage all UK-based CERN alumni to register with ORCID to allow easier identification of people within the growing number of public access databases.

There would also be merit in STFC looking to do similar development work relating to students and schoolchildren involved in CERN training and visits. The current arrangements are gathering good time-series data on participation levels, by type of training and education initiative and by institution (and geography). However, the **exit polls and follow-up discussions** do not seek to capture (before or after) data on participants' improved confidence in or enjoyment of science and engineering. There is also no attempt to explore participants' decisions as regards post-18 education (in further or higher education) or the subject choices they make and no view as the career choices of students.

Public engagement: The STFC communications team maintains a good overview of CERN related news items and articles in the media, which show that major CERN discoveries do register a strong interest with the public. However, this kind of media analysis is event driven and can be quite irregular; it also doesn't tend to provide any insight about the effects on audiences. Surveys of 'public attitudes to science' do a better job of profiling and tracking trends in attitudes, by definition, however, opinion polls rarely test people's awareness of specific scientific institutions or programmes. Nor do they attempt to explore the links between specific institutions and people's views and behaviour. While our stakeholder surveys and interviews were clear that CERN has a strongly positive impact on scientific attitudes and literacy of the general public, we were not able to obtain a view of these matters from the public themselves.

To that end, it may be worthwhile STFC looking to launch its own **attitudinal survey of the UK public** to explore awareness and appreciation of CERN, as well as the effect of CERN on people's choices in education (subjects) and careers. This could be done as a one-off study focusing on CERN exclusively. However, if it were carried out regularly (every other year), tracking trends over time, it would need to be more broadly based to justify the investment. Ideally, the survey would explore awareness of several other high profile scientific organisations (in physics in the UK, in other fields and internationally), and possibly explore the relative importance of different types of messages (major scientific breakthroughs, major social benefits, scale and complexity of scientific endeavour) and the types of communications channels (from major documentaries through to blogs and online videos). We would not suggest the surveys attempt to review awareness of all STFC facilities, however, as that would over-complicate matters and may reduce the analytical power of the findings; it would also risk creating unhelpful rivalry amongst institutions.

STFC might usefully discuss its options with the National Coordinating Centre for Public Engagement (NCCPE) in Bristol, as this team has built up more than 10-years' experience in researching public engagement across the UK

11.5 Evaluation arrangements

The experience of conducting the current study has uncovered gaps in evidence and research/analysis methods to support an holistic, robust assessment of the impact of CERN. Hence a priority for STFC is to improve its understanding/access to evaluation approaches that would enable this to happen. This would have benefits for assessing the impact of CERN but also research infrastructures more generally. A future evaluation should also be able to build on a strengthened STFC / CERN monitoring system, with the latter focusing most heavily on documenting activities, outputs and outcomes and the evaluation itself being used to corroborate those data and extend the benefits-realisation perspective to the wider effects on science, innovation and skills. It should also be able to identify, quantify and monetise more of the total spectrum of CERN benefits than was possible with this evaluation. This will move the evaluators closer to being able to carry out a cost-benefit analysis that provides a more complete and fair account of CERN-derived benefits.

The timing of future evaluations is a matter for discussion, as there is no clear advice in existing UK evaluation guidelines and the periodicity and scope of the government's comprehensive spending reviews is rather changeable. Historically, the grant-awarding research councils and their research institutes were subject to 5-yearly, or quinquennial reviews, and while this is no longer the case, the periodicity feels appropriate to a major science programme (three years is arguably too short, and 10 years is arguably too long). The other point of reference is CERN itself, and its periodic review process. The current review cycle is to be launched in 2019, with a decision on performance expected to be made by the CERN Council in 2021 based on the review findings. The results of this current (UK-focused) impact assessment may be fed in to the CERN review process, or will at least serve to inform the contributions of UK members (of council, finance and science committees) to the wider review. Assuming such input is helpful and appropriate, STFC might usefully choose to time its future evaluations to coincide with the CERN review cycle, expected in around five years' time.

STFC should also give due consideration to its budgeting of future evaluations. It is not possible to carry out rigorous and wide-ranging evaluations of large, complex scientific infrastructure, at current levels of budgeting. While it is not advisable to think simply in terms of a proportion of programme spend, the allocation of a tiny fraction of one percent of the UK's CERN programme spend – as was the case here – will inevitably result in resourcing becoming a factor in the study design. The work by Massimo Florio and his research team at the Centre for Industrial Studies (CSIL) to quantify CERN's social and economic benefits (notwithstanding this was a much narrower exercise than the one that has been run for this report) benefited from a 3-year programme of research and more than €5m in funding. STFC's evaluations may still be run at the £100k-£200k price point, however, that will inevitably demand trade-offs between breadth and depth, even where it greatly increases its investment in monitoring. It should also invest in the necessary methodological studies, if it is going to achieve the robustness it desires.

We have estimated the approximate costs of each of the additional monitoring activities and targeted studies suggested above, based on our view of typical market prices for similar work being commissioned. Some elements could be undertaken internally, but this is unlikely to significantly change the overall resource costs. We first calculated a cost per occurrence (one-off, biennial or annual) and then a total cost for a 5-year period (approximate length of UK comprehensive review and CERN review cycles), with biennial activities assumed to take place just twice over a five year period.

These estimates suggest a total monitoring and evaluation budget of £300k - £600k per year on average, which would seem appropriate for an international research programme where the UK has invested tens of billions of pounds over the last 50 years and will continue to invest £150m+ a year going forward. However, these ambitions are likely to go beyond the resources currently available within STFC.

technopolis group

Evaluation of the benefits that the UK has derived from CERN

Evidence Document

01 July 2020

APPENDICES

Appendix A Impact pathways

The study has identified and defined **12 main impact areas** that should flow from CERN. Table 20 shows the basic structure: four objective areas, with three main areas of benefit identified under each. In line with the objectives of the study, we have been careful to focus on benefits *to* the UK, rather than benefits *from* UK involvement (although the two are often linked).

Table 20 Overall structure for impact areas – benefits from UK investment in CERN

Impact objective	Benefits to UK
1. World-class research	1.1 Pushing the frontiers of knowledge and enabling UK scientific progress 1.2 Access to facilities and opportunities for UK research excellence 1.3 Attracting investment and talent to the UK
2. World-class innovation	2.1 The wider application of CERN technologies 2.2 The wider application of CERN research findings 2.3 Improved performance amongst UK suppliers
3. World-class skills	3.1 Increased skills and capabilities of the UK workforce 3.2 Increased UK public appreciation of science 3.3 Increased UK STEM uptake
4. Science diplomacy	4.1 The UK's influence in the international S&T landscape 4.2 Improved diplomatic relations and engagement 4.3 The UK's image as a 'great science and innovation nation'

This appendix takes each of the 12 main impact areas identified by the study and traces the impact pathway, from investment in CERN through to eventual benefit and impact for the UK. Inevitably the pathways are somewhat intertwined. We have tried to keep each pathway distinct and then highlight [in red] where other benefits are likely to flow, but where these are picked up through another pathway.

A.1 Impacts relating to world-class research

1.1. Pushing the frontiers of knowledge and enabling UK scientific progress

The UK research community benefits from new knowledge in fundamental physics (generated at CERN, including by the UK) on which they are able to build further scientific progress and innovation.

Impact Pathway

- The UK's investment in CERN supports state-of-the-art research in fundamental physics, which advances our understanding of the basic properties, materials and forces in the Universe
- Scientists in the UK (and elsewhere) build on this enhanced understanding in their research, enabling them to better address complexity, ask the 'right' questions and set up experiments that continue to push the boundaries of knowledge.

- This supports the UK research community's scientific achievements and progress (in particle physics and beyond).
- This will also help to sustain the UK's global research ranking and its position as a world leading research nation. [see impact area 1.2]
- It may also lead to unexpected developments and spin-offs of societal and economic value in the long term [see impact area 2.2]

1.2. Access to facilities and opportunities for UK research excellence

The UK scientific and engineering community gains access to facilities and opportunities that would not otherwise be available, supporting it undertaking world-class research.

Impact Pathway

- Pooled resources and expertise at CERN have enabled instruments, facilities and infrastructure to be built that could not have been developed by any one individual country.
- The UK's investment in CERN has contributed to, and continues to enable, the development and building of state-of-the-art (unique) instruments and facilities.
- In turn, the UK's investment provides UK scientists with the opportunity to:
  - Access state-of-the-art instruments and facilities (it is the UK's national laboratory for PP)
  - Participate in (or lead) research underpinning CERN's technology development projects - including for those funded by non-STFC sources (e.g. EPSRC).

  This includes access to:
  - Technology and capabilities not otherwise available (even more important as research is becoming more capital-intensive and infrastructure dependent)
  - International collaboration networks and knowledge sharing/building with leading scientists
  - World-leading / frontier science and experiments
  - The latest theories and developments in understanding the physical world
  - New methods and techniques
  - Training / learning opportunities for the next generation [see impact areas 3.1 and 3.3]
- The opportunities and access afforded to UK scientists and engineers supports the strength of the UK research community and its scientific achievements and progress (particle physics and beyond), helping to sustain the UK as a world leading research nation.
- Ready access to CERN, coupled with the UK research community's high performance, also makes UK institutions attractive for top research talent (from the UK and abroad) [see impact area 1.3].

1.3. Attracting investment and talent to the UK

The UK's international reputation of research excellence makes it attractive for international funders and top talent.

Impact Pathway

- CERN membership contributes to the UK's international presence and visibility, and enhances its network of collaborations and connections in S&T.
- The UK's participation in and role at CERN increases the recognition of UK research excellence, and enhances the perception of the UK as a great research nation (i.e. world-leading, cutting-edge, international, significant, innovative, creative, ambitious, dynamic) and the place to do science and innovation at the highest level.
- This 'brand' of the UK as a 'science nation' helps to attract public/private funding and talent, as well as other forms of recognition of UK research excellence, e.g. awards and honours
- It also supports the UK's continued involvement in international research and collaborations, e.g. as a partner of choice for international projects and the development of new facilities

A.2 Impact pathways relating to world-class innovation

2.1. The wider application of CERN technologies

The UK derives socio-economic benefits from the development of CERN's innovative facilities, techniques and technologies and their wider application.

Impact Pathway

- CERN's scientific breakthroughs have often required major technological advances, both in terms of the core facility technologies (accelerators, detectors, etc.) and the supporting infrastructure (e.g. microelectronics, GRID computing, data analytics, machine learning, modelling, etc.)
- These technological advances may constitute new products or services for suppliers, which can be sold more widely to other research facilities and beyond. In several notable cases, the new solutions developed at CERN have provided the platform for a major new technology that has come into general use and had a transformative effect in all walks of life
- While the World Wide Web is a special case, there are numerous examples of technologies that have been developed further for wider application, and a good proportion of these involve UK researchers and UK businesses and the realisation of commercial benefits beyond the value of the immediate CERN procurement contract
- Knowledge transfer occurs either:
  - Directly, through researchers and companies involved in CERN technology development (which includes getting to 'preview' new ideas in the making), or through movement of staff who trained at CERN [see impact area 3.1], or
  - Indirectly, supported by CERN's and the STFC's KT activities (e.g. STFC-CERN BIC, STFC Business Opportunities Team, STFC awards through CLASP and ISP, etc.), to individuals and organisations not part of the CERN community.

  Both involve take-up of CERN technology through open access or IP licencing.
- Developments based on CERN technologies and methods with commercial potential can hence lead to economic impact for UK business and the UK economy.
- CERN research findings in fundamental physics can also contribute, albeit likely within a longer timeframe [see impact area 2.2]

- New applications underpinned by technologies developed at CERN deliver societal impact by bringing benefits to UK consumers, patients, the environment, etc., depending on where and how these are applied. New insights can feed into government policies and improved public services.

2.2. The wider application of CERN research findings

The UK derives socio-economic benefits from the wider application of research findings emerging from CERN.

Impact Pathway

- The UK's investment in CERN enables scientists at CERN to advance knowledge in the field of fundamental physics. This leads to a better understanding of the basic properties, materials, and forces in the Universe.
- Scientists in the UK (and elsewhere) build on this enhanced understanding in their research, enabling them to address complexity, ask the 'right' questions and set up experiments that continue to push out the boundaries of knowledge [see impact area 1.1].
- Based on an enhanced understanding of fundamental physics, further research may lead to unexpected developments and spin-offs of high societal and economic value in the long term.

2.3. Improved performance amongst UK suppliers

UK organisations gain economic benefits from being contracted suppliers to CERN, or through working with research groups holding CERN-related funding.

Impact Pathway

- Membership gives UK companies access to CERN contract opportunities (some low tech / high tech, some off-the-shelf / innovative). Research groups working on technology development for CERN may also partner with or contract companies as part of their projects.
- Awarded contracts bring direct additional revenue to UK organisations and support employment (industrial return).
- CERN contracts and involvement in CERN-related research projects can also bring additional benefits to these businesses. These include:
  - Development of skills, knowledge and understanding [see impact area 3.1]
  - Increased global outlook, networks and understanding of developments/requirements
  - Additional reputation and prestige for the organisation and its products and services
  - New or improved products / services – developed for CERN, or off-the-back of CERN work, which either could not or would not have been developed entirely in-house (e.g. too costly, insufficient expertise)
- These benefits may support increased market share, turnover, employment, and profitability of UK companies. This includes further (improved) ability to supply CERN, as well as through sales to other third parties of the same or other products and services.

A.3 Impact pathways relating to world-class skills

3.1. Increased skills and capabilities of the UK workforce

The UK benefits from increased knowledge, skills and capabilities as a result of training at, or related to, CERN.

Impact Pathway

- CERN can serve as an inspiring training ground for a high-quality UK workforce. Various activities support improved knowledge and skills amongst different stakeholder groups:
  - Amongst UK suppliers - where involvement in CERN contracts leads to improved knowledge and skills amongst the UK workforce involved
  - Amongst UK researchers - where involvement in CERN experiments leads to improved knowledge and skills amongst the UK scientists and engineers
  - Amongst UK CERN employees - where involvement in CERN governance/operations leads to improved knowledge and skills amongst a workforce that may return to UK-based employment (in similar or different sectors)
  - Amongst UK trainees and students from across a wide spectrum - where involvement in CERN training programmes (within limited direct cost to UK) leads to improved knowledge and skills amongst individuals at various levels of education and experience within the UK science base
- The acquired knowledge and skills can relate to various domains, e.g. technical, scientific, digital, project management, multi-lateral / international team working, cultural awareness, problem solving, process improvements, etc.
- The increased knowledge and skills can be deployed and applied in a variety of fields, and lead to an increase in the quality, productivity, and value of UK research and economy.

3.2. Increased UK public appreciation of science

The UK benefits from a public that is more informed and enthused about science, and become active citizens of a scientifically advanced contemporary society.

Impact Pathway

- CERN research and technology address fundamental questions of the Universe, at a facility of unprecedented scale, and CERN technologies have underpinned the development of innovations and products. CERN, its researchers, and the media undertake dissemination activities and public outreach work, celebrating its achievements and thereby raising the profile of CERN.
- This excites the general public (broadly – including e.g. politicians and the media) and awakens interest in CERN, the science that it supports and the outcomes and benefits of this work.
- The public's engagement with CERN's activities and findings promotes scientific literacy and fosters the development of a culture valuing science. This leads the public to be interested and more engaged with science in general. Young people may also be inspired to take up and pursue STEM-related studies and careers [see impact area 3.3].
- Enhanced scientific literacy and a culture valuing scientific investigation leads to cultural and societal impact by enabling the UK public to become active citizens within a scientifically advanced contemporary society. The public becomes able to engage in the socio-scientific debate and to make

better personal choices, being better able to critically assess claims and evidence (consumer, healthcare, political, etc.).

- The UK public is more supportive of public (financial) support for science (and CERN specifically)

3.3. Increased UK STEM uptake

The UK benefits from an increase in STEM graduates within the workforce.

Impact Pathway

- CERN is a research facility that inspires students and young people through the its scale, the types of 'universal' questions it addresses, and its international nature.
- CERN undertakes various activities to engage, enthuse and educate students and young people (teach/school visits, educational materials…). As a result:
  - Teachers gain the confidence, capabilities, resources, and refreshed enthusiasm to support (more/better) teaching of CERN-related subjects
  - Students increase their knowledge, understanding and interest (through visits, materials and teaching) in CERN-related subjects
- Young people may then be more likely to, and capable of, pursuing STEM subjects in school. Scientific literacy and appreciation and valuing of science within the UK public and general workforce, may increase as a result.
- Young people engaging with CERN may also be more likely to / capable of pursuing degrees in STEM subjects, leading to an increase in STEM graduates in the UK's (potential) workforce.
- This nurtures the pipeline of future talent and contributes to ensuring that the UK has access to a scientific and technically skilled workforce that will sustain the UK as one of the world's leading research nations and support the growth of a high technology economy.

A.4 Impact pathways relating to science diplomacy

4.1. The UK's influence in the international S&T landscape

The UK's involvement in CERN enhances its ability to influence international science and policy direction and priorities, thereby securing opportunities and (potential) value to the UK.

Impact Pathway

- Membership of CERN allows greater UK involvement in various levels of CERN governance (decision making bodies, staff, researchers).
- This provides the UK and its science base with a platform for international S&T engagement, leadership and agenda-setting.
- Benefits include some ability to influence CERN decision making (funding, priorities, etc.), thereby enhancing alignment of CERN activities with UK needs, capabilities and priorities.
- As a result, the UK may benefit from

- A better 'fit' of resulting opportunities and activities for its research community and companies (e.g. supplier contracts), and
- Increased relevance of CERN experiments/projects to UK research interests/capacity

- CERN activities/priorities, and the UK's input to these, may also influence the decisions of other bodies (e.g. national funding bodies).
- UK membership of CERN enables building of coherent relationships with the international research community that is broader than the confines of individual partnerships, and represents efficiencies in terms of time and effort required to build and maintain key connections.
- Hence, going beyond CERN, the UK's membership contributes to the UK's international presence and visibility, and enhances its network of high-level connections in S&T. These connections lend 'weight' to the UK's views on science matters and research policies, e.g. the UK holds key positions in international S&T committees.
- The UK's involvement in international research partnerships and fora ensures that global research strategy decisions take into account the UK's interests, opening avenues for enhanced opportunities and benefits to the UK (e.g. new funding programmes or facilities).

4.2. Improved diplomatic relations and engagement

The UK benefits from 'diplomatic spill-overs' from CERN.

Impact Pathway

- CERN provides a platform for international collaboration and exchange. This occurs through various means / at different levels:
  - Joint investment / decision making (i.e. CERN governance)
  - Joint experiments (multi-country teams of researchers / scientists / businesses)
  - A 'neutral' space for wider diplomacy, interaction or discussion (beyond CERN issues)
- CERN's activities have established processes for engagement and contribute to building relationships and trust between its members. CERN's international platform has also enabled engagement between countries that traditionally have limited interaction.
- The UK may benefit *directly* from improved interaction / relations with other countries, e.g. through enhanced international influence.
- The UK may also benefit *indirectly* from improved interaction between countries, e.g.:
  - Countries discussing global socio-political challenges, with global (incl. UK) benefits
  - Certain countries improving their 'relationship' that may increase e.g. peace / security

4.3. The UK's image as a 'great science and innovation nation'

The UK benefits from its image (or 'brand') as a great science and innovation nation, open for international collaboration and business

Impact Pathway

- CERN is highly visible internationally and acknowledged as (one of) the most advanced and cutting-edge research endeavours in the world.
- The UK's membership of CERN (and its key role within the organisation), provides the UK with international visibility at the highest level, nurtures its perception as a great science and innovation nation, signals that the UK is open to, and experienced in, international collaboration and business, and demonstrates that it is committed to science and innovation for the 'long haul'.
- This reputation supports the UK's position in the international science landscape, able to attract international talent and making it a 'collaborator of choice' for R&D [see impact area 1.3].
- The image of an internationally-engaged science nation may also have wider implications, i.e. beyond the S&T community. By fostering a positive attitude towards the UK, foreign governments, businesses, and the general public may be more interested in and inclined to engage with the UK, with positive effects on diplomatic and economic relationships, and tourism.

Appendix B List of stakeholder interviews

Name	Role	Organisation
Pippa Wells	Head of S Relations	CERN
Alan Silverman	Industrial Liaison Officer Assistant for the UK (retired)	CERN
Paul Collier	Head of Beam Engineering Department	CERN
Giovanni Annelli	Head of Knowledge Transfer	CERN
Amy Bilton	CERN Knowledge Transfer Officer	CERN
Ray Veness	Senior Engineer	CERN
Charlotte Jamieson	Head of enabling themes. Former chair of STFC finance committee.	STFC
Sarah Verth	Particle Physics Programme Manager	STFC
Allanah Baylis	Industrial Liaison Officer - Business Opportunities Team	STFC
Elizabeth Cunningham	Public Engagement Programme Manager	STFC
Delyth Lloyd	Business Development Manager	STFC
Steph Hills	European Communications Officer, CERN Press Office	STFC
Graeme Reid	Chair of Science and Research Policy	UCL
Dr Adam Baker	Assistant Director	BEIS
Professor Keith Ellis	Director of the Institute for Particle Physics Phenomenology (IP3), Durham University / STFC. Chair of CERN Scientific Policy Committee since 2017.	Durham University
Prof. Roger Cashmore	Retired. Former Director of Research and Deputy Director General of CERN. Former Chair of the United Kingdom Atomic Energy Authority. Professor of Experimental Physics at the University of Oxford.	Oxford University
Sir Chris Llewellyn Smith	Director of Energy Research	Oxford University
Prof. Jon Butterworth	Professor of Physics. Member of UKCC. Scientific advisor to the UK's delegation to CERN Council.	UCL
Prof. Pete Clarke	Member of STFC's Science Board, Professor of Physics	University of Edinburgh

Dr. Rob Appleby	Reader	University of Manchester
Prof. Graeme Burt	Senior Lecturer, Associate Director	University of Lancaster
Prof. Matthew Wing	Deputy spokesperson, AWAKE experiment.	UCL/DESY
Peter McIntosh	Technical Director	Accelerator Science and Technology Centre (ASTeC)
Prof. Neil Geddes	Director of STFC Technology	Rutherford Appleton Lab Technology Department (RAL TD)
Dr Anna Orlowska	Applied Science Division Head	Rutherford Appleton Lab Technology Department (RAL TD)
Dr. Stephen Haywood	Acting Head of RAL Particle Physics Department	Rutherford Appleton Lab (RAL)
Prof. Mike Charlton	Professor of Physics, Founding member of ATHENA collaboration	Swansea University
Prof. Niels Madsen	ALPHA Deputy Spokesperson	Swansea University
Prof. Sir. Tejinder Virdee	Former deputy spokesperson and deputy spokesperson for CMS.	Imperial College London
Mark Langley	Professional Development Leader	National STEM Learning Centre
Dr. Becky Parker	Director	Institute for Research in Schools (IRIS)
Geoff Hall	Professor of Physics	Imperial College London
Jose Luis Martinez	Chair of the ESRFI Strategy Working Group on Physical Science and Engineering	A comparable body to capture the broader picture of CERN. Chair of the ESRFI Strategy Working Group on Physical Science and Engineering. Also been on ILL and ESS Council.
Prof. Nikos Konstantinidis	ATLAS Operations UK PI	UCL
Prof. Dave Newbold	Head of RAL PPD	RAL PPD
Prof. Gavin Davies	CMS Operations UK PI	Imperial College London
Prof. Chris Parkes	LHCb Upgrade UK PI	University of Manchester
Prof. Tim Gershon	LHCb Operations UK PI	University of Warwick
Prof. David Evans	ALICE UK PI	Imperial College London

Prof. Christina Lazzeroni	NA62 UK PI	Birmingham University
Prof. Dave Charlton	Former ATLAS Experiment Spokesperson (global management)	Birmingham University
Prof. Guy Wilkinson	Former LHCb Experiment Spokesperson (global management)	University of Oxford
Prof. Themis Bowcock	Former Head of Particle Physics	Liverpool Semiconductor Detector Centre (LSDC)
Prof. Phil Allport	Professor of Particle Physics	Birmingham University
Prof. Jasper Kirkby	Spokesperson for CLOUD experiment	CERN
Michael Campbell	Spokesperson for Medipix Collaboration	CERN
Dr Maurizio Bona	Advisor to the Director General at CERN - CERN Senior Advisor – Relations with Parliaments and Science for Policy	CERN
Maria Teresa Dova	ATLAS Experiment	Universidad de La Plata, Argentina
Marta Losada	ATLAS Experiment	Universidad Antonio Nariño, Colombia
Carlos Avila	CMS Experiment	Universidad de los Andes, Colombia
Zeblon Vilakazi	ALICE experiment	University of the Witwatersrand, South Africa
Patrick O'Hara		UHV Design
Thomas Rak	Project manager	TG Engineering
Mike West	Managing Director	Arcade UK Ltd
Mike Fairclough	Business Development Director	Stevenage Circuits
Mike Devine	Technical Sales Director	Exception PCB
Amanda Boothby Mark Bullough Susan Walsh	Finance Director R&D Manager Head of Design	Micron Semiconductor Ltd
Alan Crow	Technical Support Manager	H.V. Wooding
Dr Alexander Reip	CEO	Oxford nanoSystems
Prof. Pankaj Vadgama	Founder	Camstech
Neil Burns	Founder and Co-Director	Croft Additive Manufacturing

Appendix C Survey results

C.1 Survey of the UK scientists and engineers

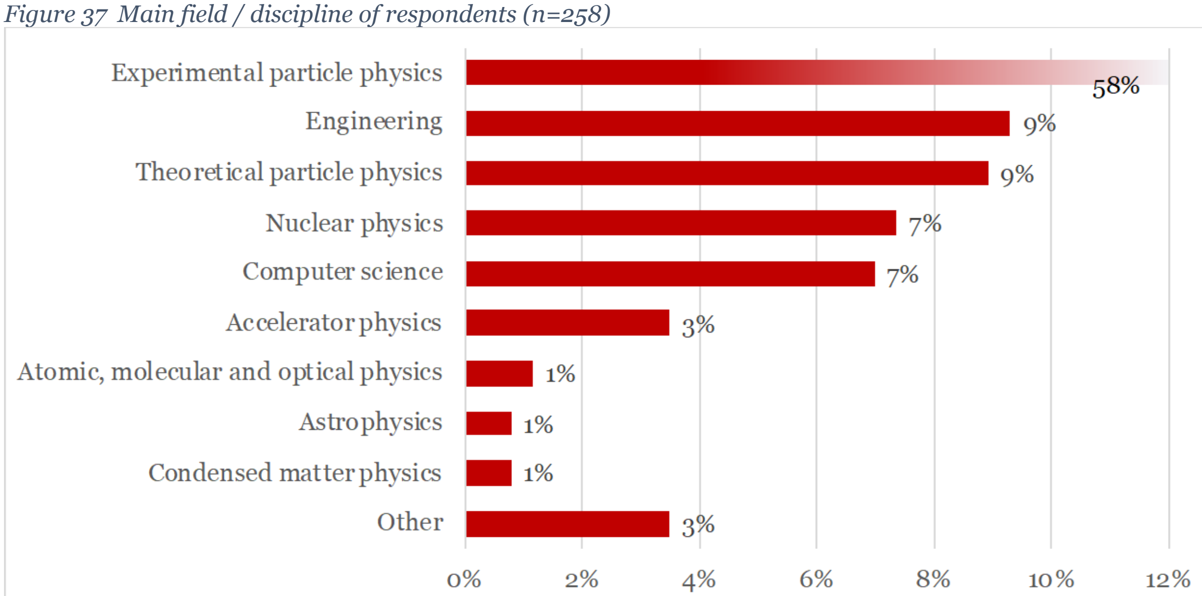
There were **262 useable responses to the community survey** (UK scientists and engineers). These are respondents who answered at least some of the questionnaire and who gave their consent for their answers to be used for the study. Questions were not mandatory and so respondent numbers do vary by question (as indicated against the relevant tables and figures presented below).

C.1.1. About the responding individuals

Respondents come from over **30 different organisations**, including 23 different UK universities, 5 public research institutes and facilities, and 6 commercial organisations.

More than half (58%) of **respondents work mainly in experimental particle physics**. The remainder are spread across a range of fields and disciplines (engineering, theoretical particle physics, nuclear physics, computer science, and so on, as shown below). Other fields mentioned by respondents (but not classified in the list) included medical physics, applied physics, plasma physics and safety.

Figure 37 Main field / discipline of respondents (n=258)



C.1.2. About their involvement with CERN

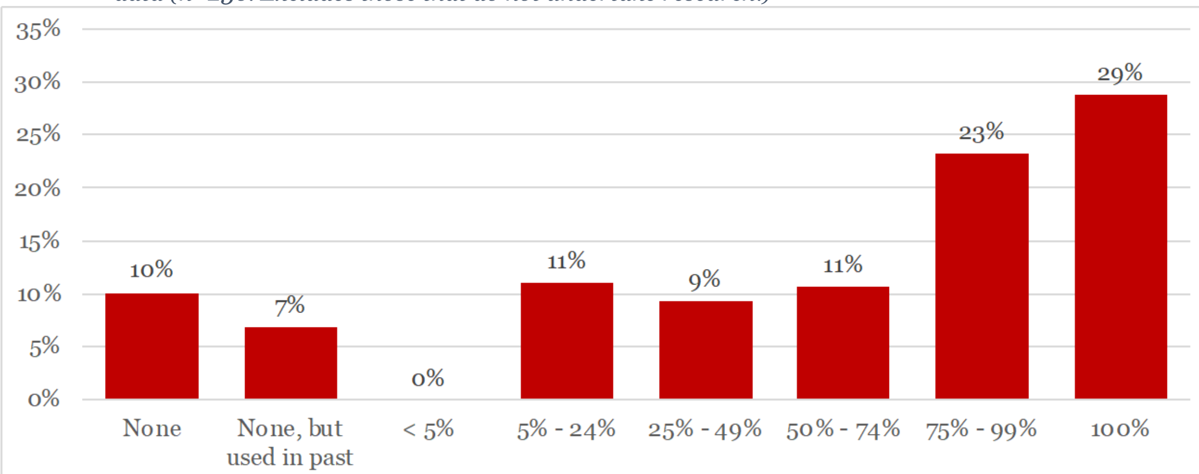
We asked various questions to understand how, and the extent to which, the UK science and engineering community was **interacting with and making use of CERN**, as part of their research or work.

<u>Working at CERN and / or on CERN-related projects and experiments</u>: The vast majority of the respondents (89% of 261) have worked *at CERN* as part of their research or work, usually (in three quarters of cases) for sustained periods and / or on a frequent basis. Indeed, 30% of the survey respondents are currently working at CERN. A further 8% have worked regularly or for sustained periods *on CERN related projects or experiments* (but not at CERN). Only 3% of respondents have never worked at CERN or on a CERN related project or experiment.

<u>Using CERN experimental data</u>: Leaving aside the handful of respondents that do not undertake research activities, we asked respondents about the proportion of the research / work time in the last few years that

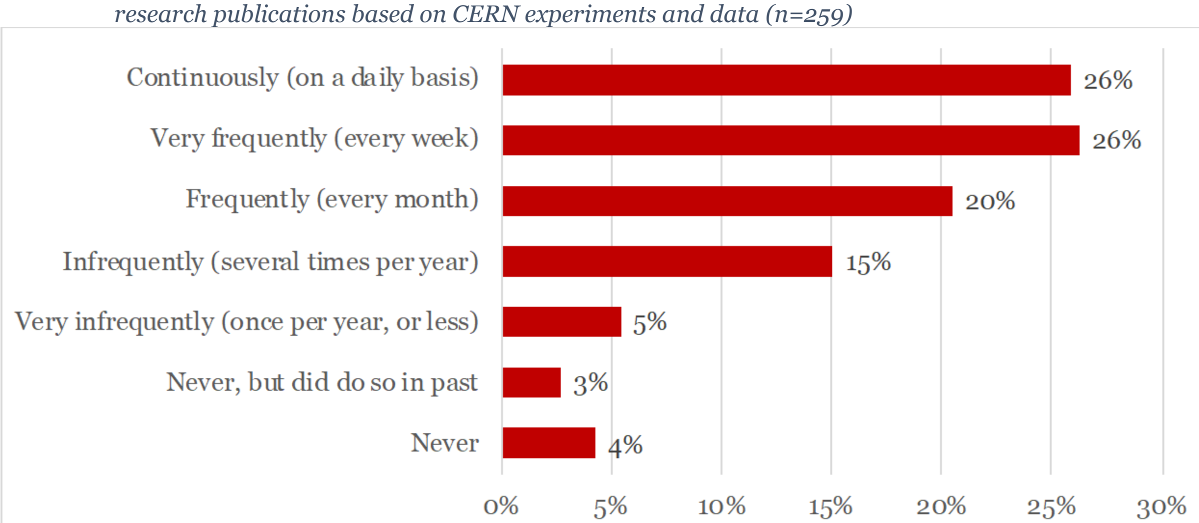
has included the use of CERN experimental data. The vast majority (83% of 236) had made some use of CERN data recently, including 29% that said that they had done so *all* of the time. A further 7% of respondents had made use of CERN data historically, but not in the past few years. Just 10% of the respondents had never used CERN data as part of their research or work.

Figure 38 Proportion of research/work time over past few years that has included the use of CERN experimental data (n=236. Excludes those that do not undertake research.)



Reading, referencing and / or citing publications based on CERN experiments and data: We also asked respondents about the extent to which, over the past few years, they had read, referenced and / or cited research publications that were (at least in part) based on CERN experiments and data. Nearly all the respondents had done so to some degree (93%) or had done so in an earlier period (3%). This includes a quarter of respondents that reported using such publications on a daily basis, and another quarter who use them every week. Only 4% have never read, referenced or cited CERN-based publications.

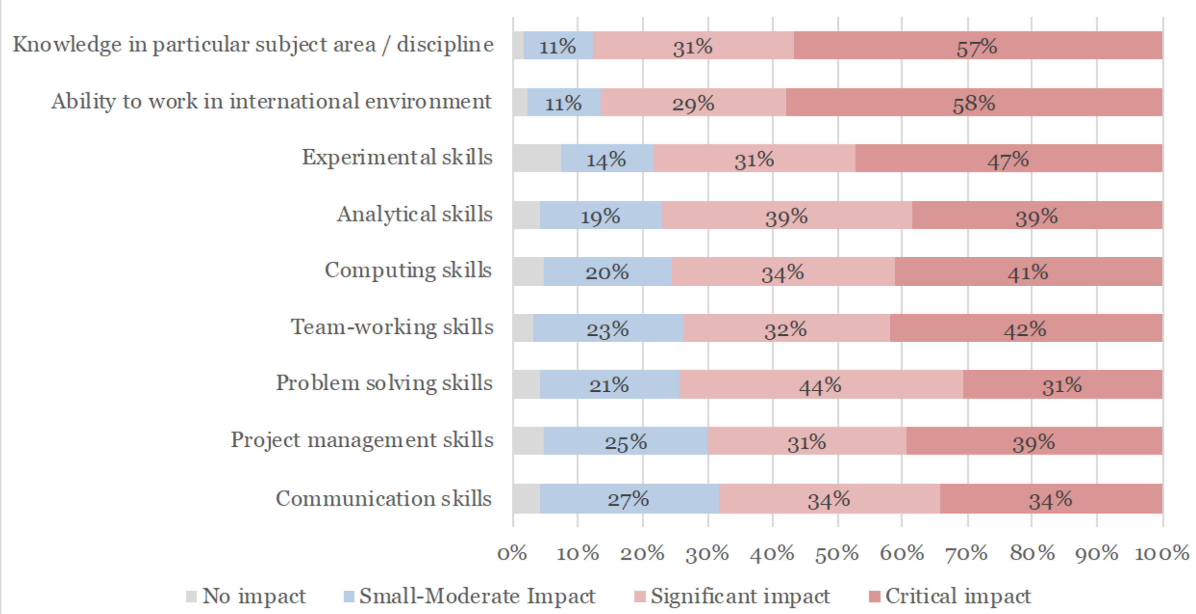
Figure 39 Frequency (during the past few years) with which respondent has read, referenced and / or cited research publications based on CERN experiments and data (n=259)



C.1.3. Impacts on their skills and capabilities

Respondents were asked about the **impact of involvement in CERN on their skills and capabilities**, and those of their wider group / department. Nearly all (90%+) of the respondents reported some impact in each of the nine areas listed (see figure). However, significant and *critical* impacts were most widespread in relation to subject area knowledge and the ability to work in an international environment. Respondents pointed to other areas (beyond those listed below) where there had been skills benefits from involvement. These included presenting / public speaking, communication, writing, languages, cultural awareness, design, outreach, teaching, time management, international diplomacy, networking, and collaboration.

Figure 40 Extent to which involvement in CERN has had a positive impact on skills and capabilities of the respondent and their group / department (n=176-194)



Some specific examples of important skill / capability benefits that have been realised by respondents as a result of their involvement with CERN were given in the survey and are shown below for illustration.

> *"My time at CERN (three months in 2017) made me much more aware of the skills needed and operations required to successfully run a research facility"*
>
> *"By working in large collaborations at CERN, I (and my group) immediately built international reputations and networks.*
>
> *"State of the art computing techniques. This is a fast moving area and it is vital that advances are appreciated and employed quickly to improve the performance of both data taking and analysis. The techniques the students learn are often very important for those leaving particle physics for their future careers"*
>
> *"I have been largely formed at CERN. 80% of what I am professionally comes from CERN."*
>
> *"Contact with the best experimentalists has injected realism into my phenomenology research"*

"My computational analysis skills, which I have applied to projects outside of my particle physics research and have used frequently to solve numerous unrelated problems"

"Improvement in data analysis skills, including machine learning."

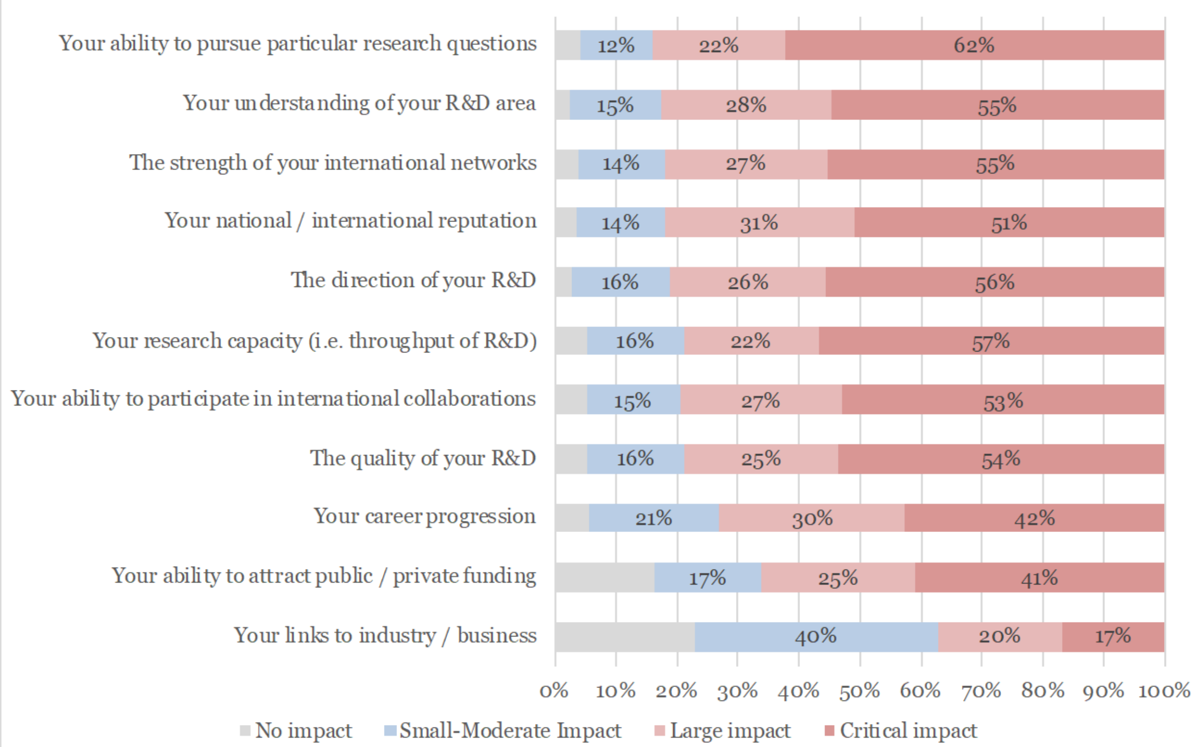
"I'm now much better at working in a team. I have been working extensively with 5 people and we had to overcome several organisational and personal issues, which we solved successfully, and I have gained invaluable experience in the process of this."

"The impact on training literally hundreds of engineers and scientists that then move to other sectors is hugely important."

C.1.4. Impacts on their research and technology activities

Respondents were asked about the extent to which their involvement and interactions with CERN had **impacted on their own research and technology activities**. Across all of the eleven aspects asked about, more than three-quarters of respondents said that there had been some degree of impact, and in most areas, CERN was seen as critical for at least half of those responding.

Figure 41 Extent that CERN has impacted on respondents' research and technology activities (n=183-236)



Many of the respondents took the opportunity to provide further details of an area in which CERN had had a particularly **significant impact on their activities**. Most focused on their ability to pursue their research (to the same extent / at all). However, below we provide a selection of other examples, to illustrate areas of impact.

Ability to pursue particular research questions:

"CERN experimental results are the foundation upon which my phenomenology research is built. I consistently use CMS/ATLAS public results and papers to build on and inform my research"

"CERN operates globally unique machines which enable my field of research. It would literally be impossible to pursue this line of research elsewhere at present".

"My theoretical work is motivated and driven by the experimental achievements made at CERN"

"It is a unique (in the world) source of experimental data for my research"

Strength of international networks:

"For theoretical particle physicists, CERN is the place where they can interact face-to-face with the other leading people in their field, both theoretical and experimental. Most of my research contributions have arisen from such contacts at CERN."

"Without CERN, I would not have had the opportunities to work internationally; particularly this early in my PhD"

"Interaction with the international community has been an important driver since I was a CERN summer student some decades ago."

National / international reputation

"I was elected to the key Coordinator role as part of a CERN international collaboration - a major signature of my standing in the field and that of the UK. I could not have achieved similar international recognition without participation in a CERN experiment."

The quality of your R&D

"I received an education in principles of data analysis which is unsurpassed in any other field in which I have been associated, including medical imaging, computer vision and machine learning."

"Working at CERN gave me a good grounding in how to undertake research and how to work in international collaborations. These experiences stood me in good stead."

"It set me up with high level research and technical skills"

Your career progression

"My six years at CERN in the 1960s gave me an international outlook, fluency in French and interest in other languages, plus the confidence to work internationally. This has been of great value for my career."

I am an apprentice and completed a 2-month placement at CERN. It was invaluable to my development as an engineer and will remain a career highlight for many years."

"I have spent crucial periods of my career as a younger scientist on long term attachment at CERN."

"I was elected to the key role of Coordinator by the international collaboration - a major signature of my standing in the field and that of the UK. I could not have achieved similar international recognition without participation in a CERN experiment."

"My two appointments in the CERN Theoretical Physics department were pivotal in my career. I produced my career-best work in these periods."

"The highlight of my young career. Years later I'm still asked about it in interviews and by my peers."

The direction of your R&D

"The data and the large experimental collaborations enable new directions of research."

"CERN enabled me to branch into the field of design and installation for the LHC experiments (ATLAS, NA62 & LHCb)."

Respondents also provided a long list of examples of **important scientific or technological advances** that they personally had made (or were involved in), which would not have been possible without CERN. Some are shown below for illustration.

"Octupole deformation in nuclei, research done with REX-ISOLDE and miniball."

"Measurements in flavour physics which were made using the data collected by the LHCb detector installed on the LHC, both operated by CERN."

"Development of computer control systems over many years as well as links to industry for their production."

"We discovered pear-shaped atomic nuclei in 2013; the results were published in Nature. CERN provided the accelerated radioactive beams that enabled this research; it is the only facility world-wide having this capability."

"Proof of the convergence of the heavy quark expansion was only possible with the measurements of Delta Gamma_s at CERN and a comparison with my calculations"

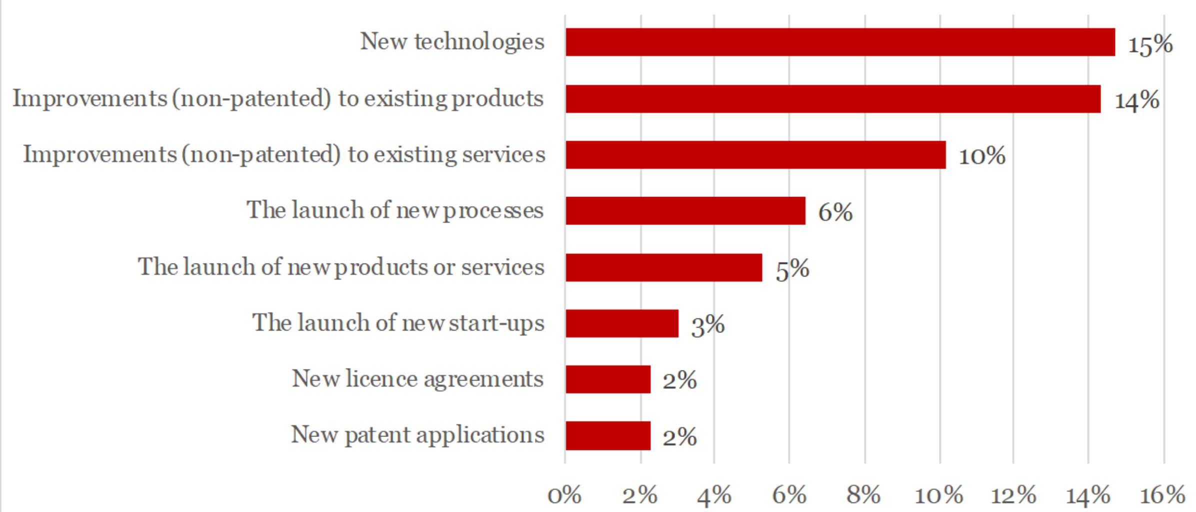
"Development of fast, digital, synchronous pipelined electronics systems for large particle physics experiments"

"I worked on an analysis which produced the world leading upper limit on the cross section times branching ratio of the decay of a Higgs boson into two muons. Without the data collected by the LHC, this would not have been made possible."

C.1.5. Outcomes of their CERN-related R&D

Respondents were asked whether their involvement with CERN (CERN-related projects, or using experimental data) had led to any of a series of **innovation-related outputs**. New technologies were most often cited (15% of respondents), followed by improvements (non-patented) to existing products and services. A minority (2-6% in each case) also reported the launch of new products or services, processes, or start-ups, as well as new licence agreements or patent applications.

Figure 42 Extent to which CERN projects and experimental data have led to innovation outputs (n=265)



In a small number of cases, specific examples were given. These are shown below:

New patent applications

"We started bunched-ion-beam experiments at ISOLDE, building the ISCOOL ion beam cooler-buncher with an EPSRC grant. This has made possible many laser spectroscopy measurements on radioisotopes and enabled a greatly-improved technique of Collinear Resonance Ionization Spectroscopy. A member of my group has a number of patents arising from this development."

"I have direct knowledge of one very recent patent being sought for a novel magnet solution."

New technologies

"Worked with UK companies to develop radiation resilient ultrasound technologies for application in the nuclear power industry."

"The manufacture and sale of Medipix detectors, integrated into a retractable mount, for use on a range of commercially available electron microscopes from several manufacturers. Medipix is now used on the IO6 beamline at Diamond Light Source, to name a single application."

New products and services

"Improvements to client support in the retail sector, using machine learning techniques and processes developed using CERN".

The launch of new start-ups

"Recently received funding to start consultancy services based on knowledge gained from CERN."

"Several of my PhD students, trained at CERN have gone on to found start-ups."

"Our group leads work on modelling the radiation environment in the ATLAS detector, which has led to a spin-off with the nuclear industry involving testing of ultrasonic sensors for high radiation environments."

"We have filed 3 patents and launched a start-up company (Artemis Analytical Ltd.) based on techniques developed at CERN".

"I was involved in a start-up to use photon detection to do quality assurance of silicon wafers using ideas gained from my particle physics research from CERN and also from elsewhere."

Respondents were also asked whether they had **applied CERN-related R&D or technology to applications in other fields** (e.g. beyond physics). A number of examples were put forward:

- The application of accelerator beam dynamics to studies for synchrotron light sources and free electron laser
- The application of CERN research to classroom scenarios
- The development of active plasma lenses
- The application of holographic metrology from a CERN experiment to the recording of marine plankton.
- The application of radiation detectors to high temperature scenarios such as in civil nuclear and oil/gas exploration activities
- The application of an understanding of nuclear radiation on silicon sensors and electronics to UK space and nuclear industries
- The application of Grid Computing in other areas of science

- The application of computer simulation techniques in other fields (finance, defence, energy, telecoms, etc.)
- The use of gaseous detectors developed at CERN for homeland security projects
- The application of orbital welding for industrial research in aerospace and nuclear industries
- The application of CERN radiation modelling software used in the ATLAS experiment and LHC to pressure vessel diagnostic systems for the nuclear industry.
- Currently working on the application of methodologies developed for the ATLAS trigger to network security and image recognition

C.1.6. Wider impacts of their CERN related R&D

Respondents were also asked whether their involvement with CERN had contributed to wider **tangible impacts on the UK economy or society**.

Most of those providing a response pointed more generally to the experience and skills developed by those engaging with CERN, which have then been transferred into other walks of life:

> *"Those trained at CERN have had leading roles in other technology led areas having once left the field. They seem to be the only ones who understand the fundamental principles involved in quantitative analysis of scientific data and indeed the scientific method."*
>
> *"The main impact is through training of highly skilled people who then enter the UK economy."*
>
> *"I have worked with students who have now left particle physics (who will not be answering this survey) who have moved into areas that include: financial services, proton therapy, and software development. In all cases the students used transferable skills they picked up working at CERN alongside me."*
>
> *"PhD students I've supervised going into industry."*
>
> *"Transfer of skills from CERN to the UK more widely."*
>
> *"Past students and postdocs are now data scientists at TfL and other places".*
>
> *"The PhD students I have trained have all gone on to take important roles. Examples include one student went on to work in the commercial cyber defence sector, another works on R&D for our navy's submarines and another has gone on to pioneer data analytics work at consulting companies in London."*

Or they pointed to the use of CERN for public engagement or to encourage STEM uptake:

> *"Outreach at school events to excite kids about the wonders of science and engineering."*
>
> *"Last year we e.g. visited the Orkney Science Festival with ten scientists. During that stay we also visited small schools on very remote islands like Sanday, Stronsay and Westray, which were probably never before visited by scientists working in fundamental research. In all our activities we present research results, that are based on the experimental measurements performed at CERN."*

“Encouraging school students to study physics and IT related subjects through talks about / direct involvement with CERN.”

“Inspiring the next generation of scientists by teaching them how we discover new particles at CERN”

“All scientific outreach activities carried out by me have had a huge component of CERN physics, many exclusively based on LHC physics.”

“I have initiated several public engagement projects, which have, for example provided CERN data to UK school pupils. This has directly inspired students to continue with physics at university level.”

“Analysis of UCAS forms of students applying for physics at Oxford strongly suggests that CERN-based science is one of the primary drivers of bringing school students into physics at university. (The other major driver being astronomy/astrophysics.)”

“We use data from CERN as part of our "masterclass" for A-level students in the School of Physics. This is one of the key events we run to try to encourage students to pursue physics (and more broadly science) degrees, which is critical for providing the highly skilled graduates needed for the future UK economy. The CERN data allows the students to have hands-on experience of analysing particle physics data and is a key part of the masterclass.”

“Each person who visits, studies or works there becomes an ambassador for STEM subjects. This has a knock-on effect that is seldom measured.”

While a small number mentioned the <u>wider impact of particular innovations</u> that they had been involved in developing at CERN:

”I have worked with a UK company [name withheld] to help refine their commercial electron detectors. Their turnover in this application is millions of GBP p.a”

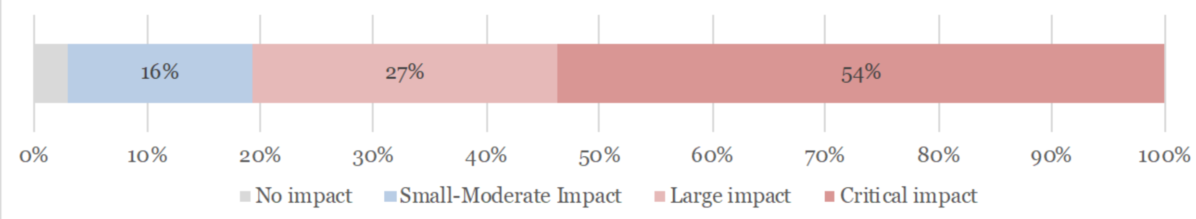
“New and improved welding and remote handling technologies marketed by UK companies. These new technologies developed out of R&D conducted for the ATLAS experiment at CERN. Without CERN and UK involvement this work would not have taken place.”

“The Medipix based system we developed, sold by Quantum Detectors, is earning revenue from all round the world. The development of multi spectral x-ray imaging is also expected to significantly improve the diagnostic power of CT scanning. Both of these were through our work on silicon-based detector technologies, as part of a CERN hosted collaboration.”

C.1.7. Supporting UK research and innovation

Respondents were asked about **CERN’s impact on the speed of progress** in their field or discipline more widely. Overall, CERN was thought by most respondents (81%) to have been critical, or to have contributed to a large extent. This increases to 90% if we only consider the responses from experimental particle physicists (n=139).

Figure 43 Extent that CERN has impacted on the speed of progress in their field / discipline (n=237)

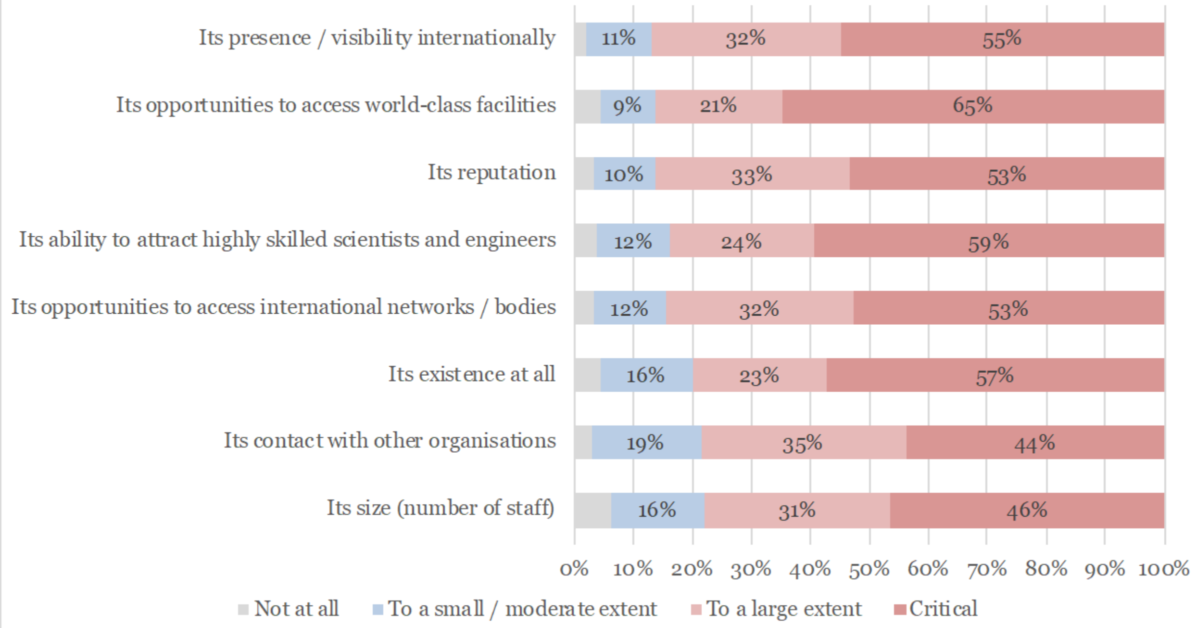


Many additional comments were provided regarding the criticality of CERN in this regard. Just a small selection of such feedback is shown below for illustration.

> *"Without CERN, particle physics as a whole would be grossly diminished."*
>
> *"This lab is responsible for the vast majority of innovations in particle physics, most major discoveries and a thriving international scientific community of which I am part."*
>
> *"The vast majority of UK Particle Physics research would not be possible without the UK CERN subscription and UK involvement in international collaborations based at CERN."*
>
> *"It provides the infrastructure and resources that allows this research to take place and the essential collaboration among scientists from around the world to analyse the data."*
>
> *"CERN operates globally unique machines which enable my entire field of research."*
>
> *"The field of particle physics has reached a point where no single country alone can provide the necessary infrastructure and community for the field to flourish. CERN is about the only organisation left in the world that is able to provide the required expertise and facilities."*

Respondents were also asked to assess the extent to which the UK's membership of and involvement in CERN had **positively affected their wider group or department** in various ways. The response was very positive across all aspects, with the great majority claiming that CERN impacted to a large extent, or was critical in every case. Indeed, over half of respondents (57%) claimed that CERN was 'critical' to the very existence of their group or department.

Figure 44 The impact of UK membership / involvement in CERN on UK groups and departments (n=178-184)



More widely, a majority of respondents said that CERN (facility and experiments) had been critical to:

- Advancing knowledge in the field of fundamental physics (89% rated CERN as critical in this regard)
- The development of technologies that have been instrumental in making discoveries (80%)
- The development of the skills and capabilities of individuals (68%)
- Training the next generation scientists and engineers (69%)

A majority of respondents also believe that CERN had been 'critical' in supporting the UK's science and engineering community in undertaking R&D that is (each of) cutting edge, world-leading, international, significant, innovative and ambitious.

When asked to point to the most **significant advance in knowledge /understanding** that has been enabled by CERN, most respondents mentioned verification of the Standard Model and confirmation of the Higgs boson (2012). Beyond this, other advances highlighted included the discovery of weak neutral currents (Gargamelle bubble chamber, 1970s), the discovery of electroweak (W and Z) gauge bosons (SPS collider, 1980s), the measurement of the number of lepton generations (1990s) and the null-result showing a lack of supersymmetry.

Many also highlighted that the development of technologies relating to CERN (see next section), such as the World Wide Web, high-end computing, data management and accelerators / imaging for use in healthcare, have also themselves enabled and supported very significant advances in knowledge and understanding through the subsequent application of these technologies.

C.1.8. Wider application of technology

Respondents were also asked specifically for examples of **technologies** (beyond the World Wide Web, and those used in medical imaging) that originated at CERN (i.e. developed at / for CERN, at least in part) and **that have had wider application and benefit**. A number were identified:

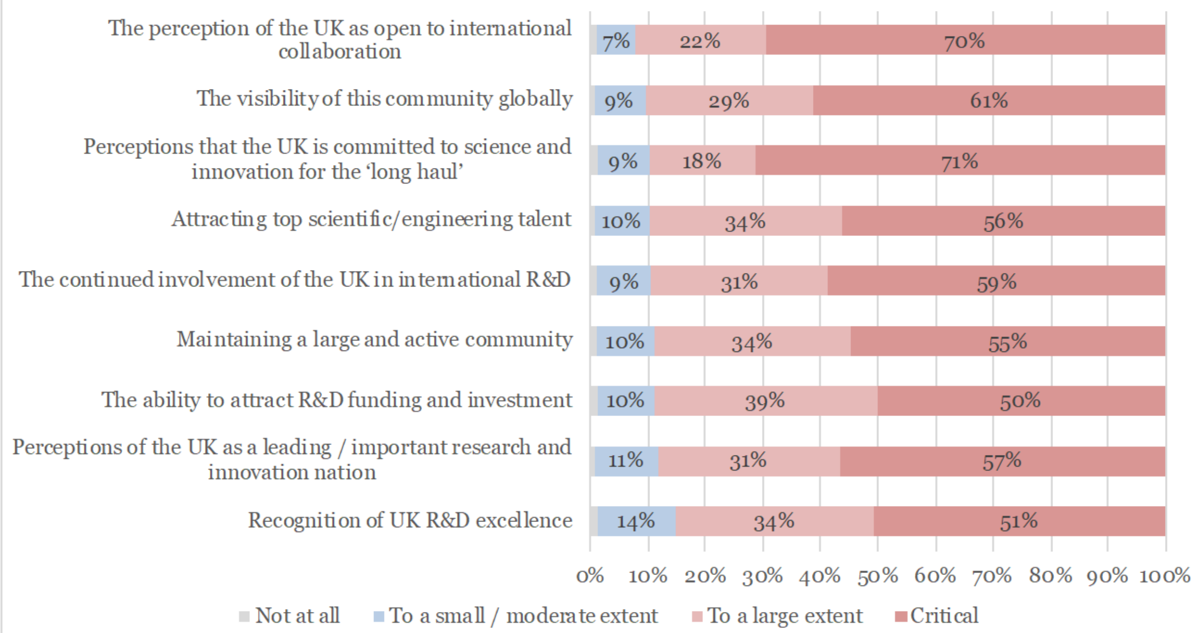
- Software tools developed at CERN (Geant4, ROOT, PAW, FLUKA) used in physics and other fields, as well as in e.g. the space, nuclear, medicine and aviation sectors
- CAD packages developed at CERN (as open source code) being used routinely by electronic industry
- Grid computing and distributed processors, as well as advances in machine learning, pattern recognition, server networks and big data analyses
- Tracker ball and computer-programmable knob
- Flat-screen computers, developed for tightly spaced server rooms at CERN SPS
- High-speed digital optical transmission lines
- Underground superconducting power transmission, which is leading to the development of large-scale power grids with negligible resistive energy loss
- Zenondo, which has had an important impact on open-access publishing and data transparency throughout the sciences.
- Statistical techniques developed at CERN (e.g. nerubayes) are now used within the finance sector
- Fast & compact electronics which were designed for use in trigger systems for the large experiments but have applications in any area requiring fast processing of large data sets
- Gas electron multiplier for radiotherapy
- Medipix chips (pixel radiation detectors), used for various imaging applications (medical imaging, x-ray for art restoration, archaeological artefact analysis, nanosatellites, etc.)
- Electrochemical sensors for water pollution measurements
- Monorail inspection robots for underground water pipelines
- Pipe-cutting tools for oil and gas pipes (compact universal orbital cutter) – developed by CERN technician Didier Lombard
- Fibre optic sensors to help manage water shortages (FOSS4)
- Silicon detectors, such as those used in cameras, are constantly being pushed forward by the demands of experiments like those at CERN.
- New high precision welding techniques for cooling tubes being repurposed for use in aircraft turbine blades. This is cutting the cost, and therefore should make air travel cheaper
- Radiation damage modelling for nuclear decommissioning operations (including simulations of expected human doses from human activity in such environments)
- Development of radiation hardened robotics for decommissioning/disaster relief
- Many radiation-hard electronics/chips are developed for CERN projects, working with international suppliers, which can have applications in the nuclear industry as well as for military use.
- Radiation testing facilities for satellites
- Steel developed at the CERN PS, widely used for electrical motors.
- Vacuum technology for solar thermal panels
- Muon tomography is used for border protection
- The invention of Wire Chambers (Charpak) led to the modern security scanners at airports

One respondent also highlighted that global IT companies collaborate with CERN and use the challenging performance demands of the facility to stress-test their products.

C.1.9. The UK's international influence

The questionnaire asked respondents to gauge the importance of CERN to the UK science and engineering community overall, particularly in relation to its **perception / role internationally**. Across all of the aspects listed in the figure below, a majority (50%+) reported that UK membership / involvement in CERN had been critical.

Figure 45 The impact of UK membership / involvement in CERN on UK science and engineering (n=171-181)



Examples were given to demonstrate many of these impacts:

Visibility, perceptions and recognition of the UK globally

"The large number of non-European countries currently applying for associate or full membership of CERN demonstrates that non-member states see this membership as a KPI for scientific excellence and a hi-tech society and industry, in order to attract inward investment in these sectors. The UK must maintain its membership to continue to send the signal to the world that it is committed to the knowledge economy and promoting the latest ideas and scientific developments, to further encourage this inward investment."

"Recognition usually starts within the field itself, so by participating and leading CERN activity the UK maintains its position as a world leader in science."

"CERN only hires staff and fellows from member states, so although the UK could be involved as a non-member through collaborating institutes (mainly universities), it is incredibly useful to have a real influence within these globally-visible scientific projects with engineers and scientists on the front line."

"CERN allows the UK to show the quality of its work on an international display." For example, through:

"The leading role of the UK in development of GRID computing concepts essential to the large quantity of data produced by CERN experiments"

"Leading roles for the UK in CERN experiments (UK people being spokespersons of experiments, leading analysts in discovery papers, leading roles in collaborations …)"

"The UK science & engineering community's vital role in the construction of the ATLAS detector and in key analyses performed with data collected from that detector."

"The UK's dominant role in some vital projects, such as the ATLAS trigger system."

"Because of CERN, the UK is seen as a partner of choice in particle physics and related research".

"The UK signing MoUs for the LHC upgrades helps to reinforce the perception that the UK values science and innovation"

Maintaining a large and active UK community

"One needs to consider how a nation's fundamental physics would appear if one were not in a CERN member state. A suitable case-study might be Ireland, which is not a CERN member state. As a result, it has only a small number of theoretical and experimental physicists in this field. The absence of CERN membership means it is not a place where one can undertake this sort of experimental science."

"UK universities are constantly sending students to CERN to train and improve their skills."

"In outreach, I have noticed that work with CERN greatly interests and inspires young minds. This helps us in recruiting the next generation of scientists and engineers".

"It is self-evident. You cannot have an active community without something for them to be active about."

"The UK particle physics community would simply die and be isolated without CERN."

"The newly formed CERN Alumni group has set up a number of successful events, bringing together people based in the UK who have previously been at CERN and allowing them to network. They have also run informational sessions about what people have done after leaving CERN, which could be beneficial to the UK Science and Engineering community."

"The LHC experiments need large number of scientists. The amount of data is such that a very large number of PhD students can be trained in meaningful research. Such experiments are therefore important in maintaining a large and active community".

Attracting top scientific / engineering talent

"The vast majority of the members of my group (from PhD students to postdocs to faculty) are either very talented UK researchers who have worked at CERN or elsewhere abroad (connected to CERN) before returning to the UK, or are excellent foreign scientists who have decided to come and work in the UK because of the excellent reputation that, through its affiliation to CERN, the nation has as a world-class science

hub internationally. This is a pattern that repeats itself universally across UK physics departments that have an active particle physics group."

"Much of modern particle physics requires the use and interpretation of current experimental data, the most important of which comes from CERN. A country that does not have membership to CERN is automatically discounted as a working environment for a large number of particle physicists"

"My group, like most others, consists of excellent people from around the world. Because of our work at CERN, we've attracted physicists from other countries and also 'brought back' UK-educated particle physicists who spent a significant part of their research career abroad".

"Universities would struggle to attract brilliant scientists if they did not have a presence at CERN"

"Many top researchers from overseas countries who were attracted to the UK by the high-quality CERN-related research performed by the groups."

"We actively use our involvement in CERN to attract engineering talent, as well as to encourage and engage new students".

"We have colleagues from all over the world come to work here on CERN data and experiments. Without CERN we would not attract these researchers. Many would move elsewhere."

"Many of our DPhil students apply to our program in order to participate in CERN experiments."

"More than 40% of the 40 highly skilled researchers in my group are from outside the UK, attracted to the UK by CERN research and the perceived openness of the UK to international collaboration."

"The top scientific talent in particle physics wants, generally, to work on the questions that are at the cutting edge of particle physics. That physics is being done, almost entirely uniquely, at CERN. If the UK wishes to continue to attract such talent, membership in CERN is necessary."

<u>The ability to attract R&D funding and investment</u>

"Several researchers have joined our group with ERC grants. If we were not involved in CERN they would not have joined us, and instead would have taken their expertise (and the funding to create jobs and PhD places) to other EU countries."

"The UK has been extremely successful in attracting high value ERC grants for CERN-related research, including my own ERC Advanced Grant which is entirely based on CERN research. Without CERN membership I would probably have had to leave the UK for an overseas university, depriving my university of a research group of 40 members, built up by me from approx. 4 members in 2004."

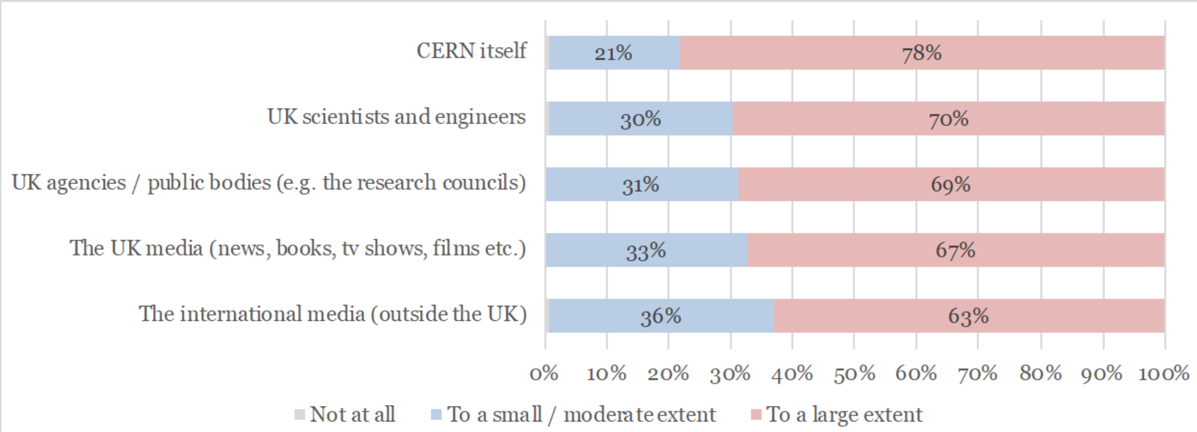
"UK-based scientists have been very successful in obtaining funding outside the main research council route for research that relies on involvement in CERN experiments. Examples include European Union starting / consolidator / advanced grants. Securing this funding would not have been possible without CERN membership"

C.1.10. Public outreach / STEM uptake

Respondents were asked about the extent to which they, personally, have referenced CERN (the facility, experiments and discoveries) to **communicate with the UK public** over the past 10 years. Nearly all (94%) reported that they had done so, including 62% who had done so 'to a large extent'.

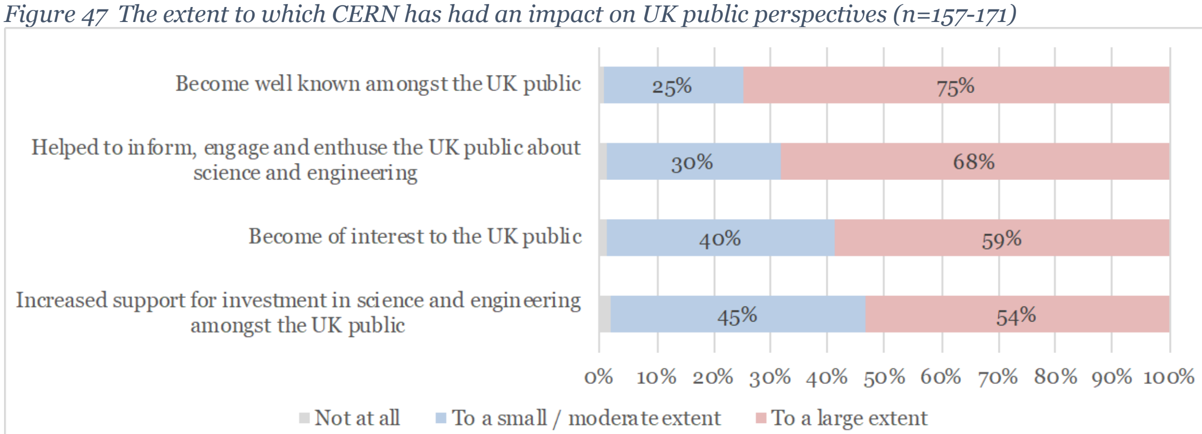
They were further asked about the extent to which other individuals and organisations had referenced CERN to communicate with the UK public. All five types of organisation suggested were near-unanimously thought to have done so to some extent. More than three-quarters thought that CERN itself had done so to a large extent, with only slightly fewer (~two-thirds) saying the same was true of UK scientists and engineers, UK agencies and public bodies and the UK / international media.

Figure 46 Extent to which organisations have referenced CERN to communicate with the UK public (n=146-164)



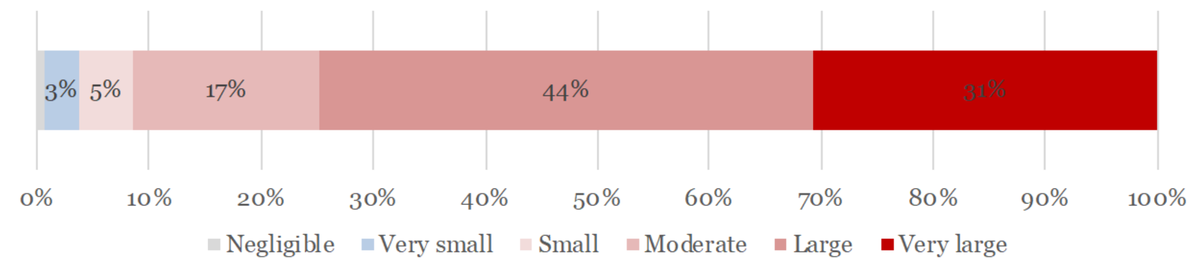
Following on from this, respondents were also asked about the extent to which CERN (the facility, its activities and achievements) has had an impact on understanding and **perspectives of the wider public**. Nearly all respondents thought CERN had had some influence on all four areas listed, with the largest impacts seemingly on the UK public's knowledge of CERN and its understanding, engagement and enthusiasm for science and engineering. However, a majority also felt CERN had 'to a large extent' become of interest to the UK public and had helped increase public support for investment in science and engineering. To a separate question, 84% also stated that particle physics is now recognised more widely by the UK public 'to a large extent' because of CERN.

Figure 47 The extent to which CERN has had an impact on UK public perspectives (n=157-171)



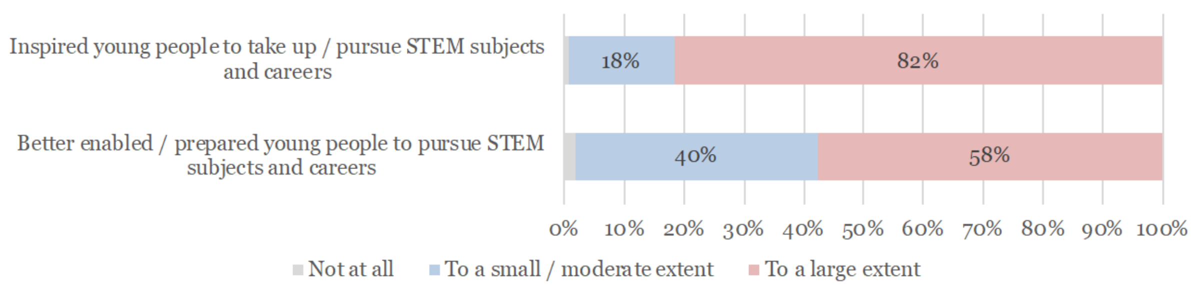
Three quarters of respondents felt that CERN's contribution to overall efforts to increase UK public understanding of and support for science and engineering was 'large' or 'very large'.

Figure 48 CERN's contribution to overall efforts to increase UK public understanding of / support for science and engineering (n=163)



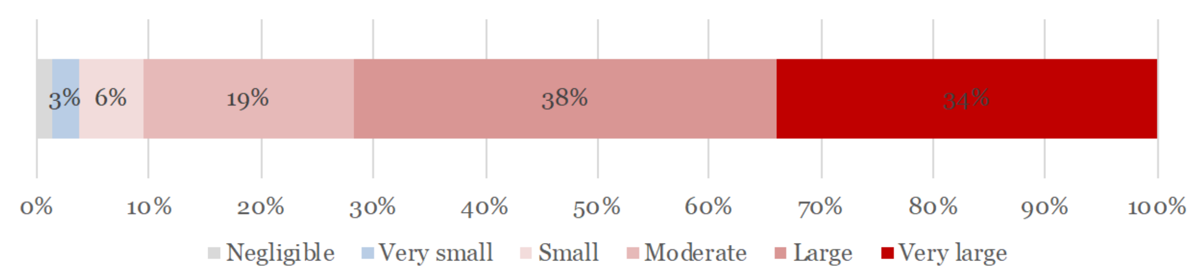
Respondents were also asked about the impact of CERN specifically on young people in the UK, and their **involvement in STEM subjects**. The great majority (82%) of respondents felt that CERN had 'to a large extent' inspired young people in the UK to take up and pursue STEM subjects and careers. A majority (58%) also felt that CERN had, to a large extent, better enabled and prepared young people to pursue these routes.

Figure 49 The extent to which CERN has had an impact on ***UK STEM involvement*** *(n=163-169)*



Indeed, three quarters (72%) of respondents felt that CERN's contribution to overall efforts to increase the uptake of STEM subjects at different levels of education in the UK was 'large' or 'very large'.

Figure 50 CERN's contribution to overall efforts to increase UK uptake of STEM subjects (n=159)



When asked to give **examples of specific CERN-related events or announcements** that had had a significant impact on the UK public (including young people's) understanding, interest or support for science and engineering, the majority pointed to the discovery of the Higgs boson (and associated Nobel

Prize, particularly given the UK role in the Higgs theorisation), while others mentioned the operation of the LHC (the first collision and each restart) and the Future Circular Collider study Design Report.

For instance, respondents remarked:

"I regularly speak to members of the public, some of whom I meet in an entirely non-scientific context, who recall the CERN discovery of the Higgs boson"

"Discovery of the Higgs' boson captured the public imagination. This had a positive impact on the public's knowledge of science and the uptake of STEM subjects."

"The Higgs boson discovery was a major news item almost everywhere in the world."

"People who didn't know me, but knew I was a physicist, would (and still do) ask me about the Higgs boson."

"The Higgs boson - the most important discovery in the history of science and known to everybody (even taxi drivers!)"

"I lecture annually in a Future Learn MOOC on the discovery of the Higgs boson explaining the fundamental theory of the Higgs mechanism and the CERN discovery evidence. It takes around 5000 participants per year"

"The announcement of the Higgs boson discovery at CERN catapulted particle physics to the forefront of the public sphere. Although the media may not have communicated the facts as well as the scientists working on these experiments may have liked, it is hard to deny that the public was flooded with buzz about the 'God particle'"

"The FCC plans were on the front page of the Times"

"Whenever the LHC restarts at higher energies, tabloids typically circulate nonsense articles about the dangers of the LHC. This does however generate discussion about the power of the machine, and encourage people to research how the machine actually works."

"The first collisions at LHC sparked wide public interest, so much so that media web-sites (BBC, Telegraph, CNN) were overwhelmed by the demand for information (given the capacity of the Internet/broadband at the time)."

"The discovery of the Higgs boson brought ideas about fundamental physics to the public like nothing else I've known in my lifetime."

Other events and activities highlighted by respondents included:

- Teacher/school visits to CERN (one respondent mentioned that the impact of this programme of visits was "visible when interviewing incoming undergraduates")
- Public visits to CERN
- The various work of the Institute for Research in Schools (IRIS), encouraging children to be interested in and supportive of science
- The Collider exhibit at the Science museum in London
- Particle Physics Master-classes
- The appearance of CERN in school text books

- CERN's use of social media (to allow the public to engage directly with scientists)
- CERN's proactive approach to getting information into "traditional" media.

C.1.11. CERN's uniqueness

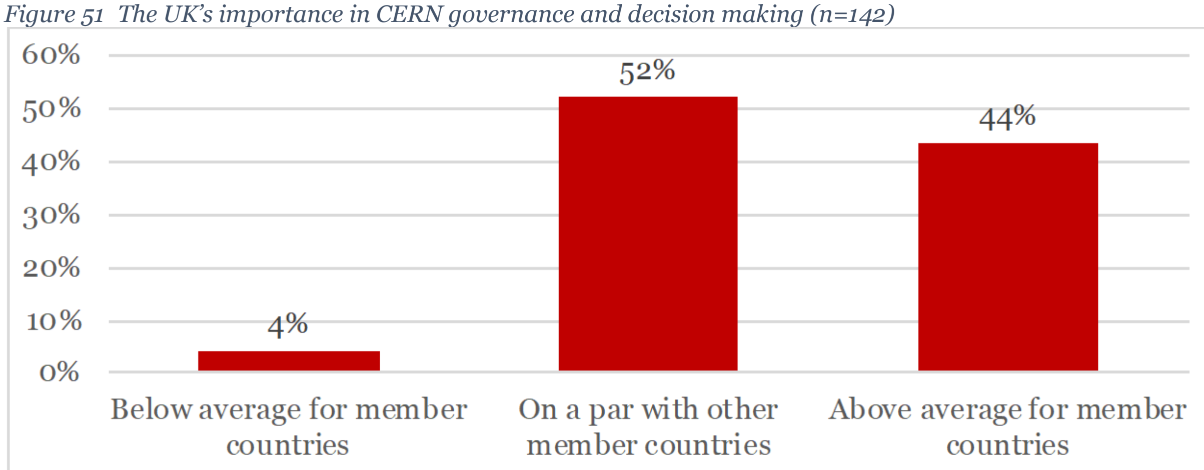
Respondents were asked whether the nature of CERN offered anything unique or special (i.e. that other international bodies and platforms don't do, or don't do so well) in terms of **bringing together different individuals, organisations or countries**. A large number of comments were given, which we have attempted to encapsulate within the following main points:

- CERN is open to all, regardless of nationality, sex, religion or background
- It exposes young scientists to new skills, opportunities and international working
- It offers a collaborative, rather than competitive environment for working, which inspires and motivates
- It has developed a work culture that makes things happen, on time and on budget, while still operating at the cutting edge
- It provides a truly international centre, rather than a regional/national centre with "add-on" collaboration. It is not dominated by any one country and acts as a diplomatic buffer that prevents debate or ownership drawn on national lines.
- It fosters and demonstrates successful international collaboration – whereby the world comes together to overcome challenges and make progress towards common goals, but yet lacks an explicit political nature
- It acts as an international hub for meeting and interacting with colleagues from across the globe, offering the largest international network, where researchers, engineers and students can come together easily
- It supports the pooling of multi-disciplinary expertise from a wider range of areas and countries than would otherwise be possible, combining new technologies, new experimental discoveries and theoretical explorations
- It provides focus and coherence to entire fields, offering a central hub for areas of science and engineering
- It is the largest scientific organisation performing fundamental research and maintains a strong belief in the advance of fundamental science for its own sake. This 'blue skies' spirit is embedded in the organisation's DNA and is increasingly rare in the modern world of funding allocation and research direction
- It is an unusually open and democratic organisation, with little top-down management, in which all participants are able to pursue new ideas without prejudice. "Vertical" managerial structures exist (and are necessary), but these are not rigid and preserve an element of "democracy" (e.g. electing spokespersons). Objectives are defined bottom-up, all partners are equal, and decisions are consensual.
- It provides the exemplary case of how to arrange scientific collaboration on a long-term and large-scale project. Its long-term stable funding (via the treaty) is unique [contrast with US model and cancellation of the Superconducting Super Collider (SSC)]

C.1.12. Science diplomacy

Most respondents believe that **the UK's importance in CERN's governance and decision making** is on a par with other member countries (52%), or even above average (44%).

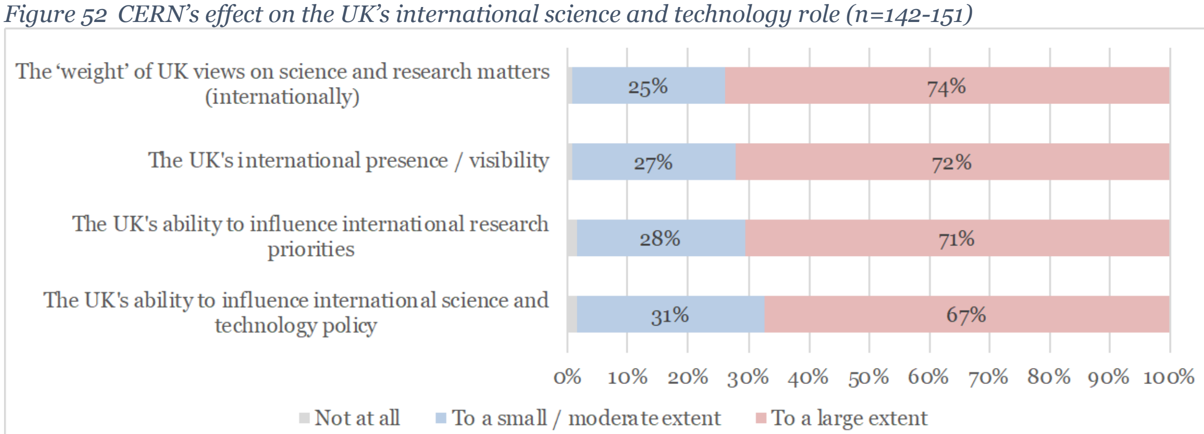
Figure 51 The UK's importance in CERN governance and decision making (n=142)



Most also believe that the UK's membership of / involvement in CERN has a large effect on its **role and place in international science and technology** matters, including is visibility, the weight of its views and its ability to influence policy and priorities.

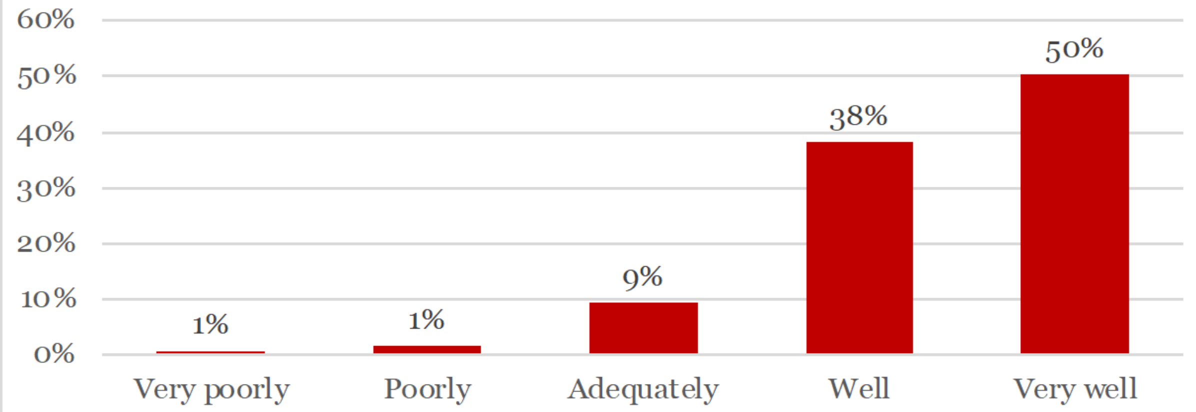
Respondent reported that these effects on the UK's international role were visible, for instance, in CERN Council, in EU strategies (through the role of ESFRI), in the European Particle Physics Strategy Group, through the number of UK scientists invited to speak at major conferences or quoted in the media, in the number of UK representatives on various relevant panels and committees (e.g. the committee for future accelerators), and in the central involvement of the UK in experiments in other countries (e.g. Japan, the USA). They also highlighted prominent UK roles within various CERN experiments, governance and activities, as well as within the management and governance of other facilities (e.g. SESAME and ITER).

Figure 52 CERN's effect on the UK's international science and technology role (n=142-151)



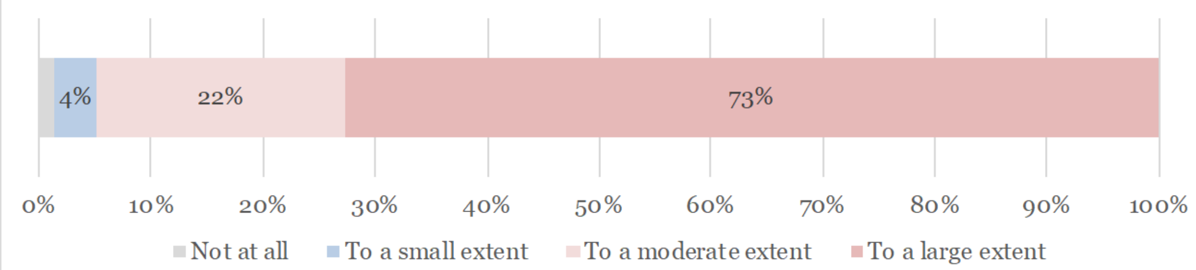
Possibly as a result of this, the great majority (88%) also believe that **CERN's priorities and activities align** 'well' or 'very well' with the UK's research interests and capabilities.

Figure 53 Alignment of CERN's priorities/activities with UK research interests/capabilities (n=151)



The great majority of respondents also believe that CERN is very important in providing a **platform for international diplomacy**, engagement and trust/relationship-building between countries, both for the UK and more generally. Three quarters reported that CERN served this role 'to a large extent'.

Figure 54 CERN as a platform for diplomacy, engagement and trust/relationship-building (n=154)



Some respondents provided additional comments regarding the role of CERN in international diplomacy and relations that bring benefits to the UK.

"The UK has benefited from CERN contributions to the establishment of peaceful scientific cooperation"

"CERN brings together people, and particularly students, from different environments with different cultures to work together to a common goal, advancing human knowledge. This is precious and very valuable for young UK scientists. Where else do Iranians and Americans, Indians and Pakistanis collaborate on common goals."

"CERN's role (with a significant internationally agreed/approved mission) is even more important in the context of Brexit, a rise of nationalism and an emerging breakdown of international cooperation."

"An intangible benefit, easily overlooked, is the model of open collaboration which is very hard to quantify and very likely not easily appreciated. I think that similar

collaborations in important areas, e.g. climate science, would be hugely beneficial but difficult to establish for commercial reasons, i.e. exploitation of IP, and political motives. I would favour attempts to do so, using CERN as a model."

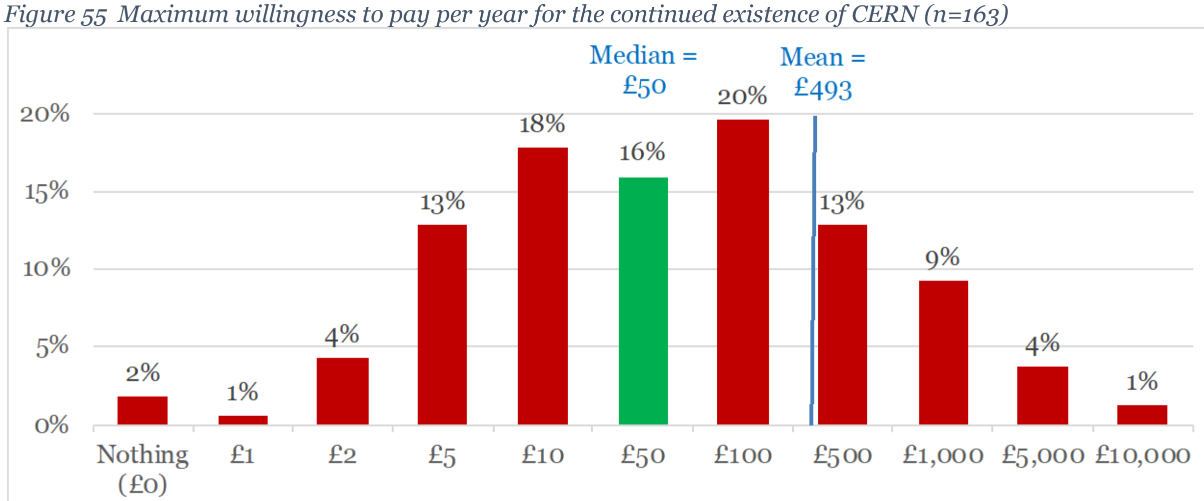
"It is a shining example of what can be achieved via cooperation at the European level. It is an institution which illustrates perfectly why the current political trend in the UK, namely to isolate ourselves for cooperation at the international level, is lunacy."

C.1.13. Valuation

In order to come forward with a monetary estimate of the value of the UK's investments in CERN, and of the knowledge, data and technology produced through its experiments, we invited scientists and engineers to provide a financial view as to the benefits. Specifically, we asked respondents what the maximum is that they would **personally be willing to pay** each year (for the next 20 years) to ensure the continued existence of CERN in its current form (and all of the benefits that flow from it). For comparison, we noted that the UK's subscription to CERN currently costs the average tax payer around £2.10 per person, per year (although we are clearly here not polling the general public, and are instead looking for a researcher-community perspective of CERN's benefits/value).

The spread of responses is shown below. (Note the increasing difference between answer options, left to right). While there is a spread of responses from £0 to £10,000, the majority (53%) of respondents opted for a figure in the range £10 to £100, and indeed the median response was £50. The (mean) average is higher (driven by a relatively small number of multi-thousand pound answers), at £493.

Figure 55 Maximum willingness to pay per year for the continued existence of CERN (n=163)



A handful of respondents raised concerns about the question of placing a value on access to CERN. Their points are noted here:

- *This question needs information about the overall tax allocation that I do not have available*
- *This question will produce biased results. It also requires knowledge of spending of taxation money not available*
- *I pay UK taxes and the government decides on how to use these taxes, according to its priorities and the national interest as it perceives them. I would be happy if 10% of my taxes were allocated to support science and development including CERN.*
- *A lot, but this would depend on how it was paid, and I can't easily imagine that.*

C.2 Survey of suppliers

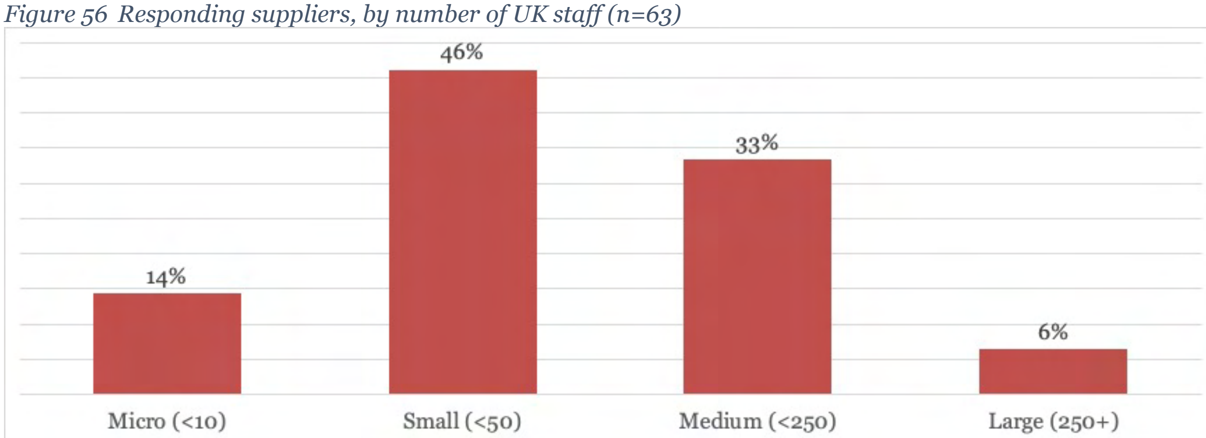
There were **65 useable responses to the supplier survey**. These are respondents who confirmed that their organisation had provided goods/services for CERN (either directly to CERN, or through supplying research groups/institutions on CERN-related activities) and who gave their consent for their answers to be used for the purposes of this study. Questions were not mandatory and so respondent numbers vary by question (as indicated against the relevant chart or table below).

The database of UK contracts valued at over CHF10K suggests that ~500 separate companies were awarded contracts during the 2009-2018 period. Our survey respondents therefore represent 10-15% of UK suppliers over the past decade.

C.2.1. About the responding organisations

Respondents to the supplier survey included organisations with **annual turnover** (where known, n=36[139]) of anywhere between £45K and £62m per annum (£7.8m of turnover each on average). They employ anywhere between 1 (i.e. just the respondent) and more than 5,000 members of staff (152 staff each on average). Most (75%) of the responding companies are **based solely in the UK,** while a further 15% are *predominantly* (i.e. 75%+ of staff) based here. The number of UK staff varies between 1 and 625 (722 on average) per supplier (see figure below).

Figure 56 Responding suppliers, by number of UK staff (n=63)



Nearly all the respondents work within the manufacturing **sector**. However, the sample does include a small number of companies from other sectors (software, consultancy, academia and communications).

C.2.2. About their CERN-related contracts

One third (30%) of the respondents had both (i) been awarded contracts by CERN directly and (ii) been awarded CERN-related contracts by research groups and institutions. A further 67% had only been awarded CERN contracts directly, while 3% had only been a CERN supplier through other institutions.

For simplicity, the questionnaire (and the results presented below) refer to “CERN contracts”. However, respondents were advised that this should be taken to include both sales directly to the facility, as well as CERN-related sales to research groups and institutions.

[139] We have removed one outlier from this first sub-section of analysis (a global engineering company headquartered in the UK, with a UK staff of ~40,000 and turnover in the billions of pounds) as it heavily skews the averages presented.

Those who had been awarded a contract through one or other route were asked about the total number and the total value of contracts awarded. Within our sample of organisations (n=60), **2,337 CERN contracts** had been awarded (2,153 from CERN, 184 from others). The number of contracts obtained by each organisation varied between 1 and over 700, with ~39 contracts each on average.

The responding suppliers are split between those that were **awarded their first CERN contract** in the last 5 years (45%), those that began working with CERN in the decade before this (33%), and those that have been working with CERN for longer (23%) – in some cases back to the 1960s.

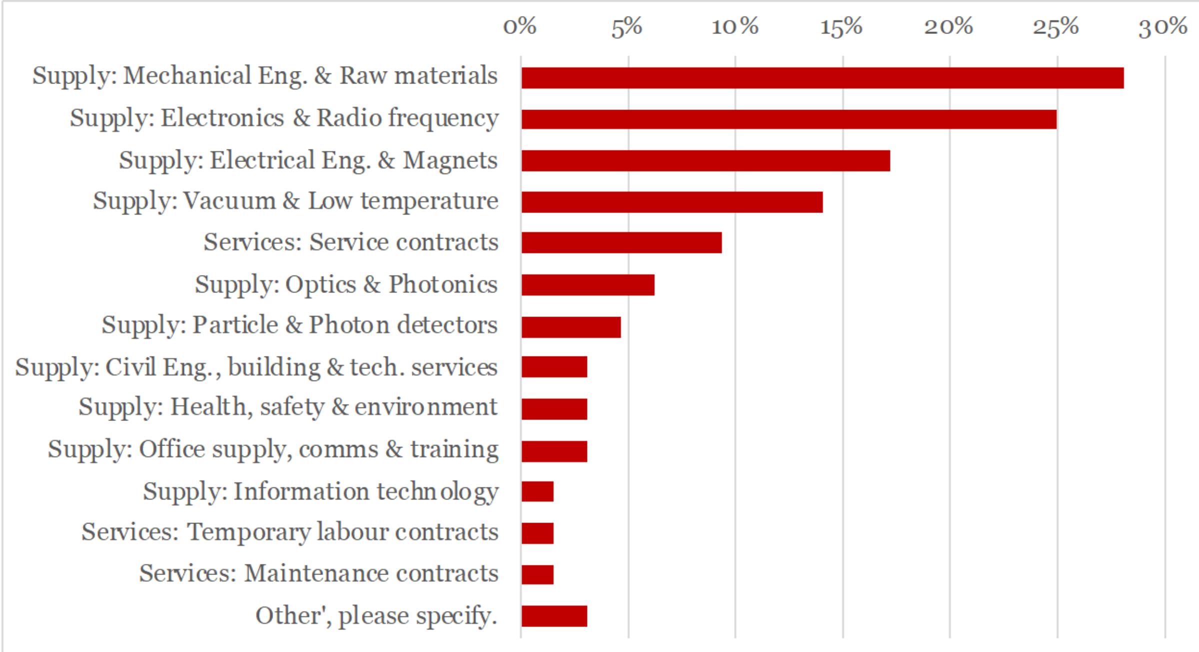
Together, contracts awarded to responding suppliers (n=58) were **valued at over £78m** (mostly from direct CERN contracts). On average, each of the respondents had received £1.4m in CERN contracts in the past, although this varied considerably between individual suppliers, from just £1K to £40m. The average size of an individual contract within this sample was £34k.

Table 21 Number and value of contracts awarded

Number of contracts (n=suppliers)	**Contracts from CERN** (n=58)	**CERN-related contracts from other institutions** (n=20)	**All CERN-related contracts** (n=58)
Total contracts awarded	2,153	184	2,337
Average number of contracts (where >0)	37	9	39
Range	1 - 700	1 - 56	1 - 700
Value of contracts	**from CERN**	**from other institutions**	**All contracts**
Total value of contracts awarded	£71.9m	£6.7m	£78.7m
Average total value to a supplier (where >0)	£1.3m	£0.4m	£1.4m
Range	£1k - £40m	£1k - £3m	£1k - £40m
Average value of a single contract	£33k	£37k	£34k

Respondents were asked to select one or more **categories** that best reflected their CERN contracts. The categorisations employed by CERN were used. The following figure shows that there are a reasonably wide spread of supply and service contracts covered by respondents, although supplies of electronics, mechanical and electrical engineering were most frequent.

Figure 57 Main categories of CERN contracts (n=64)



The vast majority (92%) of respondents anticipate **tendering for CERN contracts again in future**, including 63% who stated that they would "definitely" do so. The small number (n=4) who indicated that they would not tender again, pointed to the length or complexity of the tendering process or to restrictions around the location of supply / manufacture, as reasons for this.

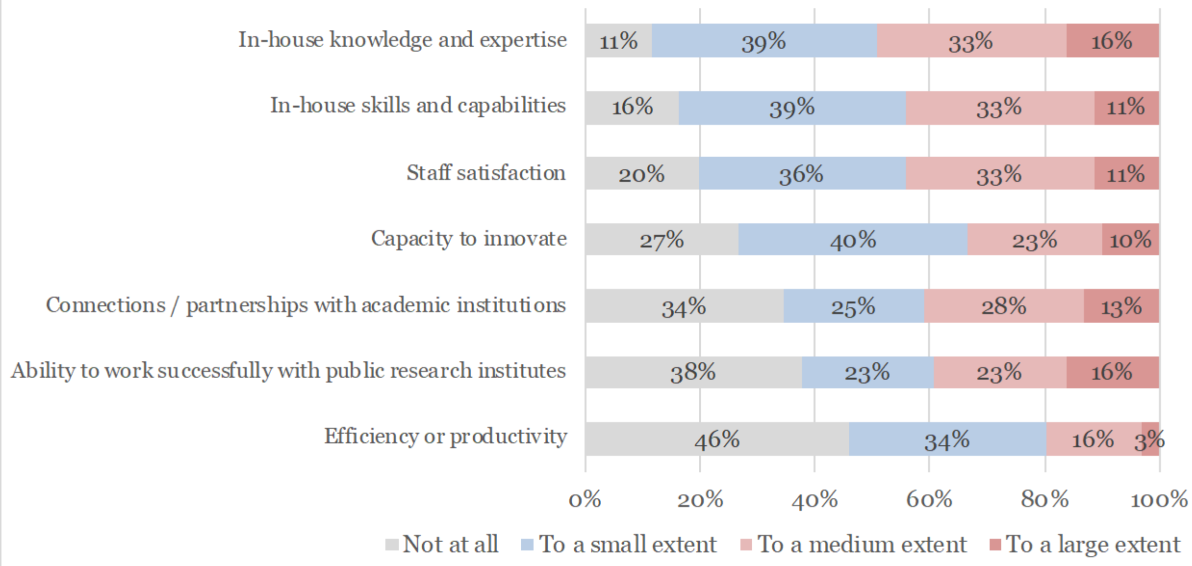
C.2.3. Effects of CERN on the organisations

Suppliers were asked about the extent of **improvements** in various aspects *within* their organisation, as a result of past CERN contracts. A majority reported at least some improvement in each of the seven areas addressed. In particular, around half of suppliers have seen medium/large improvements in: knowledge and skills within their organisation; and in staff satisfaction.

Around three quarters of suppliers have seen some increase in their capacity to innovate, as a result of CERN contracts, while over half have seen some improvement in their efficiency or productivity.

Other aspects mentioned included improvements seen in attention to detail / quality control, the ability to apply techniques (from elsewhere) to CERN, and the additional prestige and confidence that had been felt as a result of working with such a high-profile customer.

Figure 58 Extent to which past CERN contracts have led to improvements within the organisation (n=61)



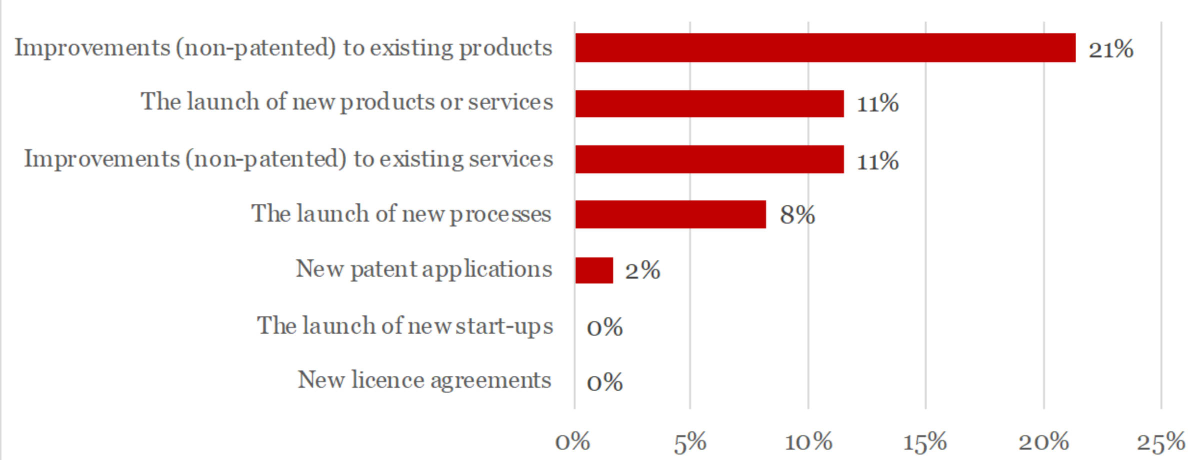
Some suppliers provided further insight into the specifics of the improvements seen within their organisation. For example:

- <u>In house knowledge / expertise</u>: "It has developed our expertise in the design and manufacture of large multichannel cryogenic transfer lines and complicated valve boxes"; "The knowledge and expertise gained has allowed us to develop products for other larger markets"; "While the design itself may not be used again, knowledge from it has been helpful"; "Increase in technical awareness and integrity of the fabrications".
- <u>In house skills and capabilities</u>: "We were able to work with like-minded engineers and scientists on product development"; "The increased skills in the machining of new metals (for the manufacture of CERN components) has enhanced capabilities across all internal sectors of our business"; "We focus on aspects which we previously deemed to be normal and low risk, to double check and plan based on risk"; "It has pushed us to develop additional manufacturing capabilities and skills"; "We have seen improvements to our quality processes"; "Our level of attention to detail".
- <u>Staff satisfaction</u>: "The CERN name encourages recruitment candidates to want to work with us"; "Supplying CERN means you are good at what you do and the goodwill/satisfaction is great for staff morale"; Working as a supplier to CERN provides a feeling of prestige and value amongst the workforce, it is good to be able to feel that one is contributing to worthwhile discoveries even if in only a small way".
- <u>Capacity to innovate</u>: "We have innovated to meet ever-increasing demands on our manufacturing technology"; "We were able to successfully apply techniques to CERN programmes which had been developed in another area of application"; "Working with CERN has enhanced our ability to innovate. - the vastly different requirements have enabled us to look at other manufacturing processes, that have not previously been required".
- <u>Connections / partnerships with academic institutions:</u> "CERN represents a large body of scientists from many fields and backgrounds"' "We have been very impressed with the CERN links and the ability to share project opportunities".
- <u>Ability to work with public research institutes</u>: "Continually encourages us to improve both internal and external processes."; "The interface with a high-profile customer like CERN has given excellent confidence to our business"; "We have seen new materials come through, testing procedures, and have gained an understanding of what CERN does for the world, and how we could be part of that".

C.2.4. Innovation and commercial benefits

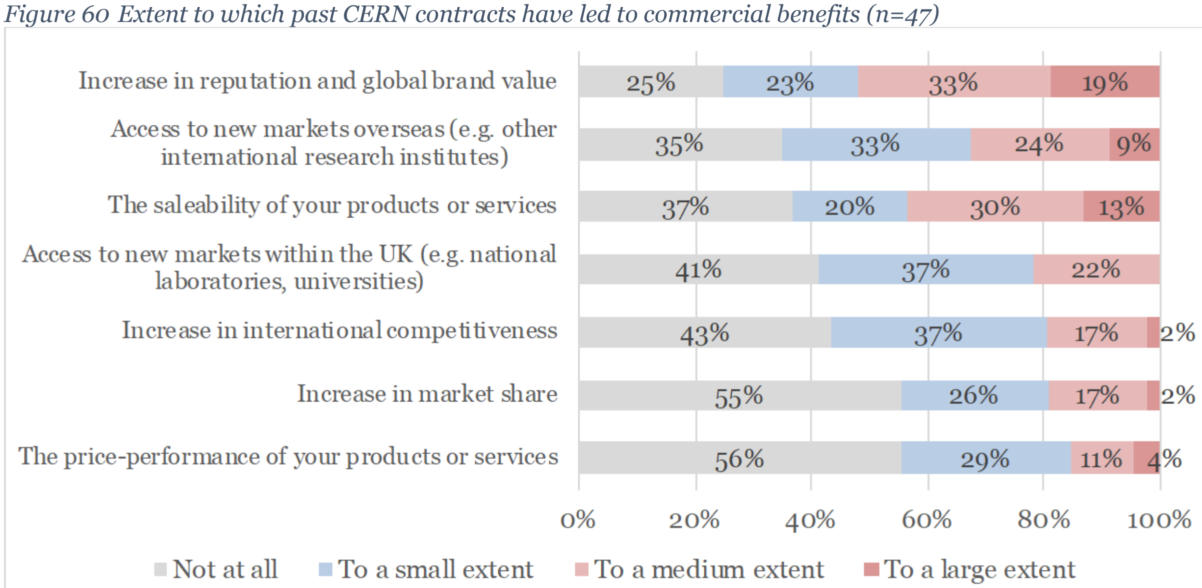
Suppliers were asked whether their CERN contracts had also led to any of a series of **innovation-related benefits**. As the figure below shows, around one-third of respondents had seen improvements to *existing* products and / or services, while ten respondents reported the launch of *new* products and services and / or new processes, flowing from their past work with CERN. One also reported a patent application.

Figure 59 Whether CERN contracts have led to innovation benefits for UK suppliers (n=61)



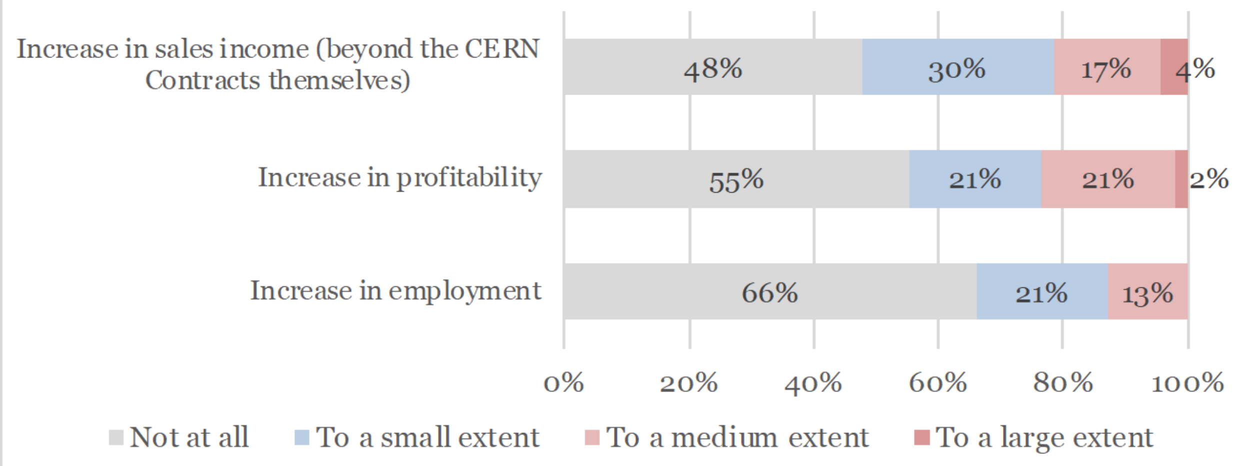
Respondents were asked about the contribution of past CERN contracts to a range of **commercial benefits.** In most cases (75%), there has been some benefit for the suppliers' reputation and global brand value. In addition, between a half and two-thirds of respondents reported an impact on their access to new markets (in the UK or overseas), on their international competitiveness and on the overall saleability of their products or services. Just under half reported benefits in terms of market share or price performance.

Figure 60 Extent to which past CERN contracts have led to commercial benefits (n=47)



They were also asked about the impact on their bottom line. Over half (52%) reported an increase in sales income, beyond their CERN contracts, while a similar proportion (45%) reported an increase in profitability. Around one-third has also experienced some increase in employment that was attributable to past CERN contracts. Indeed, when asked to point to the most important commercial benefit of having been a CERN supplier, most respondents pointed to: the commercial income from CERN contracts; the prestige, recognition and status this afforded them; the exposure to international clients it provided; and to the additional sales and income that resulted.

Figure 61 Extent to which past CERN contracts have led to financial benefits (n=47)



Just over half (59%) felt that it would not have made any difference (i.e. the CERN contracts had not had any wider impact on sales, beyond the value of the contract itself). In the remaining cases, respondents believed that their current annual turnover (from non-CERN contracts) had been boosted by anywhere between 2% and 28%, as a result of their past work for CERN. The largest estimated increase (+28%) was from a company that had been a supplier to CERN for several decades and had received millions of pounds worth of CERN contracts in total over this period. Across the sample, the average impact on turnover was thought to be around +4%.

Below, we quote some of the comments provided by respondents explaining the wider commercial benefits of being a CERN supplier:

> *Our company would not have grown as much if we had not made our CERN-related sales [electro-magnets supplier]*
>
> *We are now in discussion with other universities about providing similar support [printed circuit board supplier]*
>
> *We are an SME and want to publicise the fact that were chosen by CERN for such a prestigious contract award. It offers prestige and endorsement [electronics supplier]*
>
> *CERN provided an introduction to others requiring our products and technical skills [machined component supplier]*
>
> *The reputational benefit (and seeing our product in use by CERN) has allowed us to make sales to commercial and other academic customers. The experience with CERN also enables us to do a better job with subsequent customers. There are years when*

supplying to CERN has lost us money, but we believe the benefit outweighs the cost [software supplier]

Improvements in in-house knowledge and expertise has allowed us to develop products for other larger markets. We now manufacture 1,000 units per year and generate around £20m annual revenue supporting 100 jobs [magnet supplier].

Without CERN, we would have had to chase smaller value sales in riskier areas [manufacturer].

The opportunity has helped us to develop new materials and processes, and we have been able to showcase our expertise, which has resulted in additional sales [precision engineering supplier]

CERN has increased our visibility in the market place, improved our sales revenue and contributed to annual growth of the business [manipulation product suppliers]

The CERN name impresses our clients and potential clients in the STEM sectors. Without our past contracts, it would have taken us longer to get where we are today [communications supplier].

CERN has agreed to the use of their name in our advertising flyers which will increase customer confidence and hopefully boost orders [vacuum technology supplier].

In the 1990s in particular, CERN work allowed the company to establish itself. The company might not have survived in the early years. Now we are sustainable without CERN work. [manufacturer of meters and probes]

Our interactions with CERN reflect well on us as a company (prestige) and successful supply of equipment increases awareness of our company and its products among scientist and engineers working in lasers and optics so is good for future business opportunities. [electro-optic supplier]

As a result of CERN contracts, we have been able to successfully offer services to ITER – so far worth £80k [design consultancy]

C.2.5. Valuation (willingness to accept)

Building on questions of commercial benefit, suppliers were asked to put a **financial value to the wider benefits of being a CERN contract**. Specifically, they were asked what the minimum amount would be that their organisation would accept as compensation for not being able to bid for any further CERN contracts. With this, the study is attempting to capture the additional value to suppliers, above and beyond the cost of supply (in the form or profit, additional sales elsewhere, improved knowledge, or any other benefits that companies derive).

Those suppliers who felt able to respond to this question (n=33) gave answers varying between £0 (i.e. where supplying CERN provides negligible additional benefit beyond the value of contracts) and £3m per annum (in this particular case, the organisation has received on average £1m-worth of contracts per year from CERN). On average, suppliers would be willing to accept £138k per year (although this average is heavily skewed by one supplier – without whom the average falls to £48k).

The figures given represent between 0x and 7x the average annual contract value to the businesses concerned, with a multiple of 1x on average. This suggests that the value of being a CERN supplier is considered, on average, to be double the annual direct income they receive from CERN contracts (i.e. worth the direct income from the contract, plus the same value again).

Appendix D Bibliometrics analysis

This Appendix presents the findings of a bibliometric analysis subcontracted to Science-Metrix. It begins by providing an explanation data sources and indicators used for the analysis. A general overview of research performance at national level is then given, followed by sub-sections that consider three of the four main impact areas addressed by the study (relating to research, innovation and science diplomacy).

D.1 Data sources

This project was executed primarily on the **Scopus bibliometric database** (produced by Elsevier, the parent company of Science-Metrix). The Scopus database indexes about 22.5 million papers published 2008–2017; these appear in some 25,000 peer-reviewed journals indexed in Scopus, in addition to many published conference proceedings. The database offers comprehensive coverage of the most-cited scientific literature in the natural sciences and engineering fields. As part of Science-Metrix' routine database preparation process, the journals and proceedings in Scopus are assigned to our taxonomy of science. This three-level taxonomy divides scholarly research into 6 domains, 22 fields and 176 subfields.[140]

To identify **CERN publications** within the Scopus data, three approaches were used:

- CERN Document Server: As part of its online presence, CERN maintains the CERN Document Server (CDS), a repository of journal articles, conference papers, books, presentations, reports and other types of media touching on particle physics and related technologies. Most, but not all, of these items are connected to the activities of CERN. In total, the CDS contains more than 660,000 items. For the purposes of this project, we extracted data from the CDS collection entitled "CERN Published Articles," which contains about 95,000 items including both journal articles and conference proceedings. These items were extracted in JSON format and cross-linked to the Scopus database.
- INSPIRE HEP: This is a high-energy physics literature database maintained by a group of organisations active in physics research, including CERN. Entries are tagged by institution, and there are approximately 62,500 entries associated with CERN. Science-Metrix extracted these entries in MARC-XML format, parsed them, and cross-linked them to the Scopus database.
- Additional enrichment with Scopus: Any papers within Scopus that listed CERN as an affiliation address (but that were not in the CDS and INSPIRE HEP lists) were also added to the set.

Publications were de-duplicated (i.e. to remove cases where the same publication was identified multiple times). Those papers published outside the period of analysis (1997-2017) were also excluded. In total, 40,740 CERN articles published over the past 20 years were identified.

Additionally, **patent data** was used for the technometric analysis components. Science-Metrix used the PATSTAT database, which covers patent data from over 150 offices worldwide and has been formatted especially for statistical work and is widely used to measure patent activity at the world level. Data from the European Patent Office (EPO) were used, as this was considered to be of highest relevance to the project. Patent data were used in two ways, requiring two types of data preparation. First, citations to non-patent literature were matched to the Scopus database to enable the measurement of patent uptake of published research. Second, patents that build on CERN activities were identified; this was accomplished by using the Google Patents search engine, which was used to identify patent applications that made mention of "CERN" and variants of its name in their description.[141] The list of patent IDs was cross-referenced to Science-Metrix' implementation of PATSTAT, and complemented with a list of patents where CERN is listed as an assignee and therefore formally holds the IP.

[140] http://science-metrix.com/?q=en/classification

[141] Identification of patents mentioning CERN was initially planned to proceed through the use of RegEx case-sensitive-queries for the names of CERN experiments and applied to EPO patent applications' abstracts. This strategy could not be conducted as initially planned, however, because mentions to CERN and its experiments appeared to be overwhelmingly restricted to the description section of patent applications, and PATSTAT does not include full-texts from the description sections of EPO patents.

D.2 Indicators

The following indicators are used in the analysis.

Publication output volume

Number of publications, using full counting: This indicator shows the number of publications for a given entity. Each country that has a researcher on the list of authors gets a full count (1 publication) for that paper. E.g. if a paper is authored by two researchers with addresses in the UK, one from Spain and one from the US, the paper will be counted once for the UK, once for Spain and once for the US.

Number of publications, using fractional counting: An alternative method for counting articles that divides publications based on the proportion of authors from a country contributing to that article. In the above example, the publication is divided into four parts, with the UK receiving two parts (0.5 publications), Spain receiving one (0.25 publications) and the US receiving one (0.25 publications).

Data based on full counting indicate only which countries are involved in the production of an article, whereas fractional counting provides an indication of the share of work contributed by a given country.

Growth ratio (GR): Measures the rate at which a given entity's production changed between two ranges of years (here, between 2008–2012 and 2013–2017). A GR of 1 indicates no change, a GR above 1 indicates growth, and a GR below 1 indicates decreased production. Because the GR does not show the yearly fluctuations, output trend data for each entity is also included as a bar graph in the results tables.

Growth index (GI): The GR of a country divided by the GR of the world. E.g. if a country has increased production by 32% (GR=1.32) in a given area, and the global output in that area has increased by 10% (world GR=1.10), then the country's production has been growing 20% faster than that of the world (GI = 1.20).

Specialisation index (SI): This indicates how much research output a given entity produces in a field or subfield, relative to the global average in that field. E.g. if 20% of a country's publications are in physics, but only 15% of papers globally are in physics, then the country is said to be specialised in physics. The SI reference value is 1 (i.e. the world level is always equal to 1); accordingly, an SI above 1 shows that an entity produces proportionately more output than the average in a given area. Three points are worth noting here: (i) these proportions of publications are computed relative to all publications in the database used; (ii) countries that produce large output volumes (e.g. the US, China, the EU) represent a large share of the global total and so it is difficult for them to stand out from the global trend (their performance plays an important role in constituting the reference value); and (iii) the SI is a zero-sum game because it is measured as a proportion of total output. If the proportion of an entity's output in one area increases, there must be relative decreases elsewhere. Accordingly, one cannot be specialised in all areas at once.

International collaboration

International collaboration rate (CR): A measure of how many articles are co-published with international partners (i.e. with at least one author from another country) as a proportion of the given entity's total output.

Mean and median number of collaborating countries: Because physics is an area of extremely strong international collaboration, with many very large international projects, computing the CR tells only one facet of the story. E.g. a paper that involves 2 countries or 22 countries would be treated exactly the same way through the CR. In light of the fact that participation in large international consortia is an interesting and distinct storyline — one that is observed frequently when measuring physics research — the CR indicator is complemented here with the mean and median number of countries involved in a set of papers.

Collaboration index (CI): There is often a power law relationship between an entity's number of papers and its number of international co-publications. In cases where a power law relationship exists between two variables, it is better to use scale-adjusted indicators instead of percentages to appropriately take account of the relative size of entities being compared (as percentages assume a linear relationship).[142] When both indicators are log transformed, power law relationships can be analysed using linear regression models. Therefore, the approach used to compute the CI consists in performing a log-log linear regression analysis between the number of co-authored publications and the number of publications at a specific aggregation level (e.g. countries) in order to estimate the constants (a and k) of the power law relationship: *Expp (M) = a *(M^k) [Where Expp = The expected number of co-authored papers of an entity (e.g., a country) based on the regression model; and M = The observed number of publications of the entity (e.g., country) being measured.]* The indicator is simply the ratio of observed to expected international co-publications. When above 1, an entity produces more publications through international partnerships than expected.

<u>Collaboration affinity (CA):</u> In the above explanations, the concept of the CI is applied to international co-publications irrespective of the countries with which a given country collaborated; in other words, the countries' total number of international co-publications (across all countries) are regressed against their total number of papers. The indicator informs on the propensity of a given country to co-publish with international partners (irrespective of their location) accounting for the size of its scientific production. In the current study, the CI is applied to international co-publications with a specific country (e.g. the UK); in other words, the countries' number of international co-publications (with the UK) are regressed against their total number of papers. The indicator informs on the propensity — the CA — of the UK to co-publish with other countries, while accounting for the respective size of their scientific productions. A score above 1 denotes a positive affinity of the UK toward a given country, while a score below 1 denotes a negative affinity. A regression analysis is performed for each country on the y-axis (i.e. once with the co-publications with the UK, then with France, and so on). This way, it is possible to obtain an asymmetric view on the CA. From the regression with the UK's co-publications on the y-axis, we get the CA of the UK toward France and from the regression with France's co-publications on the y-axis, we get the CA of the France toward the UK. Note that the fit (i.e. the squared correlation coefficient) of the regression model to the data must be equal or higher to 0.75 for this indicator to be computed. While it is possible to compute the affinity of the UK toward most countries, it is not always possible to compute the affinity of all countries toward the UK. Also note that scores are not reported for countries with fewer than 100 papers.

<u>Centrality in international co-publication</u>: A collaboration network is defined using organisations as nodes, and collaborative publications between authors at those organisations as the edges connecting these nodes. The PageRank indicator offers a robust measure of the importance of each node within that network. In particular, it integrates three elements: (i) the number of nodes to which a given node is connected; (ii) the intensity of that connection (i.e., how many co-authored publications they share); and (iii) the importance of those partner nodes within the network. PageRank scores were normalised against the highest performance measured, in the absence of a readily available world reference level.

Scholarly impact

<u>Relative citation (RC) scores:</u> Counting citations can be used as a proxy for measuring contributions to subsequent knowledge generation; however, because citation practices vary between scientific disciplines, simple counting would create unwanted biases in the results. To correct for these potential distortions, individual publications are evaluated relative to the average citation rate for publications in the same subfield and published in the same year. This is known as the RC rate. For all citation-based measures, a certain amount of time must be allowed for the published work to have an impact on subsequent research and for articles to be cited. A recent analysis conducted at Science-Metrix shows that only a small handful of subfields reach citation peak within two years; that is to say, citation attention for papers is still continuing to increase even several years after publication, and therefore a measurement taken too early risks not effectively reflecting the total attention that a body of work will receive. For this reason, Science-Metrix did not compute impact statistics for papers published in 2016 or later.

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[142] J. Sylvan Katz, "Scale-Independent Indicators and Research Evaluation," *Science and Public Policy* 27, no. 1 (2000): 23–36.

Average of relative citations (ARC): The average of the RC scores of all the articles published by a given entity. The ARC is normalised to 1, meaning that an ARC above 1 indicates that the entity's articles have higher-than-average impact. Because RC scores are known to be skewed in their distribution—with a small number of papers receiving a large share of the total citations—the ARC offers a useful snapshot of overall performance but can hide important underlying nuance. For this reason, the ARC is complemented with additional impact indicators that communicate the underlying distribution of scores (e.g. HCP measures).

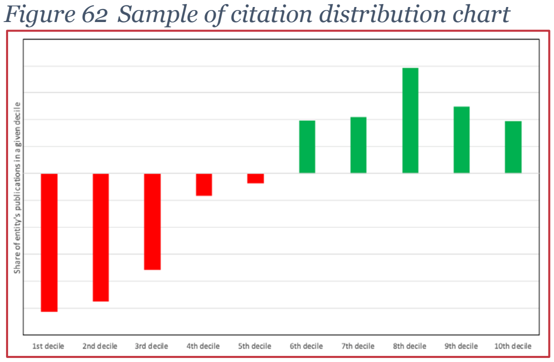
Average of relative impact factors (ARIF): The impact factor (IF) of each journal in a given year is measured by counting the total number of citations received in that year by the papers that appeared in that journal in the previous five years. The IF is then obtained by dividing the total number of received citations by the number of articles that appeared in that journal in the previous five years. To account for the differences in citation practices across disciplines, the IF for a journal in a given year is adjusted relative to the average IF of other journals in the same subfield and year. Every published paper is given the IF score of the journal in which it is published. The ARIF of a given entity is simply an average of the IF scores of its articles, relativised to the disciplines in which they are published. The ARIF is normalised to 1, meaning that an entity with an ARIF above 1 publishes in higher-than-average-impact journals.

Highly cited papers (HCP): These have the highest RC scores in their respective field. The indicator is used to examine research excellence (how many high-impact articles are produced by an entity, relative to their expected contribution). Contributions to the top 10%, 5% and 1% of publications are measured.

Citation distribution chart (CDC): This tool facilitates a simple but nuanced visual inspection of an entity's research impact relative to worldwide performance. To prepare the charts, we divide all publications in a research area into 10 groups of equal size, or "deciles"[143] based on their RC scores. The 1st decile contains the 10% of publications with the lowest RC scores; the 10th decile is the 10% with the highest RC scores. For a given entity, it is expected that the RC scores of publications will follow the global distribution, with an equal number of publications falling in each of the deciles. The CDC compares the entity's scientific impact by showing how its performance compares to the world level in each of the deciles.

In the example below, the CDC shows 10 colour-coded bars for a hypothetical entity; each bar represents the relative presence of this entity's papers in each corresponding decile. The world level, in contrast, is represented by the central horizontal line, with no bars, as it represents the uniform distribution of all the publications across the 10 deciles. The bar's colour shows whether the specific entity has more or fewer publications in that decile than expected (i.e., the horizontal line). A green bar denotes production exceeding expectation in that decile, a red bar denotes production below expectation in that decile.

Figure 62 Sample of citation distribution chart



Source: Prepared by Science-Metrix

[143] Two adjustments are made in order to ensure high-quality results, and these pertain to (a) cases where a number of publications are tied in their scores, and (b) cases where the total number of publications is not divisible by 10. For (a) papers tied at the margin of two deciles will be grouped together and then divided proportionately to ensure that each decile contains the right number of papers. In (b) papers will be fractioned to ensure that the deciles are always of exactly equal size.

The length of the bar shows how far above/below expectation the entity is in that decile. The longer the red bar, the fewer articles that are found in that decile relative to expectation. Conversely, the longer the green bar, the more publications are found in that decile, relative to expectation. Cases where a decile has no bar associated with it show that the entity's performance is exactly in line with expectations based on global performance. Accordingly, a CDC with no visible bars shows that the entity in question has 10% of its papers in the 1st global decile, 10% of its papers in the 2nd global decile, and so on, which, as previously noted, corresponds to the world distribution of papers based on their RC scores.

Ideally, one hopes to have more papers than expected in the highest deciles (where the most impactful publications are found) and fewer papers in the lowest deciles (where the least impactful publications are). Thus, strong research performance is shown by long red bars on the left of the CDC and long green bars on the right. In contrast, weaker research performance is depicted with long green bars on the left and long red bars on the right. The figure below presents various distributions for best-case and worst-case scenarios.

Figure 63 Various scenarios of citation distribution charts and their citation distribution index

Source: Prepared by Science-Metrix

The citation distribution index (CDI): The CDC can also be summarised numerically using the CDI. For each decile, the performance of a given research organisation is compared to the global average, and this ratio is then multiplied by a weight corresponding to that decile. Once a score has been produced in this fashion for each decile, the scores are summed to calculate the CDI. Thus, having a higher-than-expected number of publications in the 1st decile (the lowest-impact decile) will reduce the CDI more than having a higher-than-expected number of publications in the 2nd decile. The CDI ranges from -50 (worst-case) to 50 (best-case) with 0 representing parity with the world level. Compared to mean-based normalised citation metrics, the combined use of CDC and CDI makes it possible to provide reliable citation metrics even when dealing with entities having produced few publications (from 10 to a couple of hundred).[144]

Table 22 Decile weighting to compute citation distribution index

Decile	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Weight	-5	-4	-3	-2	-1	1	2	3	4	5

Source: Prepared by Science-Metrix

Patent indicators

Number of patents, using full counting: This indicator shows the number of granted patents for a given entity. Patents were counted at the national level for both inventors and assignees (i.e. those who create the IP and those own it). Using the full counting method, each country that has an inventor or an assignee associated with a given patent gets a full count (1 patent) for that patent.

[144] David Campbell et al., "An Approach for the Condensed Presentation of Intuitive Citation Impact Metrics Which Remain Reliable with Very Few Publications," in *Proceedings of the 21st International Conference on Science and Technology Indicators*, ed. Ismael Rafols et al. (Valencia, Spain, 2016), 1229–1240, https://doi.org/10.4995/STI2016.2016.4543.

D.3 General context

Before examining the outcomes of CERN research in the UK, it is useful to secure a broader understanding of the Laboratory in the international landscape of the natural sciences.

Given that a large share of CERN publications are found in the scientific subfield of Nuclear & Particle Physics (NPP), a first international comparison exercise (section D.3.1) is presented specifically for publications in this subfield. In a second exercise (section D.3.2), a broader context is examined by including publications in the 15 subfields where CERN is most active (referred to as the S15 analysis going forward).

In both cases, tables provide an overview of trends in CERN's volume of publications, rates of papers authored as international co-publications, and the citation impact of its research. Temporal changes in performance are also be analysed over four periods (1996–2000; 2001–2005; 2006–2010; and 2011–2015), providing an opportunity to isolate trends or turning points in publication practices. In addition to findings obtained for the whole of CERN, for both NPP and top 15 subfields, performance has also been computed for the full set of world publications in the relevant subfield(s), as well as for country participations in the CERN publication portfolio. The first group of findings provides a reference point rather than a benchmark. The second makes it possible to compare the achievements of UK researchers at CERN with that of contingents from other Associate and member states, and with others with co-operating or observer status.

When comparing CERN performance to country findings, the reader should bear in mind that these entities are not only organisationally distinct (as is obvious enough), but that they will also include different blends of research streams, priorities and classes of experimental instruments. Findings for CERN should not be directly compared to country-level performance. However, careful interpretation and the exercise of sound judgment do allow for the use of comparisons as pragmatic referents to contextualise CERN achievements.

It should also be stressed that results presented in this section are descriptive, whereas the findings in subsequent sections amount to more definitive tests of CERN's contributions to UK research performance.

Finally, it should be noted that country-level output figures discussed below are for findings computed using the fractional counting method. This method divides and weights the attribution of publications to countries according to the number of contributing co-authors' affiliated with institutions from each participating country. Given the very large number of authors (and countries) participating in many CERN papers, this approach can provide a clearer assessment of respective contributions to the publication set. World, CERN and citation metric measures were not computed using this method. Tables will provide publication counts obtained through both full and fractional counting, providing more comprehensive output profiles.

D.3.1. Country-level research performance in Nuclear & Particle Physics

CERN-associated publication practices are highly concentrated in one specific scientific subfield: Nuclear & Particle Physics (NPP). Indeed, more than 77% of the 40,740 CERN publications retrieved were assigned to the NPP subfield as per the Science-Metrix classification. Therefore, an analysis of performances in this field provides bibliometric profiles of great relevance and precision for understanding CERN achievements, although this gain comes at the cost of restricted coverage (recall) of the facility's activities.

Country-level output and impact outcomes, 1996–2017

Findings presented in Table 23 show that the UK was a leading country in the NPP subfield. It was among the top tier (i.e. top 10) of countries for the volume of its publication output (irrespective of the use of fractional or full counting methods). Within this top tier of largest producers in the NPP subfield, the UK positioned itself as one of the top 3 countries with the best citation metrics.

On the output-volume front, the UK published almost 25,000 papers (fractional counting) between 1996 and 2017. The United States is far ahead of other countries, with almost 100,000 papers. Germany, Russia, Japan, China and Italy also surpass the UK, with counts between 35,000 and 45,000. Out of these seven countries, only two have growth indexes above 1: China and Russia. The other five countries' yearly increases in output lag behind the growth observed at world level, although the UK's performance is the strongest of this group, being nearly tied with world growth level. Relative to other countries, the UK has a slight specialisation in the NPP subfield (specialisation index of 1.18). Switzerland (3.03), Russia (2.57), Italy (2.21) and Mexico (2.09) have the greatest relative portions of output in the NPP subfield.

Almost 67% of UK NPP papers are written as international co-publications, a figure that is a few percentage points above the average but right on the median. Put differently, the UK is among a middle pack of rather collaborative countries, below the highly collaborative (with shares between 70% and 80%), but above a group of countries where authors favour national collaborations (e.g. Iran (27%), China (35%), India (38%)).

Turning to impact metrics, the UK consistently came in third rank within the top tier of large publication volume countries and across the indicators computed. This conclusion held for the ARC (1.66), the CDI (13.3), the $HCP_{10\%}$ (18.0% of papers falling in this category), the $HCP_{5\%}$ (9.6%) and the $HCP_{1\%}$ (2.2%). The only exception is for the UK's performance on the ARIF indicator, where it comes in at fourth rank, together with Spain. Switzerland takes the top spots in the selection of countries now under consideration, always a fair margin ahead of the second best performer, Spain. For example, Switzerland displays an ARC of 1.95, CDI of 14.7 and $HCP_{1\%}$ of 3.3%. Spain's scores were 1.74 on the ARC, 13.5 on the CDI and 2.5% of $HCP_{1\%}$. At the other end of the performance range, China posted an ARC of 0.89, a CDI of -6.2 and an $HCP_{1\%}$ of 1%.

The impact metrics just presented focused on findings for the largest producers of NPP publications. Findings obtained in this analysis are particularly meaningful because the combined effect of volume and impact define the strongest nations and entities in scientific activity. Additionally, it is generally difficult for an entity to maintain a very high impact as production volume goes up. Nevertheless, the group of countries with lower volumes in Table 23 include many of the best performances on citation metrics.

From a broader perspective (i.e. also including countries with smaller productions of NPP publications), the UK is still a leading country on citation metrics, though it falls outside of the top 3. The group of leading countries differs considerably from that found for output metrics, with six smaller European countries (and Spain) displaying the best performances. Countries with stronger citation profiles in the NPP subfield than the UK include Austria, Greece, Hungary, the Netherlands and Portugal, alongside Spain and Switzerland. The UK's citation distribution index (CDI) of 13.3 indicates that the bulk of its publications are tendentially well cited, with the highly cited publication (HCP) findings showing that a sizable portion of publications are also among the most cited in the subfield. By contrast, a country such as Belgium has a higher CDI (14.0) than the UK, while having slightly lower performances on HCP indicators—in other words, its middle range of moderately cited papers is denser than the UK, but it has fewer among the most-highly cited publications.

CERN output and impact outcomes, 1996–2017

As one would expect, CERN's specialisation index for the NPP subfield is a full order of magnitude above that of many of the countries included in the comparison, with output amounting to almost 6% of the world total (1996-2017). Although CERN researchers have intensified their publication activities between the first and second halves of the period (growth rate of 1.57), this trend is nevertheless slightly under the trend at the world level. This slight lag in growth is captured by the Centre's growth index measure of 0.95.

Almost 62% of CERN papers are written as part of international co-publications. While this is high, it might contrast with expectations of the "archetypal" CERN paper as containing hundreds of authors originating from multiple countries. In fact, many countries have higher shares of international co-publications in NPP.

On citation metrics, CERN achieves performances that are above world levels, especially for the three HCP indicators. Its CDI of 8.2 is higher than the expected score of 0 (world reference) and its ARC (1.72) is slightly greater than for the UK (1.66). However, the UK's CDI (13.3) is higher than that of CERN (8.2). The inversion is certainly due to positive outliers for CERN (highly cited papers that pull up the ARC and have less influence on the CDI). For example, CERN has 2.8% of its papers in the top 1% most-cited papers, compared to 2.2% for the UK. Accordingly, CERN's citations are less evenly distributed than the UK's, pointing to the existence of a greater proportion of highly influential papers for CERN.

While CERN's impact is below that of some of the leading countries in NPP, it should still be noted that the share of CERN output within national portfolios has a much higher impact than that of remaining national NPP publication sets, as will be seen in section D.4.2.

Longitudinal trends in NPP research

Table 24 gives a longitudinal analysis of findings from the CDI, the top 10% most-highly cited publications ($HCP_{10\%}$) and international co-publication rate indicators. From this table, it becomes apparent that CERN's citation metrics have seen some fluctuation over the years. Its 2011–2015 CDI, at 11.4, amounted to a marked rebound from an exceptionally lacklustre performance for the 2006–2010 period (measured at 3.6). Examining disaggregated data (not included in this report), it appears that for the 2006 to 2010 period, the share of papers falling within the 10% and even 20% most cited in their subfield was sharply down, and simultaneously associated with a marked rise in the numbers of articles that fell among the least cited in their field. Performances over the two prior periods remained between 7.0 and 9.0. Fluctuation in the CDI for CERN, particularly between 2000 and 2008, are largely due to the closure of the LEP in 2000 after which the LHC did not start until 2008. Furthermore, the fluctuations may also be attributed to the commonly made observation that high-risk research is frequently associated with uneven citation profiles.

Again for CERN, $HCP_{10\%}$ measurements very slightly decrease from an initial measurement of 15.7% until 2006–2010, followed by a sharp increase (reaching 22.2%). This trend is also seen at the level of the ARC (data not shown), moving from 1.62 to 1.57, to 1.50, and finally up to 2.08 across the four periods.

The UK's longitudinal trends for its citation metrics have been almost uniformly upwards. Its CDI has increased from 11.0 to 17.3 from the first to the last periods, and shares of $HCP_{10\%}$ increased from 15% to 22% (close to the CERN measurements already reported). These performances from UK NPP researchers, however, appear to be part of larger trend in which almost all countries participate. Hungary, for example, has seen its CDI performance move from 11.1 to 21.6 and its $HCP_{10\%}$ measurement from 8.6% to 30.8%. Turkey has seen a negative CDI of -2.1 transform into 14.5, while its $HCP_{10\%}$ moved from 6.2% to 23.3%. France, whose fractional publication output is closest to the UK's, has also seen similar trends to the UK.

No general trend across countries can be isolated when considering shares of international co-publications. UK measurements moved up from 62.9% in the initial period to 69.2% in the final one. By contrast, a similar evolution was of a much more restricted magnitude in France, with scores increasing from 69.0% to 71.1%. Turkey (39.8% to 64.2%), Ukraine (50.3% to 69.6%) and Australia (58.8% to 74.2%) saw the largest increase in shares of international co-publications over the overall period. Romania (79.2% to 64.0%), Iran (34.1% to 28.8%) and Russia (51.5% to 46.3%) saw the largest drops.

Table 23 National research performance in Nuclear & Particle Physics (1996–2017)

Country	Publication output (fractional count)					Publication output (full count)					Intl. collab.	Citation impact						
	Papers	Trend	GR	GI	SI	Papers	Trend	GR	GI	SI		ARC	CDC	CDI	ARIF	$HCP_{10\%}$	$HCP_{5\%}$	$HCP_{1\%}$
World	535,813		1.65	1.00	1.00	535,813		1.65	1.00	1.00	-	1.00		0.0	1.00	10.0%	5.0%	1.0%
CERN	N/A	N/A	N/A	N/A	N/A	31,898		1.57	0.95	14.56	61.7%	1.72		8.2	1.16	17.2%	9.9%	2.8%
United States	98,632		1.16	0.70	1.06	136,768		1.26	0.76	1.19	48.0%	1.56		10.0	1.12	16.8%	9.1%	2.1%
Germany	45,422		1.53	0.93	1.59	76,404		1.61	0.97	1.89	65.8%	1.50		11.1	1.18	16.5%	8.7%	1.9%
Russia	44,146		2.01	1.22	2.57	64,166		1.81	1.09	2.96	47.2%	0.97		-4.9	0.79	9.2%	4.8%	1.2%
Italy	34,744		1.52	0.92	2.21	55,919		1.60	0.97	2.59	62.5%	1.38		7.5	1.12	14.0%	7.4%	1.7%
Japan	40,623		1.48	0.90	1.06	53,180		1.57	0.95	1.21	39.9%	1.17		4.6	1.05	11.5%	5.7%	1.2%
China	38,856		2.77	1.68	0.33	50,531		2.77	1.68	0.40	35.3%	0.89		-6.2	0.88	8.5%	4.2%	1.0%
United Kingdom	24,538		1.61	0.97	1.18	44,800		1.75	1.06	1.46	66.8%	1.66		13.3	1.16	18.0%	9.6%	2.2%
France	23,199		1.74	1.05	1.19	44,090		1.83	1.11	1.54	70.5%	1.59		10.9	1.17	16.7%	9.2%	2.1%
Switzerland	15,204		1.66	1.01	3.03	32,425		1.67	1.01	3.70	75.7%	1.95		14.7	1.21	20.7%	11.9%	3.3%
Spain	12,974		2.14	1.29	1.23	26,457		2.39	1.45	1.74	73.5%	1.74		13.5	1.16	18.5%	10.0%	2.5%
India	18,758		1.85	1.12	0.88	25,183		1.97	1.19	1.06	38.1%	1.08		1.7	1.01	9.5%	4.9%	1.2%
Poland	11,782		1.33	0.80	1.68	22,813		1.49	0.90	2.41	64.5%	1.33		4.7	1.02	13.7%	7.8%	2.2%
Brazil	11,977		1.49	0.90	1.67	18,480		1.75	1.06	2.05	51.6%	1.20		5.1	1.12	11.7%	6.2%	1.6%
Canada	9,273		1.44	0.87	0.78	18,203		1.56	0.95	1.09	69.0%	1.61		12.3	1.11	16.7%	9.1%	2.1%
Rep. of Korea	7,602		2.08	1.26	0.45	13,857		2.17	1.31	0.70	60.4%	1.48		9.6	1.12	14.3%	7.5%	1.9%
Netherlands	4,761		1.51	0.91	0.86	12,027		1.83	1.11	1.35	78.6%	1.98		15.2	1.20	20.4%	11.5%	3.0%
Sweden	4,384		1.53	0.92	1.02	10,544		1.78	1.08	1.54	77.4%	1.74		12.4	1.18	16.5%	9.3%	2.6%
Belgium	4,412		1.62	0.98	1.18	10,327		1.85	1.12	1.74	78.5%	1.72		14.0	1.18	16.8%	9.4%	2.3%
Czech Republic	4,671		2.26	1.37	1.40	10,108		2.57	1.56	2.17	68.2%	1.56		7.3	1.04	16.5%	9.8%	2.9%
Mexico	6,171		1.36	0.82	2.09	9,932		1.69	1.02	2.45	53.3%	1.21		-1.0	0.96	10.5%	5.9%	1.8%
Australia	4,077		1.58	0.95	0.54	8,128		2.02	1.22	0.74	70.1%	1.62		10.3	1.17	16.3%	8.6%	2.1%
Romania	3,501		4.48	2.71	1.31	7,957		2.95	1.79	2.26	68.0%	1.23		2.7	0.95	12.2%	6.6%	1.8%
Portugal	3,538		2.07	1.25	1.33	7,929		2.59	1.57	2.04	76.2%	1.86		15.0	1.18	19.5%	11.2%	3.0%
Greece	3,049		1.62	0.98	1.07	7,677		2.01	1.22	1.91	76.5%	1.83		14.8	1.25	19.7%	11.3%	2.9%
Austria	2,929		1.77	1.07	0.98	7,462		2.17	1.31	1.58	79.6%	1.91		13.7	1.27	18.9%	11.1%	3.0%
Israel	3,714		1.09	0.66	1.29	7,487		1.32	0.80	1.78	68.8%	1.73		12.4	1.23	17.4%	9.0%	2.2%
Iran	5,631		6.60	4.00	0.95	6,926		6.82	4.13	1.05	27.1%	1.03		-1.6	1.00	9.5%	5.0%	1.3%
Ukraine	3,834		1.52	0.92	1.00	7,099		2.01	1.22	1.45	62.1%	1.18		-2.4	0.92	11.7%	6.9%	2.1%
Hungary	2,280		1.51	0.91	1.62	6,446		1.81	1.10	2.83	79.8%	2.08		14.5	1.19	19.0%	11.3%	3.9%
Turkey	3,384		2.20	1.33	0.76	6,169		3.42	2.07	1.16	56.2%	1.48		6.8	1.08	14.2%	8.3%	2.6%

Note: Scale for trends in output are not the same across countries. For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level.

N/C: Not calculated due to insufficient sample size (minimum of 30 papers required). N/A: Not applicable as CERN papers were identified using lists of publications, not addresses, which are the basis for calculating fractional contributions (e.g., a paper with four authors with two from the UK and one each from France and the US would have 0.5 attributed to the UK, and 0.25 each to France and the US).

Source: Calculated by Science-Metrix using data from Scopus

Table 24 National research performance in Nuclear & Particle Physics (1996–2017)

Country	Papers (fractional count)				Papers (full count)				CDI				$HCP_{10\%}$				International collaboration rate			
	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015
World	79,246	98,645	133,923	155,768	79,246	98,645	133,923	155,768	0.0	0.0	0.0	0.0	10.0%	10.0%	10.0%	10.0%	-	-	-	-
CERN	N/A	N/A	N/A	N/A	5,062	5,981	7,095	9,892	9.1	7.3	3.6	11.4	15.7%	15.2%	14.8%	22.2%	66.3%	62.4%	57.9%	59.5%
United States	17,973	23,053	24,720	24,341	23,854	30,519	33,511	35,518	8.3	7.2	11.9	12.4	16.0%	15.6%	17.2%	18.6%	43.2%	43.5%	45.9%	52.7%
Germany	7,305	8,428	11,829	13,414	11,559	14,225	19,116	23,085	9.0	8.7	11.2	15.0	14.4%	15.0%	16.0%	20.0%	63.3%	67.2%	62.4%	66.3%
Russia	6,578	6,140	9,798	12,242	9,928	10,153	14,376	17,800	-3.7	-1.7	-7.0	-6.2	8.0%	9.5%	8.8%	10.2%	51.5%	58.5%	48.6%	46.3%
Italy	5,233	6,797	9,454	9,627	8,203	10,659	14,389	16,217	5.3	6.3	6.3	11.3	10.7%	12.7%	13.6%	18.2%	61.4%	61.3%	58.1%	65.0%
Japan	6,194	8,157	11,600	10,958	7,722	10,339	14,660	14,929	1.5	2.2	5.0	9.2	9.0%	10.0%	12.0%	14.7%	33.6%	38.3%	36.8%	43.0%
China	3,124	5,251	10,145	13,655	4,128	6,910	12,617	17,923	-10.1	-8.3	-7.2	-3.3	5.5%	7.3%	8.0%	10.2%	35.2%	35.5%	31.0%	36.2%
United Kingdom	3,764	4,443	6,616	7,212	6,370	7,922	11,373	13,787	11.0	10.4	13.0	17.3	15.1%	15.7%	17.6%	22.0%	62.9%	66.0%	62.4%	69.2%
France	3,439	4,048	6,081	7,141	6,200	7,538	11,029	13,943	7.9	8.4	10.5	15.2	13.4%	14.5%	16.3%	21.0%	69.0%	71.0%	67.4%	71.1%
Switzerland	2,275	2,663	3,928	4,786	4,972	5,704	7,725	10,249	12.6	11.7	13.8	19.1	18.0%	17.2%	19.5%	26.3%	76.9%	76.0%	70.6%	76.3%
Spain	1,647	1,984	3,441	4,323	3,019	3,845	6,440	9,448	10.3	9.3	13.0	17.6	14.7%	15.5%	17.6%	22.5%	68.3%	71.3%	69.2%	76.3%
India	2,687	3,239	4,125	5,924	3,385	4,232	5,472	8,261	-2.3	-0.4	4.1	3.4	6.0%	8.8%	9.5%	11.8%	32.2%	36.7%	37.3%	40.5%
Poland	1,772	2,776	2,650	3,122	3,388	4,857	4,946	6,519	0.5	-1.4	7.6	11.0	10.1%	9.4%	13.5%	20.2%	63.8%	59.2%	63.5%	67.2%
Brazil	1,739	2,570	2,825	3,352	2,539	3,484	3,864	5,828	-1.3	0.8	5.1	11.0	5.4%	8.1%	10.5%	17.8%	50.3%	43.2%	42.4%	58.1%
Canada	1,511	1,870	2,389	2,601	2,779	3,506	4,539	5,350	7.8	7.2	15.9	16.1	11.6%	13.4%	17.9%	21.5%	65.7%	66.8%	66.2%	71.7%
Rep. of Korea	878	1,330	1,905	2,406	1,537	2,358	3,269	4,543	8.0	6.1	11.3	11.1	12.6%	10.5%	13.4%	17.8%	54.9%	60.0%	57.0%	61.9%
Netherlands	834	856	1,133	1,429	1,728	2,011	2,739	3,983	9.4	11.4	15.2	20.7	14.2%	16.1%	20.4%	26.6%	71.3%	77.9%	76.8%	80.6%
Sweden	705	846	1,012	1,335	1,594	1,820	2,203	3,464	10.4	8.5	10.8	17.2	13.1%	11.8%	14.3%	23.0%	77.3%	73.6%	74.4%	78.9%
Belgium	657	836	1,115	1,290	1,342	1,858	2,421	3,214	11.3	10.8	12.8	18.9	13.0%	13.9%	14.8%	22.8%	73.2%	76.4%	74.9%	81.2%
Czech Republic	537	638	892	1,874	1,079	1,294	1,903	4,072	-0.9	1.6	8.0	12.4	7.4%	9.4%	16.0%	23.0%	67.3%	68.3%	70.2%	66.1%
Mexico	1,027	1,312	1,369	1,653	1,419	1,883	2,104	3,056	-10.2	-5.5	-0.2	7.6	4.8%	5.3%	10.0%	18.4%	45.7%	47.0%	50.2%	59.8%
Australia	648	773	911	1,265	1,020	1,371	1,653	2,826	7.7	4.6	7.3	17.0	11.7%	10.8%	13.2%	24.1%	58.8%	66.6%	65.1%	74.2%
Romania	292	277	953	1,410	853	966	1,686	3,056	6.6	7.0	-5.5	4.2	8.8%	8.6%	6.8%	17.3%	79.2%	86.0%	57.3%	64.0%
Portugal	333	660	932	1,168	689	1,199	1,801	2,920	9.3	8.6	13.5	20.4	9.7%	14.1%	17.0%	26.3%	71.8%	69.8%	72.3%	79.1%
Greece	391	610	849	890	984	1,245	1,764	2,614	13.6	9.1	10.6	21.2	13.4%	13.7%	15.3%	28.9%	77.3%	69.5%	71.0%	80.3%
Austria	489	459	742	891	1,073	1,033	1,568	2,543	8.5	10.6	9.1	21.2	9.8%	13.8%	15.1%	29.1%	79.2%	77.8%	72.8%	81.6%
Israel	756	852	836	917	1,406	1,524	1,588	2,094	12.9	7.1	10.7	17.3	16.2%	12.6%	14.8%	24.0%	65.0%	64.9%	66.4%	73.1%
Iran	155	407	1,293	2,353	211	479	1,490	2,959	4.4	0.1	-0.2	-3.0	11.1%	4.9%	8.6%	10.6%	34.1%	25.9%	20.8%	28.8%
Ukraine	659	649	1,093	1,058	987	1,063	1,667	2,351	-9.3	-4.1	-8.7	6.0	5.0%	7.7%	6.8%	20.4%	50.3%	59.8%	51.9%	69.6%
Hungary	380	433	552	675	1,052	1,039	1,178	2,165	11.1	8.7	10.2	21.6	8.6%	12.0%	15.1%	30.8%	80.2%	77.2%	73.2%	80.9%
Turkey	275	618	787	1,114	364	812	1,133	2,503	-2.1	-4.4	1.5	14.5	6.2%	2.9%	6.1%	23.3%	39.8%	39.4%	42.7%	64.2%

Note: For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level.
N/C: Not calculated due to insufficient sample size (minimum of 30 papers required).

Source: Calculated by Science-Metrix using data from Scopus

D.3.2. Country-level research performance in a broader set of relevant subfields

Despite the marked concentration of CERN publications in one subfield, it is also useful to consider CERN's achievements in a broader context. Of the 40,740 CERN articles published between 1996 and 2017, more than 97% were published in 15 scientific subfields:

- Nuclear & Particle Physics (31,898)
- General Physics (3,641)
- Applied Physics (1,164)
- Astronomy & Astrophysics (731)
- Nuclear Medicine & Medical Imaging (411)
- Fluids & Plasmas (393)
- Electrical & Electronic Engineering (312)
- AI & Image Processing (201)
- Optoelectronics & Photonics (154)
- Energy (153)
- Mathematical Physics (135)
- Distributed Computing (132)
- General Science & Technology (131)
- Materials (130)
- Networking & Telecommunications (103)

The remaining 3% or so of CERN papers were distributed in a long tail of 95 additional subfields. This section will repeat the analyses already presented in the previous one, but using the broader data set of publications belonging to the top 15 subfields (abbreviated to S15 going forward) of CERN publication activity. Doing so, it will provide insights into how CERN's scientific achievements are positioned against a more diverse field of scientific activity. Put differently, an analysis of performances in these 15 subfields provides better coverage (recall) of the full bibliometric profile of CERN, comparisons between country-level performances will have comparatively less precision than the prior analysis.

Indeed, if CERN papers amounted to ~6% of all papers in NPP subfield, they only amount to 0.4% of the 9,700,000 publications in the 15 subfields identified above and published for the period from 1996 to 2017.

Country output profiles

As shown in Table 25, the UK contributed close to 376,000 articles in the S15 between 1996 and 2017 (remembering, that the numbers provided in the text are for results with fractional counting). The country posted a positive growth rate of 1.50 between 1996–2000 and 2000–2017. Only 5 out of 29 other countries showed lower figures on this indicator, however. Indeed, the country's yearly increases in output was below a world trend measured at 2.09. Consequently, the UK's growth index was measured at 0.72, below the world level of 1.0. This finding indicates that the UK is losing ground to other countries in S15.

The United States (with almost 1.7m papers) and China (with 2.1m units) together contributed to more than 40% of the 8.8m papers summed for the 30 countries included in the table. Whereas the US has one of the lowest growth rate figures (1.30) and is losing ground in output productivity relative to other countries (growth index of 0.62), China was the country with the third highest growth rate (at 4.21). Iran and India experienced even higher increases in output between the full period's two halves, with growth rates measured at 10.34 and 4.73. Among the top 10 countries with the highest publication output in S15, only three displayed positive growth indexes: India (2.26), China (2.01) and the Republic of Korea (1.07).

Turning now international collaboration, the UK was among the top tier of most-collaborating countries, with a share of international co-publications at 53.2%. Switzerland (66.1%), Belgium (59.8%) and the Netherlands (58.8%) obtained the highest scores on this indicator, noting that, in general, smaller countries (in terms of population) do tend to engage at higher rates in international co-publications than larger countries for a constant number of publications. At the opposite end of the spectrum, China (13.6%), India (17.5%) and Japan (23.2%) held the lowest shares of papers written as international co-publications.

Table 26 shows that shares of international co-publications have been increasing over the period of interest for most but not all countries. The UK saw the highest absolute increase in shares of international co-publications between the 1996–2000 and 2011–2015 periods, from 38.1% to 59.9%. Australia also saw a large increase over the full period (from 36.5% to 57.3%). Iran (from 34.0% to 19.8%), the Czech Republic (from 52.5% to 40.8%) and Poland (45.7% to 36.1%) saw large decreases in shares of international co-publications. Considering only the recent (2011–2015) period, Switzerland (69.8%) and Belgium (65.0%) maintain their rankings, followed this time by Sweden (62.9%).

Citation and impact profiles, overall and longitudinal

The UK's publications in the S15 placed the country among the top tier on citation metrics performances. Although exact rankings shifted from one indicator to the next, by focusing on the CDI and three HCP indicators, one can identify the following countries as outperforming the UK: Austria (although not on the CDI), Australia, Belgium, Canada, Israel, the Netherlands, Portugal, Sweden, Switzerland and the United States. Switzerland, the Netherlands and the United States held the top 3 performances, in that order. For the CDI, the United Kingdom held a score of 11.0, compared to 15.4 for Switzerland, 14.2 for the Netherlands and 12.8 for the United States. Ukraine had the lowest showing among the countries included in the analysis at -16.7. The UK's $HCP_{10\%}$ score was 15.9%, whereas Switzerland obtained 20.5%, the Netherlands 18.3% and the US 17.5%. Ukraine had a 3.7% share of S15 publications falling in this category. Of the UK's S15 papers, 1.9% reached $HCP_{1\%}$ status. This share was 2.8% for Switzerland, 2.4% for Dutch publications and 2.2% for US publications. The range of scores extended downwards to 0.4%.

If examination of citation profiles is restricted to the top 10 countries with the largest outputs in S15 instead, the UK moves up and takes second rank for its citation metric performances, behind the US. This ranking was obtained not only overall but for each indicator included in the analysis. Again, a combination of high output volume and high citation profiles can be considered a separate achievement unto itself.

Table 26 shows CDI and $HCP_{10\%}$ scores have increased in time for most countries in the table. The UK saw its CDI move from 6.8 (1996–2000) to 13.7 (2011–2015) and its $HCP_{10\%}$ scores move from 12.6% to 18.4%.

CERN output and impact profile

As seen in Table 25, CERN's output in the S15 grew between 1996 and 2017 (growth rate of 1.59), but it did so at a rate below the world level (2.09). The resulting growth index is below 1, at 0.76.

Examining the international collaboration dimension, 62.3% of CERN papers were international co-publications. Its shares of international co-publications have decreased slightly over time, from a high point of 66.4% for the 1996–2000 period, to an intermediate level of 60.4% over the 2011–2015 period.

CERN publications' high performances on some citation metrics—the HCP indicators—contrast with a more middling one for the CDI. Here again, the CERN publication record appears to contain a high proportion of "citation blockbusters" with very high visibility, while simultaneously also including multiple articles with low citation rates. With scores of 17.3% for the $HCP_{10\%}$, of 9.9% for $HCP_{5\%}$ and of 2.8% for the $HCP_{1\%}$, comparatively large portions of the CERN portfolio can be classified as belonging to the most-highly cited publications in their field. A CDI score of 7.6, while well above world level, is nevertheless below the performances observed for many countries.

In Table 26, CERN's $HCP_{10\%}$ scores are found to be stable (slightly above 15%) over the first three intervals (covering together 1996 to 2010), followed by a spike up to 22% for the most recent period. The CDI, by contrast, saw a slight drop from 8.1 to 6.7 (1996–2000 to 2001–05), followed by another, substantial drop to 40 (2006–10 to 2011–15). CERN's CDI bounced back to 10.2 in the most recent period, however, indicating a large gain in citation rates across the portfolio—from the least- to the most-cited publications.

D.3.3. Country-level findings summary

In summary, in NPP and S15, the UK obtained high citation metric scores, especially when considering the large size of its output volume. Its research was the third-most impactful among the largest producers of research in the NPP subfield, and second-most impactful among the largest producers in the S15 set.

CERN displayed both higher performances than the UK on some citation metrics ($HCP_{10\%}$ for the S15; $HCP_{5\%}$, $HCP_{1\%}$ and ARC for both data sets), and lower ones on others (CDI for both data sets). Section D.4.2 provides more evidence to characterise and isolate impact benefits from CERN participation.

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Table 25 National research performance in selected subfields of science (1996–2017)

Country	Publication output (fractional count)				Publication output (full count)				Intl. collab.	Citation impact						
	Papers	Trend	GR	GI	Papers	Trend	GR	GI		ARC	CDC	CDI	ARIF	$HCP_{10\%}$	$HCP_{5\%}$	$HCP_{1\%}$
World	9,708,607		2.09	1.00	9,708,607		2.09	1.00	-	1.00		0.0	1.00	10.0%	5.0%	1.0%
CERN	N/A	N/A	N/A	N/A	39,689		1.59	0.76	62.3%	1.70		7.6	1.19	17.3%	9.9%	2.8%
United States	1,693,573		1.30	0.62	2,086,187		1.42	0.68	33.8%	1.62		12.1	1.40	17.5%	9.5%	2.2%
Germany	517,648		1.51	0.72	730,610		1.62	0.77	49.8%	1.37		9.1	1.24	14.8%	7.6%	1.6%
Russia	311,349		1.45	0.70	392,551		1.41	0.68	34.0%	0.61		-13.1	0.63	5.1%	2.5%	0.5%
Italy	285,372		1.74	0.83	390,479		1.85	0.88	47.2%	1.28		8.2	1.20	13.3%	6.6%	1.3%
Japan	694,560		1.17	0.56	795,074		1.24	0.59	23.2%	0.91		-1.4	1.00	8.7%	4.3%	0.9%
China	2,137,332		4.21	2.01	2,290,950		4.20	2.01	13.6%	0.71		-8.3	0.75	6.7%	3.3%	0.6%
United Kingdom	375,813		1.50	0.72	556,940		1.76	0.84	53.2%	1.48		11.0	1.33	15.9%	8.3%	1.9%
France	353,818		1.53	0.73	518,674		1.70	0.81	53.2%	1.30		9.0	1.24	13.8%	7.0%	1.4%
Switzerland	90,909		1.65	0.79	158,732		1.88	0.90	66.1%	1.87		15.4	1.41	20.5%	11.4%	2.8%
Spain	191,662		2.15	1.03	275,259		2.38	1.14	51.2%	1.35		9.0	1.25	13.9%	7.0%	1.5%
India	386,519		4.73	2.26	428,810		4.48	2.14	17.5%	0.87		-1.3	0.88	8.1%	3.8%	0.7%
Poland	127,414		2.20	1.05	171,184		2.07	0.99	40.1%	0.87		-2.3	0.89	7.7%	3.8%	0.9%
Brazil	129,651		2.36	1.13	163,395		2.38	1.14	36.1%	0.96		2.1	1.05	8.8%	4.1%	0.9%
Canada	214,076		1.82	0.87	302,041		1.99	0.95	47.6%	1.55		12.3	1.36	16.3%	8.6%	1.9%
Rep. of Korea	306,587		2.24	1.07	357,239		2.29	1.10	24.9%	1.02		1.8	1.10	10.0%	4.9%	1.0%
Netherlands	100,305		1.63	0.78	161,041		1.84	0.88	58.8%	1.67		14.2	1.35	18.3%	9.9%	2.4%
Sweden	78,175		1.54	0.73	124,005		1.82	0.87	58.4%	1.47		11.4	1.28	15.4%	8.1%	1.8%
Belgium	67,928		1.63	0.78	107,390		1.88	0.90	59.8%	1.44		10.3	1.26	14.6%	7.7%	1.7%
Czech Republic	60,582		3.27	1.56	84,391		3.04	1.45	43.8%	1.05		2.4	0.99	10.1%	4.9%	1.1%
Mexico	53,559		2.03	0.97	73,452		2.06	0.98	44.7%	0.95		0.0	1.03	8.5%	4.1%	0.9%
Australia	135,968		2.11	1.01	199,034		2.44	1.17	52.3%	1.54		12.4	1.33	16.6%	8.9%	2.0%
Romania	48,267		3.98	1.90	63,678		3.46	1.65	37.9%	0.81		-5.4	0.82	7.4%	3.5%	0.8%
Portugal	48,330		2.85	1.36	70,325		3.03	1.45	50.7%	1.48		10.5	1.23	14.9%	7.8%	1.8%
Greece	51,657		1.94	0.93	72,899		2.09	1.00	46.7%	1.27		8.3	1.23	13.4%	6.8%	1.5%
Austria	54,321		2.00	0.95	85,751		2.20	1.05	58.4%	1.60		9.7	1.28	15.5%	8.3%	2.0%
Israel	52,131		1.29	0.62	76,427		1.41	0.68	51.2%	1.47		10.7	1.41	15.4%	7.9%	1.8%
Iran	107,359		10.34	4.94	119,982		9.89	4.72	20.3%	0.98		1.6	0.91	10.3%	5.0%	0.8%
Ukraine	69,152		1.33	0.64	88,943		1.38	0.66	37.2%	0.49		-16.7	0.57	3.7%	1.8%	0.4%
Hungary	25,436		1.80	0.86	41,344		1.83	0.88	57.3%	1.31		6.2	1.13	12.5%	6.7%	1.8%
Turkey	81,035		3.41	1.63	96,348		3.48	1.66	26.1%	1.10		4.4	1.01	10.7%	5.3%	1.1%

Note: Scale for trends in output are not the same across countries. For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level. N/C: Not calculated due to insufficient sample size (minimum of 30 papers required). N/A: Not applicable as CERN papers were identified using lists of publications, not addresses, which are the basis for calculating fractional contributions (e.g., a paper with four authors with two from the UK and one each from France and the US would have 0.5 attributed to the UK, and 0.25 each to France and the US). Subfields included in the analysis are based on the Science-Metrix classification and are the top 15 subfields in which CERN research has been published between 1996 and 2017 (Nuclear & Particle Physics, General Physics, Applied Physics, Astronomy & Astrophysics, Nuclear Medicine & Medical Imaging, Fluids & Plasmas, Electrical & Electronic Engineering, Artificial Intelligence & Image Processing, Optoelectronics & Photonics, Energy, Mathematical Physics, Distributed Computing, General Science & Technology, Materials, Networking & Telecommunications).

Source: Calculated by Science-Metrix using data from Scopus

Table 26 National research performance in selected subfields of science (1996–2017)

Country	Papers (fractional count)				Papers (full count)				CDI				$HCP_{10\%}$				International collaboration rate			
	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015
World	1,126,059	1,589,653	2,491,199	3,165,476	1,126,059	1,589,653	2,491,199	3,165,476	0.0	0.0	0.0	0.0	10.0%	10.0%	10.0%	10.0%	-	-	-	-
CERN	N/A	N/A	N/A	N/A	6,080	7,503	8,788	12,428	8.1	6.7	4.0	10.2	15.2%	15.1%	15.4%	22.0%	66.4%	62.4%	58.9%	60.4%
United States	293,307	359,373	424,109	447,262	335,797	425,185	518,268	576,382	10.0	10.9	14.0	12.9	16.2%	16.8%	18.3%	18.2%	23.3%	28.5%	33.0%	39.8%
Germany	81,548	101,159	130,224	147,570	106,207	139,804	182,756	214,978	6.2	6.1	9.9	12.6	12.5%	13.0%	15.6%	17.1%	41.5%	48.1%	49.4%	52.8%
Russia	55,405	59,572	60,795	80,266	68,674	78,199	79,512	100,694	-13.4	-13.6	-14.0	-11.9	4.6%	4.8%	5.2%	5.7%	31.7%	38.3%	38.2%	33.4%
Italy	38,530	52,716	72,704	85,252	49,399	70,076	98,547	120,077	3.1	6.0	9.2	11.7	10.4%	11.7%	13.5%	15.8%	39.8%	44.2%	46.3%	50.1%
Japan	127,483	156,987	177,578	169,491	139,205	176,009	202,956	200,043	-1.9	-1.6	-1.5	-0.8	8.0%	8.3%	9.0%	9.5%	16.1%	20.7%	23.3%	27.2%
China	93,627	230,248	614,242	866,684	102,078	246,821	649,613	927,383	-12.8	-10.9	-9.5	-5.9	4.8%	5.2%	6.0%	8.0%	13.9%	12.4%	10.7%	13.6%
United Kingdom	61,462	71,572	94,556	105,070	78,690	98,359	138,106	167,650	6.8	8.7	12.6	13.7	12.6%	14.0%	16.7%	18.4%	38.1%	46.4%	51.9%	59.9%
France	55,363	67,555	92,370	101,449	73,010	94,988	134,030	155,775	5.9	7.1	10.6	11.0	11.7%	12.7%	14.4%	15.3%	42.4%	49.3%	52.4%	57.6%
Switzerland	13,316	16,694	22,728	27,350	20,666	27,365	39,053	50,342	12.0	12.9	16.8	17.6	17.6%	18.2%	21.2%	22.7%	56.7%	61.6%	65.4%	69.8%
Spain	19,836	32,328	52,420	63,237	26,091	43,591	73,009	94,548	5.3	6.1	10.1	11.0	11.2%	11.9%	14.4%	15.6%	42.4%	45.0%	48.0%	54.9%
India	23,916	33,519	71,305	164,481	27,659	39,084	80,861	179,944	-3.1	-0.8	2.3	-2.8	6.6%	8.0%	9.2%	7.9%	22.2%	24.4%	20.8%	15.5%
Poland	13,627	20,582	31,555	42,267	19,185	29,043	41,733	55,257	-3.7	-2.0	-2.8	-1.4	6.6%	7.3%	7.3%	8.7%	45.7%	46.7%	39.2%	36.1%
Brazil	11,891	21,229	31,433	44,797	15,235	26,312	38,603	56,761	0.5	1.3	2.8	2.6	7.3%	8.1%	8.8%	9.6%	38.4%	34.5%	33.0%	36.3%
Canada	26,239	38,902	59,549	64,830	34,281	52,267	82,052	95,064	9.4	10.1	14.3	13.2	14.2%	14.8%	17.3%	17.4%	38.8%	42.3%	45.2%	51.7%
Rep. of Korea	25,070	52,429	88,564	99,576	28,715	60,312	101,758	117,500	1.0	2.3	2.5	1.2	8.8%	9.8%	10.1%	10.3%	21.3%	23.4%	23.2%	26.6%
Netherlands	14,376	19,168	25,706	29,806	20,540	29,010	40,189	50,423	9.6	11.6	16.9	16.2	14.6%	16.3%	20.6%	19.9%	49.0%	54.1%	56.6%	62.8%
Sweden	11,951	15,405	17,684	23,557	16,479	22,310	27,903	39,619	7.7	7.3	13.6	14.3	13.2%	12.7%	16.8%	17.4%	46.3%	51.5%	58.1%	62.9%
Belgium	9,542	13,076	17,774	19,968	13,169	19,251	27,607	33,647	5.8	8.2	11.1	13.3	11.4%	12.9%	14.9%	17.1%	47.1%	54.1%	58.5%	65.0%
Czech Republic	4,359	7,475	14,667	23,460	6,524	11,002	20,101	32,031	-1.4	-1.4	3.2	5.0	7.2%	8.3%	10.5%	11.8%	52.5%	50.5%	42.6%	40.8%
Mexico	5,352	9,523	14,352	17,071	7,392	12,979	19,204	23,461	-0.1	-0.7	0.3	0.2	7.6%	7.2%	8.2%	9.7%	46.5%	44.9%	42.6%	44.1%
Australia	16,074	21,959	34,448	44,901	20,378	29,534	48,218	69,461	8.2	9.4	13.1	14.7	13.5%	14.7%	17.1%	18.3%	36.5%	44.1%	48.4%	57.3%
Romania	3,642	4,824	14,004	17,993	5,040	7,405	17,748	23,220	-5.9	-3.1	-8.7	-3.8	5.3%	7.3%	5.3%	9.5%	41.4%	52.8%	35.1%	35.2%
Portugal	3,617	6,854	12,650	18,137	4,928	9,547	17,958	26,746	6.4	8.5	9.8	12.7	10.7%	13.0%	14.7%	16.8%	44.1%	48.6%	48.8%	51.5%
Greece	5,485	9,140	15,680	15,564	7,499	12,214	20,998	23,125	6.2	5.0	8.2	11.5	9.3%	10.5%	13.0%	17.3%	43.0%	42.2%	41.8%	51.2%
Austria	6,339	9,389	14,288	17,256	9,132	14,016	21,713	28,488	6.1	7.6	9.3	12.8	11.3%	13.2%	15.8%	18.4%	51.8%	55.0%	55.8%	61.1%
Israel	9,046	11,183	13,026	13,456	12,415	15,676	18,748	20,887	10.0	8.4	11.5	12.5	14.4%	13.6%	14.9%	17.8%	44.8%	48.0%	50.0%	55.5%
Iran	1,240	5,573	28,224	49,756	1,595	6,435	30,863	55,407	0.5	-0.2	3.9	0.8	8.7%	7.3%	10.5%	10.5%	34.0%	25.4%	16.7%	19.8%
Ukraine	12,636	14,234	15,471	17,993	15,153	18,446	20,096	23,766	-19.3	-16.6	-16.0	-15.3	2.1%	3.1%	3.5%	5.5%	28.3%	38.4%	39.3%	39.9%
Hungary	3,236	4,754	6,546	7,863	5,319	7,588	10,036	12,995	4.8	4.1	4.8	9.2	8.4%	10.2%	11.5%	17.0%	59.4%	58.0%	54.3%	56.6%
Turkey	4,632	10,296	21,265	29,660	5,471	12,044	24,475	35,906	-0.2	3.6	6.8	3.9	7.7%	9.6%	11.2%	11.5%	26.2%	25.3%	22.8%	27.5%

Note: For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level. N/C: Not calculated due to insufficient sample size (minimum of 30 papers required). Subfields included in the analysis are based on the Science-Metrix classification and are the top 15 subfields in which CERN research has been published between 1996 and 2017 (Nuclear & Particle Physics, General Physics, Applied Physics, Astronomy & Astrophysics, Nuclear Medicine & Medical Imaging, Fluids & Plasmas, Electrical & Electronic Engineering, Artificial Intelligence & Image Processing, Optoelectronics & Photonics, Energy, Mathematical Physics, Distributed Computing, General Science & Technology, Materials, Networking & Telecommunications).
Source: Calculated by Science-Metrix using data from Scopus

D.4 Assessment of world-class research achievements and their outcomes for the UK

D.4.1. Measurement of access to new knowledge

Bibliometric measurements can help gain a sense of the extent to which UK research has relied on findings from CERN experiments to build hypotheses or mobilise evidence and experimental results.

Table 27 provides an overview of UK research (articles published 1996-2017) that has relied on work conducted at CERN (indicated by citing CERN articles published 1996-2017). The main sub-fields of UK research that are citing CERN articles are also shown. The bottom half of the table then shows just the sub-set of UK publications that are citing UK-CERN papers (i.e. CERN papers with a UK-affiliated author).

Between 1996 and 2017, over 29,200 scientific articles (or over 13,600, based on factional counting) that were authored by at least one UK-based researcher made reference (through direct citation) to CERN articles. The majority (70%) of these papers were citing CERN articles involving UK researchers. NPP papers were also unsurprisingly the main source of citations to CERN articles (71% of UK publications).

It can also be noted that counts of UK articles citing CERN research have steadily increased over 1996–2017. In all subfields, increases in counts of these articles reach or surpass a factor of 1.5 between the first (1996–2006) and the second (2007–2017) halves of the period.

The second part of Table 27 examines the features of these CERN-influenced UK research articles. Shares of international co-publication rates and citation metrics were retrieved for the article sets of interest, with the assumption that dissemination of CERN findings and outcomes can be achieved not only by direct publication of observations, but also by their referencing / use by a larger group of non-CERN physicists.

The shares of international co-publications among UK papers citing CERN research (74.5%) are quite high—higher than the shares reported previously for CERN papers.

It is also readily apparent that UK-based uptake of CERN research is made to a great extent by publications that will go on to achieve exceptional degrees of visibility. In particular, 37% of UK General Physics papers citing CERN research are among the 10% most-cited publications in their field, while 27% of astronomy and astrophysics, 24% of nuclear and particle physics papers are among the 10% most cited.

CDI figures above 15 are indicative of strong performances (a set of papers tends to be cited skewed toward higher-impact performances), and CDI figures above 20 index exceptional achievements. From this perspective again, the findings presented show that CERN research uptake is made in some of the most influential papers in UK physics.

Table 28 works from much the same assumption as just presented, but testing it with a longitudinal perspective that makes it possible to identify potential trends and turning points in the impact of UK spillover research, and in its capacity to foster international collaboration. This longitudinal analysis shows mostly how the high citation metrics previously discussed appear to be supported by durable upwards trends for most subfields and for both CDI and $HCP_{10\%}$ findings.

Table 27 UK research uptake of work conducted at CERN (1996–2017)

Source taken up	Publication output: Papers (frac)	% CERN (frac)	Trend (frac)	GR	Papers (full)	% CERN (full)	Trend (full)	GR	Intl. collab.	Citation impact: ARC	CDC	CDI	ARIF	$HCP_{10\%}$	$HCP_{5\%}$	$HCP_{1\%}$
UK papers citing CERN papers	13,613	13.5%		2.20	29,221	23.8%		2.46	74.5%	2.26		20.6	1.33	25.0%	14.0%	3.9%
Nuclear & Particle Physics	9,790	16.0%		1.97	20,641	28.6%		2.21	73.8%	2.14		20.8	1.19	24.1%	13.2%	3.3%
General Physics	834	14.0%		2.40	2,590	22.9%		2.29	83.4%	3.06		28.7	2.27	37.0%	20.3%	6.0%
Astronomy & Astrophysics	734	4.2%		3.02	2,130	4.9%		3.91	88.1%	2.90		18.3	1.10	26.9%	16.3%	6.1%
Applied Physics	282	11.1%		1.91	524	18.3%		2.28	69.1%	1.06		6.8	0.96	11.9%	5.2%	0.8%
Fluids & Plasmas	225	5.7%		2.27	389	11.8%		2.93	67.4%	2.54		10.3	2.90	19.1%	14.5%	5.8%
UK papers citing UK-CERN papers	8,973	17.6%		2.43	20,427	30.1%		2.70	76.7%	2.39		21.6	1.35	26.3%	14.9%	4.3%
Nuclear & Particle Physics	6,751	20.0%		2.21	15,040	34.7%		2.46	76.0%	2.28		21.7	1.21	25.2%	14.0%	3.7%
General Physics	554	18.2%		2.71	1,897	28.1%		2.54	85.4%	3.20		29.2	2.31	37.7%	20.8%	6.5%
Astronomy & Astrophysics	500	5.4%		3.43	1,504	6.1%		4.70	88.5%	2.96		19.1	1.11	28.2%	18.1%	6.8%
Applied Physics	149	15.2%		1.85	274	25.2%		2.11	66.8%	0.97		3.5	0.93	9.2%	4.0%	0.5%
Fluids & Plasmas	138	8.6%		2.10	242	18.2%		2.78	69.8%	2.55		12.0	2.97	19.5%	13.8%	7.1%

Note: Scale for trends in output are not the same across countries. For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level. The fractional counting method was used to attribute papers at the country level for output indicators (e.g., a paper with four authors with two from the UK and one each from France and the US would have 0.5 attributed to the UK, and 0.25 each to France and the US). UK CERN Papers citing UK CERN Papers (Proportion that these UK CERN papers represent in the total citations of UK papers to UK CERN papers). % CERN refers to the proportion of papers that cite CERN work that are themselves CERN research. N/C: Not calculated due to insufficient sample size (minimum of 30 papers required).

Source: Calculated by Science-Metrix using data from Scopus

Table 28 UK research uptake of work conducted at CERN, longitudinal analysis (1996–2017)

Source taken up	Papers (fractional count)				Papers (full count)				CDI				$HCP_{10\%}$				International collaboration rate			
	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015	1996–2000	2001–2005	2006–2010	2011–2015
UK papers citing CERN papers	1,149	2,497	3,527	4,512	2,272	4,972	7,066	10,221	18.5	15.9	21.9	22.6	21.3%	21.2%	24.8%	28.1%	70.7%	70.8%	70.1%	76.9%
Nuclear & Particle Physics	981	1,880	2,517	3,142	1,979	3,621	4,900	7,069	18.6	16.4	22.5	23.0	20.9%	21.0%	24.2%	26.9%	71.9%	69.3%	69.2%	76.8%
General Physics	50	153	256	251	115	528	784	827	27.3	16.7	32.7	33.5	28.6%	25.5%	36.4%	46.1%	73.9%	84.5%	82.0%	85.6%
Astronomy & Astrophysics	11	137	172	277	33	314	469	826	12.9	19.0	18.3	18.3	30.3%	26.0%	25.4%	28.0%	97.0%	84.1%	83.6%	88.2%
Applied Physics	23	57	92	75	34	97	153	159	16.5	7.0	5.3	5.7	9.1%	15.2%	13.7%	9.0%	50.0%	67.0%	62.7%	73.6%
Fluids & Plasmas	22	40	53	78	28	61	89	143	N/C	1.9	6.5	15.9	N/C	11.3%	14.3%	26.0%	57.1%	59.0%	64.0%	69.9%
UK papers citing UK-CERN papers	707	1,539	2,164	3,168	1,506	3,232	4,533	7,591	20.0	16.3	22.6	23.7	20.5%	21.7%	25.7%	30.0%	73.9%	72.9%	72.0%	78.8%
Nuclear & Particle Physics	607	1,216	1,634	2,321	1,346	2,434	3,289	5,505	20.3	16.5	22.5	24.2	20.2%	21.6%	24.3%	29.0%	75.7%	70.8%	70.7%	78.6%
General Physics	29	93	160	188	60	374	535	672	22.1	16.8	33.2	34.0	22.4%	24.3%	37.3%	46.8%	68.3%	87.2%	83.9%	87.0%
Astronomy & Astrophysics	5	86	100	199	16	190	300	607	N/C	20.8	20.4	18.1	N/C	27.6%	28.3%	28.1%	93.8%	82.6%	86.3%	87.9%
Applied Physics	17	23	28	50	25	48	74	87	N/C	N/C	-2.3	5.3	N/C	N/C	8.7%	9.5%	40.0%	70.8%	54.1%	78.2%
Fluids & Plasmas	18	25	49	37	21	37	44	96	N/C	1029.5%	7.9	14.7	N/C	15.2%	13.5%	24.8%	52.4%	67.6%	61.4%	74.0%

Note: For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level. The fractional counting method was used to attribute papers at the country level for output indicators (e.g., a paper with four authors with two from the UK and one each from France and the US would have 0.5 attributed to the UK, and 0.25 each to France and the US). UK CERN Papers citing UK CERN Papers (Proportion that these UK CERN papers represent in the total citations of UK papers to UK CERN papers).

N/C: Not calculated due to insufficient sample size (minimum of 30 papers required).

Source: Calculated by Science-Metrix using data from Scopus

D.4.2. Measurement of access to facilities and opportunities

Table 29 and Table 30 measure the performances of seven countries in NPP research, overall, just for CERN papers, and without CERN papers included. In other words, it aims to tease out the specific contributions brought about by CERN research to national performances.

Indicators of publication output and scientific impact do not directly measure researchers' or researchers' operation of CERN facilities, of course. However, there are strong reasons to assume that publication practices and the uptake of findings (in the form of citations) can be changed by work at CERN. All CERN publications can be considered to have benefited from the use of a CERN facility in a direct or indirect manner. This work, in turn, has a high likelihood to shape a researcher's capacity to publish findings and to shape their quality, even when this researcher is working on a side project conducted outside of CERN.

Table 29 shows that CERN papers contribute quite small volumes to national publication portfolios, but that they significantly pull citation metrics and international co-publication rates upward. CERN papers amounted to roughly 15% of the full UK output in NPP between 1996 and 2017 (8% in factional counting). NPP outputs for France, Germany and the Netherlands all contain roughly 7% of CERN papers (fractional counting), while this falls to 4%, 3% and 1% for the non-European countries (USA, Canada and Australia).

For all countries, sets of CERN publications tend to obtain very strong citation profiles, a potential indication of high-quality research that has been enabled by access to specialised infrastructure. This effect is in full view in Table 30. Increases in the shares of $HCP_{10\%}$ publications range from ~8 percentage points (for Germany and the UK) to as much as 25 percentage points (for Australia) when moving from the non-CERN to CERN publications. The same general trend can be observed on all citation indicators included here. It should be noted that Australia's exceptionally high performances recorded for CERN papers are based on a rather small data set of 54 papers that may be susceptible to wider swings brought about by outliers.

For its citation-based performances in NPP, the UK ranks at number two, behind the Netherlands, in the selection of countries included in Table 29. Rankings remain close to unchanged when all countries are compared for their scores excluding CERN papers. In a hypothetical situation where UK's performance was measured without input from CERN papers, but scores from other countries would still include CERN papers, the country would slip in fifth position when considering results for the $HCP_{10\%}$ indicator. Indeed, in such a case, the $HCP_{10\%}$ figure for the UK would be 16.5%, compared to 20.4% for the Netherlands, and scores would be equal to or slightly above the UK's for France, Germany, the United States and Canada.

Longitudinal analysis of citation profiles in Table 30 reveal important fluctuations in performance between the intervals included. For all countries, the largest changes in either CDI or $HCP_{10\%}$ scores for CERN papers were seen between the 2006–2010 to 2011–2015 periods, perhaps reflecting the maturing of Large Hadron Collider experiments and of their theorisation. UK scores went from 16.1 to 27.2 on the CDI, and from shares of 22.8% to 35.9% for $HCP_{10\%}$ publications. CERN publications from the Netherlands appear to have experienced the most pronounced shift in performances between periods.

Country-level overall citations scores, as well as non-CERN performances, gradually increase in time, with a sharper gain in the last period considered. CERN-only trends are more uneven, by contrast, especially on CDI scores. It should be noted, however, that smaller numbers of publications included in the data sets for CERN categories may contribute to fluctuations in scores and decreased resiliency of findings to outlier influence.

Overall, the findings reported in this section provide strong backing for the assertion CERN provides opportunities for conducting high-impact and high-visibility research.

Table 29 Contribution of CERN to national performance in Nuclear & Particle Physics (1996–2017)

Country	Publication output: Papers (frac)	Trend	GR	Papers (full)	Trend	GR	Intl. collab.	Number of countries: Mean	Median	Citation impact: ARC	CDC	CDI	ARIF	$HCP_{10\%}$	$HCP_{5\%}$	$HCP_{1\%}$
UK	24,538		2.26	44,800		1.75	66.8%	4.31	2.00	1.66		13.3	1.16	18.0%	9.6%	2.2%
w/CERN	1,917		2.10	6,783		1.99	92.0%	13.49	7.00	2.72		22.0	1.33	26.1%	15.5%	4.8%
w/out CERN	22,622		2.27	38,017		1.71	62.3%	2.68	2.00	1.47		11.7	1.13	16.5%	8.6%	1.7%
France	23,199		2.36	44,090		1.83	70.5%	4.47	2.00	1.59		10.9	1.17	16.7%	9.2%	2.1%
w/CERN	1,784		1.75	7,011		1.82	91.8%	13.47	8.00	2.65		21.0	1.28	25.0%	15.1%	4.7%
w/out CERN	21,415		2.42	37,079		1.84	66.5%	2.78	2.00	1.37		8.7	1.14	14.9%	7.9%	1.6%
Germany	45,422		2.16	76,404		1.61	65.8%	3.57	2.00	1.50		11.1	1.18	16.5%	8.7%	1.9%
w/CERN	2,834		1.90	8,528		1.62	88.5%	11.96	6.00	2.45		20.4	1.28	24.1%	14.5%	4.4%
w/out CERN	42,588		2.18	67,876		1.61	63.0%	2.52	2.00	1.37		9.9	1.16	15.5%	7.9%	1.6%
Netherlands	4,761		1.99	12,027		1.83	78.6%	7.28	3.00	1.98		15.2	1.20	20.4%	11.5%	3.0%
w/CERN	329		1.95	2,607		1.86	94.7%	19.42	16.00	3.13		24.8	1.31	28.7%	17.3%	5.3%
w/out CERN	4,432		1.99	9,420		1.82	74.1%	3.92	2.00	1.62		12.2	1.16	17.8%	9.7%	2.3%
United States	98,632		1.71	136,768		1.26	48.0%	2.57	1.00	1.56		10.0	1.12	16.8%	9.1%	2.1%
w/CERN	3,515		2.26	9,757		1.68	88.2%	10.59	4.00	2.60		20.3	1.26	24.7%	15.0%	4.8%
w/out CERN	95,117		1.70	127,011		1.23	44.9%	1.95	1.00	1.48		9.2	1.11	16.2%	8.7%	1.9%
Canada	9,273		2.03	18,203		1.56	69.0%	4.61	2.00	1.61		12.3	1.11	16.7%	9.1%	2.1%
w/CERN	275		1.16	1,873		1.88	95.8%	18.84	12.00	3.55		25.7	1.32	27.3%	16.4%	5.1%
w/out CERN	8,998		2.07	16,330		1.53	65.9%	2.98	2.00	1.39		10.8	1.09	15.5%	8.2%	1.8%
Australia	4,077		1.99	8,128		2.02	70.1%	6.34	2.00	1.62		10.3	1.17	16.3%	8.6%	2.1%
w/CERN	54		1.62	990		7.76	98.7%	29.47	38.50	4.59		30.9	1.33	40.1%	24.7%	8.3%
w/out CERN	4,022		1.99	7,138		1.77	66.1%	3.13	2.00	1.19		7.3	1.14	12.8%	6.2%	1.2%

Table 30 Contribution of CERN to national performance in Nuclear & Particle Physics, longitudinal analysis (1996–2017)

Country	Papers (fractional count) 1996–2000	2001–2005	2006–2010	2011–2015	Papers (full count) 1996–2000	2001–2005	2006–2010	2011–2015	CDI 1996–2000	2001–2005	2006–2010	2011–2015	$HCP_{10\%}$ 1996–2000	2001–2005	2006–2010	2011–2015	International collaboration rate 1996–2000	2001–2005	2006–2010	2011–2015
UK	3,764	4,443	6,616	7,212	6,370	7,922	11,373	13,787	11.0	10.4	13.0	17.3	15.1%	15.7%	17.6%	22.0%	62.9%	66.0%	62.4%	69.2%
w/CERN	319	303	392	637	1,096	978	1,121	2,436	20.0	17.8	16.1	27.3	16.0%	20.2%	22.8%	35.9%	92.8%	91.3%	87.2%	92.5%
w/out CERN	3,444	4,140	6,224	6,576	5,274	6,944	10,252	11,351	9.1	9.4	12.7	14.7	14.9%	15.1%	17.1%	18.3%	56.6%	62.4%	59.7%	64.2%
France	3,439	4,048	6,081	7,141	6,200	7,538	11,029	13,943	7.9	8.4	10.5	15.2	13.4%	14.5%	16.3%	21.0%	69.0%	71.0%	67.4%	71.1%
w/CERN	330	340	360	546	1,192	1,060	1,202	2,453	17.0	14.7	16.6	28.0	14.3%	16.3%	22.0%	36.5%	91.6%	89.1%	89.8%	92.6%
w/out CERN	3,109	3,708	5,721	6,594	5,008	6,478	9,827	11,490	5.7	7.4	9.7	11.1	13.1%	14.2%	15.5%	16.2%	63.6%	68.0%	64.7%	66.5%
German	7,305	8,428	11,829	13,414	11,559	14,225	19,116	23,085	9.0	8.7	11.2	15.0	14.4%	15.0%	16.0%	20.0%	63.3%	67.2%	62.4%	66.3%
w/CERN	484	572	523	907	1,458	1,505	1,432	2,865	19.1	16.6	15.3	25.9	17.1%	18.3%	21.1%	33.9%	90.1%	88.2%	87.0%	87.1%
w/out CERN	6,821	7,856	11,307	12,507	10,101	12,720	17,684	20,220	7.5	7.8	10.8	13.0	14.1%	14.6%	15.6%	17.5%	59.4%	64.7%	60.4%	63.4%
Netherlands	834	856	1,133	1,429	1,728	2,011	2,739	3,983	9.4	11.4	15.2	20.7	14.2%	16.1%	20.4%	26.6%	71.3%	77.9%	76.8%	80.6%
w/CERN	65	48	58	119	492	360	303	975	21.8	16.9	14.4	32.0	17.4%	14.9%	24.6%	40.9%	95.7%	95.0%	91.7%	93.6%
w/out CERN	770	808	1,075	1,310	1,236	1,651	2,436	3,008	4.4	10.1	15.4	15.7	12.8%	16.3%	19.8%	20.3%	61.5%	74.2%	75.0%	76.4%
United States	17,973	23,053	24,720	24,341	23,854	30,519	33,511	35,518	8.3	7.2	11.9	12.4	16.0%	15.6%	17.2%	18.6%	43.2%	43.5%	45.9%	52.7%
w/CERN	513	619	718	1,187	1,669	1,660	1,870	3,194	21.7	16.8	15.1	23.9	20.5%	19.2%	19.4%	33.7%	91.8%	88.9%	87.3%	85.4%
w/out CERN	17,460	22,435	24,002	23,154	22,185	28,859	31,641	32,324	7.3	6.6	11.7	11.2	15.6%	15.3%	17.0%	17.0%	39.5%	40.8%	43.5%	49.5%
Canada	1,511	1,870	2,389	2,601	2,779	3,506	4,539	5,350	7.8	7.2	15.9	16.1	11.6%	13.4%	17.9%	21.5%	65.7%	66.8%	66.2%	71.7%
w/CERN	69	54	42	71	345	265	265	664	22.0	20.8	21.1	31.2	16.2%	18.5%	20.2%	39.2%	94.8%	94.0%	97.0%	96.1%
w/out CERN	1,443	1,816	2,347	2,530	2,434	3,241	4,274	4,686	5.7	6.2	15.6	13.5	10.9%	13.0%	17.8%	18.4%	61.6%	64.6%	64.3%	68.2%
Australia	648	773	911	1,265	1,020	1,371	1,653	2,826	7.7	4.6	7.3	17.0	11.7%	10.8%	13.2%	24.1%	58.8%	66.6%	65.1%	74.2%
w/CERN	8	6	8	19	54	45	67	533	12.7	19.2	19.7	34.9	14.8%	16.7%	31.5%	45.4%	96.2%	95.6%	94.0%	99.4%
w/out CERN	640	767	902	1,247	966	1,326	1,586	2,293	7.4	4.1	6.7	10.3	11.5%	10.6%	12.2%	16.1%	56.8%	65.6%	63.9%	68.3%

Note: Scale for trends in output are not the same across countries. For impact indicators, colour gradients are proportional to the gap with the world average. Green is indicative of impact above the world level, and red is indicative of impact below the world level. The fractional counting method was used to attribute papers at the country level for output indicators (e.g., a paper with four authors with two from the UK and one each from France and the US would have 0.5 attributed to the UK, and 0.25 each to France and the US).

N/C: Not calculated due to insufficient sample size (minimum of 30 papers required).

Source: Calculated by Science-Metrix using data from Scopus

D.4.3. *Measurement of enhancement to the UK's international reputation for research excellence and capacity for funder and talent attraction*

Higher global visibility and reputation is often acquired through intensive co-publication with foreign colleagues, and papers resulting from such partnerships tend to be cited at higher rates.

It was clear from Table 29 that for all countries under consideration, the vast majority of CERN papers (between 88% and 99%) are written as international co-publications. UK-CERN papers have a mean number of 13 contributing countries and a median of 7 contributing countries. These numbers are well above figures for non-CERN UK publications (2.68 and 2.00). It can be concluded that, in the UK—as in all other countries included in these analysis—participation in CERN clearly provided researchers with unique opportunities for engagement in highly collaborative and international projects.

Scientific publications resulting from highly collaborative and international research also tend to be cited at higher rates than national collaborations or single-author papers. In other words, they achieve greater levels of visibility. This effect was observed in Table 30 and discussed in the previous section. Again, all performances from countries in the table appear to have benefited from sizable gains in impact brought by their CERN component, limited only by its relatively small volume.

Considering specifically the subsets of publications that have achieved exceptional impact in NPP ($HCP_{5\%}$ and $HCP_{1\%}$) reinforces the conclusions already obtained as to the visibility and strong uptake of CERN research. For the UK as a whole, CERN research achieved $HCP_{5\%}$ and $HCP_{1\%}$ status for 15.5% and 4.8% of publications. These figures stood at 8.6% and 1.7% for non-CERN research.

For these two HCP indicators, the UK was surpassed only by the Netherlands (with an $HCP_{5\%}$ of 11.5% and a $HCP_{1\%}$ of 3.0%). The UK's scores fared slightly less well in the context of an international benchmark relying on CERN papers only, where Canada and Australia joined the Netherlands in having performances above those of the UK. Canada and Australia are particularly rewarded in added visibility and research excellence from their engagement with CERN, given the otherwise lower levels of performance achieved by their non-CERN NPP papers.

To summarise, when it comes to fostering their international reputation for research excellence, the UK has clearly benefited from its engagement with CERN. UK-CERN papers were more often highly cited papers than non-CERN papers in the same subfield. Almost all CERN papers are the result of collaboration with foreign peers originating from a high number of different countries. Finally, the UK would lose places in international rankings in NPP if it was to stop its CERN involvement.

D.5 World-class innovation and their outcomes for the UK

Measurements of patenting activity are commonly used to capture the extent to which research streams or programs foster innovation and economic development. Obtaining intellectual property through the filing of a patent application is often an important milestone in the process of developing a new technology product or service, and citations by patents indicate the usefulness of the results contained in the cited article for subsequent technological development activities. Technometrics, methods used to capture patenting activity, cannot measure all dimensions of the innovation process and innovation outcomes, and firms and inventors use a variety of strategies to protect innovations.[145] However, it provides a robust means of measuring the dimensions it is able to track.

It should be noted that patent application and citation of articles by patents are phenomena that usually manifest at marked delays after the research and innovation activities they are associated with have taken place. Taking into account the time required for the development of a technology and the writing, submission and approval process of a patent, several years usually elapse between (1) R&D work and associated patent application, and (2) the publication of an article and its citation by a patent.

Patents where CERN held intellectual property (for which it is the assignee), as well as all patents making mention of CERN in their description, were captured from the European Patent Office (EPO) database, PATSTAT. The set of patents (a sum of 331 patents in fractional counting) making mention of CERN or with CERN as an assignee were broken out by country, over time and by International Patent Classification (IPC) technical fields. These analyses were produced by country of origin for patent inventors (inventorship), and by country of origin for patent assignees (intellectual property). If CERN has contributed to innovation practices and systems in the UK, a number of UK-based inventors and/or assignees should make mention of CERN in their patent(s), or even share ownership with the Centre itself. The numbers obtained should also compare favourably with those of international benchmarks. In turn, patent counts act as partial evidence that UK industries, consumers, patients and society more broadly benefit from the UK's participation in CERN. It should be noted, however, that the patent analysis is subject to strong limitations.

Finally, a last analysis combined bibliometrics and technometrics by examining the shares of UK research papers citing CERN research and that are themselves cited by a patent. Such a particular combination of analytical units is expected to mirror the path of dissemination from CERN discoveries and inventions to uptake in UK-based (applied) research, and then innovation by the industry. It is hypothesised that patents would not necessarily cite CERN research, but may instead make use of research influenced and fuelled by CERN findings in more applied scientific subfields. The UK's performance on the resulting indicator was measured overall and then without the contribution of UK-CERN papers as the originally cited research; this made it possible to isolate the contributions of these entities to the innovation path. Finally, here again, performances are also measured with the six country benchmarks already used previously.

D.5.1. Measurement of extent of national innovation inspired by CERN technological development

The analysis that follows is based on the assembly of a data set of 331 European patents identified as either assigned to CERN (51), or that mentioned CERN in their description (280). The data set is subject to important limitations. Most crucially, mentions to CERN made in patent documentation were markers of variable strength in capturing the use of CERN findings or tools for technological innovation. In a small number of cases, mentions to CERN were incidental to the R&D presented or did not refer to the Centre as such (for example, a few applications referred to a chemical compound named or abbreviated to "cern"). The data set includes many applications that cited CERN reports or other documents originating from CERN but that did not make any explicit mention of a CERN experiment. Many applications related to information technologies and Internet instrumentation make mention of CERN's role, at a general level, in the development of the World Wide Web and http systems, when

[145] Julie Callaert et al., *Analysis of Patenting Activities of FP7 NMP Projects: Final Report*. (Luxembourg: Publications Office, 2015), http://bookshop.europa.eu/uri?target=EUB:NOTICE:KI0415213:EN:HTML.

discussing prior art.[146] Finally, from a non-random sampling of 110 applications included in the data set, the majority of mentions to CERN (61) were made referring to technologies used in, or findings obtained from, CERN experiments.

The resulting data set is therefore imperfect: the extent of its coverage (recall) is limited by the impossibility of using experiment names in search queries, and its precision is constrained by the number of false positives retrieved when querying for the expression "CERN" and related variants. Science-Metrix considers that limitations are more likely to be pronounced on the precision rather than the coverage dimension in the data set, after point verifications have shown that experiment names such as ASACUSA, ATRAP, Super Proton Synchrotron or NTOF retrieved null or single patent counts in Google Patents.

Moving to the results of the analysis, 198 out of the 331 patent applications were found in five main classes of technical activity (remembering that individual applications can be assigned to multiple classes but that Science-Metrix has divided and weighted attributions so that counts across classes would still add up to 331). These were Computer Technologies (62 applications), Electrical Machinery (43), Environmental Technologies (35), Chemical Engineering (33) and Measurement (25). For most countries included in Table 31 and Table 32, numbers are simply too low for assessment of any type of technological field where national technology systems would be particularly disposed to draw on CERN innovations. This statement applies to the UK in both tables.

The US was the country with the clearest specialisation in knowledge transfer, with the field of Computer Technologies involving 36 of both its 101 inventors and 96 assignees. The US also made comparatively strong showings in Electrical Machinery and Chemical Engineering in both categories of analysis, although numbers here were much lower than for Computer Technologies. Overall, roughly half the patent applications made by US inventors or assignees belonged in IPC classes not included in the table. Other comparatively stronger areas of national uptake of CERN innovation include French inventors in the fields of Electrical Machinery, Environmental Technologies and Chemical Engineering (those strengths do not carry over to French assignees); and German assignees and inventors in the fields of Electrical Machinery and Measurement. Nevertheless, country-level patent counts by IPC classes are generally low and should only be reported in combination with a discussion of the limitations.

Total figures for country counts of patents mentioning CERN innovations were similar whether considering inventorship or intellectual property, with the one exception of France. The UK fell in the middle of the ranking produced in the two analyses, although with large gaps behind the three leading countries in each case. Of patent applications making mention of CERN research, 10 had UK inventors and 13 UK assignees. The USA obtained the largest measurements here, with 101 patent applications including a US inventor and making mention of CERN innovations, and 96 applications with a US assignee and making mention of CERN innovations. France held the second rank when considering inventorship (81 applications) but was third when considering intellectual property (37 applications). French inventors appeared either unable to hold on to the intellectual property they contributed to developing, were formally prevented from doing so by institutional rules or regulations, or tended to work for multinational employers who may formally hold their patents elsewhere than their place of discovery. Germany came in third (40 applications) for its uptake of CERN technologies in novel patent applications, moving to second place for ownership of applications (39). Trailing the UK on the two dimensions of technological uptake were the Netherlands, Canada and Australia.

[146] Michel K. Bowman-Amuah, A system, method and article of manufacture for a multi-object fetch component in an information services patterns environment, European Patent Office EP1259879A2, n.d.

Table 31 Inventorships based on new innovations (EPO patent applications) emerging from technologies developed at/for CERN (1996–2017)

Country	Total Inventorships	Trend	IPC Technical fields: Computer tech.	Elect. Machinery	Environmental tech.	Chemical eng.	Measurement
World	331		62	43	35	33	25
UK	10		1	1	3	1	0
France	81		2	12	12	10	6
Germany	40		2	6	5	1	7
Netherlands	7		0	2	1	1	2
USA	101		36	5	2	5	3
Canada	6		0	0	0	1	2
Australia	1		0	0	0	0	1

Note: Based on EPO patent applications. Patents were identified using Google Patents by searching in the full text of patents as well as in the inventor and assignee fields. IPC technical fields represent the top 5 fields in which CERN-inspired patents were classified. Classes are attributed proportionally based on the number of classes assigned to a patent (e.g., a patent that is classed in both chemical engineering and number measurement will be assigned a weight of 0.5 for each class).
Source: Calculated by Science-Metrix using data from PATSTAT and Google Patents

Table 32 Intellectual property based on new innovations (EPO patent applications) emerging from technologies developed at/for CERN (1996–2017)

Country	Patent Assignees	Trend	IPC Technical fields: Computer tech.	Elect. Machinery	Environmental tech.	Chemical eng.	Measurement
World	331		62	43	35	33	25
UK	13		0	1	3	1	0
France	37		1	6	4	4	4
Germany	39		3	8	4	1	7
Netherlands	10		0	0	2	0	3
USA	96		36	7	2	5	3
Canada	6		0	0	0	1	2
Australia	1		0	0	0	0	1

Note: Based on EPO patent applications. Patents were identified using Google Patents by searching in the full text of patents as well as in the inventor and assignee fields. IPC technical fields represent the top 5 fields in which CERN-inspired patents were classified. Classes are attributed proportionally based on the number of classes assigned to a patent (e.g., a patent that is classed in both chemical engineering and measurement will be assigned a weight of 0.5 for each class)
Source: Calculated by Science-Metrix using data from PATSTAT and Google Patents

Longitudinal trends may be too sparse for robust analysis at the level of individual countries, but they do highlight the stability of CERN-inspired technological activity in the aggregate. Counts of patent applications that make mention of CERN innovation did see a peak in 1997 and 1998, and a slowdown in 2005 and 2007. However, by and large, the story that emerges from this evidence is that CERN steadily contributes to technological innovation, as measured by patent applications.

Coming back to this report's main concern, benefits to the UK from participation in CERN, these appear to be much less certain for technological innovation than they were for scientific research. While numbers of patent applications making mention of CERN innovation are quite low across all cases considered, and the analysis is subject to strong methodological limitations, UK figures are nonetheless well below German and French results, irrespective of the dimension used.

D.5.2. Measurement of extent of national innovation spurred by dissemination of CERN findings

As mentioned earlier, measuring the share of CERN-research-citing papers themselves cited in patents was used as another research strategy to capture some of the broadest socio-economic outcomes of CERN research. As citations from patents toward scientific publications are routinely captured and processed by Science-Metrix, the findings in the current section are in no way subjected to the limitations that applied to the findings from the previous section .

Here again, the figures obtained are quite low across the cases considered. Generally, the considered countries have similar scores with less than 0.5% of papers (all subfields considered) that cited CERN research being cited in at least one patent.

The share of such papers for the UK was on the lower end of the range, at 0.36% overall. This figure stood at 0.38% when papers that cite UK-CERN papers were excluded. These differences, however, are very small and do not provide strong evidence for conclusions about technology transfer capacities associated with different modalities of UK participation in CERN. The best performance on this indicator came from the Netherlands, where 1.04% of papers both cited CERN research and were cited by patents. This figure was far ahead that of the nearest competitor, Australia (scores of 0.63%).

Table 33 Share of papers citing CERN research and in turn taken up in a patent (1996–2012)

Country	Total	Share
UK papers citing CERN	64	0.36%
UK papers citing CERN (excluding UK)	40	0.30%
France	79	0.48%
Germany	108	0.37%
Netherlands	56	1.04%
USA	230	0.47%
Canada	25	0.32%
Australia	18	0.63%

Note: Based on EPO patent applications. A 5-year fixed citation window was used to calculate the uptake of research citing CERN papers in patents. This accounts for patterns and practices in patent citations that may vary between countries. It also allows sufficient time for scientific literature to be acknowledged in patent applications as there is often a lag between when research is published and when it is then applied. The Share column represents the number of papers that have cited a CERN paper that have also been taken up in a patent divided by the total number of papers citing CERN research.

Source: Calculated by Science-Metrix using data from PATSTAT and Scopus

D.5.3. Summary of CERN innovation outcomes for the UK

From the findings reported in sections D.5.1 and D.5.2, it appears that CERN innovations contribute only modestly to patenting activity, irrespective of the country or technical field considered. Nevertheless, even considering this restricted level of activity, the UK appeared to benefit less from CERN innovation than did the US, France, Germany and the Netherlands.

It should be noted that these findings do not capture only the level of output provided by CERN, but that they also assessed a more complex relationship between CERN, its audience in applied science fields and high-technology industry. This relationship is mediated by other factors such as the configuration of national innovation systems or the orientation of national policies for technology transfer.

D.6 Science diplomacy

D.6.1. Collaboration affinity

CERN has been put forward as a model platform for international exchange that doubles up as a science diplomacy achievement.[147] Science-Metrix has developed indicators that make it possible to capture, quantify and measure the relative intensity of collaborations between researchers of different countries.

As detailed in the introduction, the collaboration affinity provides an asymmetric view on the propensity (affinity) of countries to collaborate with each other. In other words, it can serve to measure the propensity of the UK to partner with France (affinity of UK toward France) as well as measure the propensity of France to partner with the UK (affinity of France toward the UK). The collaboration affinity index is the ratio of observed to expected co-publications from either of the above perspectives. It equals 1 in case of neutral relationships, it is higher than 1 in case of positive affinities, and it is below 1 in case of a negative affinities. These affinities can be computed in NPP with and without CERN papers to help disentangle the potential contributions of CERN in shaping the international collaboration landscape in NPP as well as in alleviating tense relationships. In other words, this indicator helps to capture the Centre's contribution to international rapprochement between countries.

Table 34 shows the collaboration affinity between the UK and a selection of 65 other countries. Results include findings for affinity "toward the UK" (the partner country's relative contribution to the UK's collaboration portfolio) and "from the UK" (the UK's relative contribution to the partner country's full collaboration portfolio). Findings have been produced for the NPP subfield, both with and without CERN papers, as a way to highlight the contribution of CERN to international co-publications.

Before examining findings from the collaboration affinity indicator, however, counts of collaborative papers are instructive in and of themselves. In the field of NPP, and considering even a large collaboration partner with which the UK shares a long history of joint work as well as a native language—the United States—CERN output accounts for as much as 30% of co-publications between the countries. This share was the lowest one found in the sample of 65 countries. Indeed, shares were equal to or above 50% for 50 out of the 65 countries in the sample.

The collaboration affinity index of the United States toward the UK stood at 0.84 with CERN papers and 1.46 without CERN. When considering the collaboration affinity from the opposite perspective, the indices stood at 0.30 with CERN papers and 0.77 without CERN. In other words, the inclusion of CERN papers in the NPP areas decreases the affinity of both countries for each other. The same observation can also be made for many countries with established and highly visible science systems.

Countries that see an increase in the collaboration affinity of the UK toward them when CERN is accounted for in NPP include Armenia, Austria, Colombia, Malaysia and Turkey. Unfortunately, the collaboration affinity scores of these countries toward the UK could not be computed (as is the case for many additional countries) due to data issues.

The findings may appear, *prima facie*, to be counter-intuitive: CERN papers decrease the affinity of most collaborative relations included in Table 34. However, the second set of findings above highlight that CERN facilitates a shift in the UK's collaboration landscape toward partner countries with which there is comparatively less interaction otherwise. CERN papers help to shift collaborations away from an obvious partner such as the US toward others such as Malaysia and Turkey.

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[147] Flatten A.K. 2018. Global Research Infrastructures: A Decade of Science Diplomacy. *Science & Diplomacy*. Retrieved from: http://www.sciencediplomacy.org/perspective/2018/global-research-infrastructures-decade-science-diplomacy

Table 34 Collaboration affinity to/from the UK in Nuclear & Particle Physics with and without CERN papers (1996–2017)

	Overall (1996–2017)							Overall (1996–2017)					
	NPP With CERN			NPP w/o CERN				NPP With CERN			NPP w/o CERN		
	Collabs.	towards UK	from UK	Collabs.	towards UK	from UK		Collabs.	towards UK	from UK	Collabs.	towards UK	from UK
United States	13,118	0.84	0.30	9,174	1.46	0.77	Ireland	1,380	N/C	2.15	582	N/C	3.28
Germany	10,629	0.66	0.46	6,716	1.09	1.06	Serbia	1,324	N/C	2.52	57	N/C	N/C
Italy	8,190	0.62	0.50	4,543	1.15	1.06	Ukraine	1,275	N/C	0.75	198	N/C	0.38
France	8,030	0.64	0.63	4,659	1.40	1.37	South Africa	1,246	N/C	1.33	483	N/C	1.70
Switzerland	7,247	0.52	0.80	1,402	N/C	1.58	Georgia	1,235	N/C	2.82	69	N/C	N/C
Russia	6,003	0.37	0.31	3,137	0.62	0.57	Belarus	1,203	N/C	1.99	29	N/C	N/C
Spain	5,953	0.59	0.82	3,101	1.35	1.58	Bulgaria	1,180	N/C	1.32	318	N/C	1.33
Poland	4,411	0.38	0.72	1,751	0.86	1.02	Slovenia	1,169	N/C	1.66	187	N/C	1.05
Japan	4,053	0.59	0.26	2,442	0.99	0.52	Croatia	1,151	N/C	1.69	311	N/C	1.75
Canada	3,989	0.99	0.83	2,599	1.76	1.75	Argentina	970	N/C	0.82	353	N/C	0.91
China	3,948	0.37	0.27	1,898	0.88	0.43	Chile	955	N/C	1.12	270	N/C	1.01
Netherlands	3,761	N/C	1.23	2,011	1.27	2.37	Malaysia	837	N/C	2.01	167	N/C	1.48
Brazil	3,001	0.37	0.61	1,032	N/C	0.70	Cyprus	749	N/C	2.62	123	N/C	2.52
Sweden	2,943	0.68	1.12	1,542	N/C	2.01	Pakistan	749	N/C	1.41	50	N/C	N/C
Greece	2,872	N/C	1.54	608	N/C	1.44	New Zealand	711	N/C	2.70	151	N/C	2.47
Czech Republic	2,729	0.31	1.08	769	N/C	1.14	Iran	673	N/C	0.40	112	N/C	0.20
Belgium	2,708	N/C	1.05	1,252	N/C	1.71	Morocco	658	N/C	2.49	35	N/C	N/C
India	2,357	0.46	0.34	1,274	1.15	0.60	Azerbaijan	625	N/C	3.04	5	N/C	N/C
Portugal	2,318	N/C	1.20	746	N/C	1.47	Egypt	620	N/C	1.06	85	N/C	N/C
Rep. of Korea	2,265	0.33	0.64	1,195	0.68	1.08	Lithuania	610	N/C	3.06	35	N/C	N/C
Hungary	2,193	N/C	1.43	535	N/C	1.41	Estonia	594	N/C	2.92	29	N/C	N/C
Austria	2,154	N/C	1.19	284	N/C	0.63	Thailand	563	N/C	1.93	41	N/C	N/C
Finland	2,063	N/C	1.42	840	N/C	2.19	Ecuador	368	N/C	4.65	227	N/C	9.18
Norway	1,884	N/C	2.05	648	N/C	2.99	Saudi Arabia	368	N/C	1.22	165	N/C	1.50
Australia	1,847	0.61	0.93	985	1.64	1.54	Viet Nam	298	N/C	1.60	62	N/C	N/C
Romania	1,833	0.33	0.95	521	0.84	0.95	Qatar	245	N/C	3.98	6	N/C	N/C
Denmark	1,785	N/C	1.24	586	N/C	1.44	Sri Lanka	242	N/C	4.63	3	N/C	N/C
Armenia	1,762	N/C	2.26	324	N/C	1.99	Kazakhstan	171	N/C	0.75	98	N/C	N/C
Turkey	1,729	N/C	1.18	268	N/C	0.67	Cuba	167	N/C	1.57	6	N/C	N/C
Israel	1,720	N/C	0.95	627	1.09	1.18	Peru	158	N/C	3.30	3	N/C	N/C
Mexico	1,669	N/C	0.68	646	N/C	0.82	Latvia	124	N/C	1.68	36	N/C	N/C
Colombia	1,623	N/C	2.25	314	N/C	1.90	Jordan	100	N/C	1.55	36	N/C	N/C
Slovakia	1,536	N/C	1.67	343	N/C	1.44							

Source: Calculated by Science-Metrix using data from Scopus

Where feasible (i.e. the publication data made it possible to reliably compute CA scores), CA indexes were also computed to explore the affinities between other sets of countries that are otherwise involved in tense diplomatic relationships.[148] Table 35 below shows that India and Japan enjoyed higher co-publication activity with China through CERN papers, greatly increasing the relative weight of that partner in their co-publication landscape (with the CA of India toward China going up from 0.45 to 1.00, and from 0.34 to 1.17 for the CA of Japan toward China). The collaboration affinity of Pakistan toward India was also greatly increased by CERN-related activities. To exemplify this, note that Pakistan had 797 co-publications overall in the NPP field with India, of which only 94 were not identified as CERN papers. Note the data did not enable computing the affinity of India for Pakistan.

Table 35 Collaboration affinity between countries with tense political relations in Nuclear & Particle Physics, with and without CERN papers (1996–2017)

Affinity of	For	NPP with CERN		NPP w/o CERN	
		Collabs.	CA index	Collabs.	CA index
India	China	2458	1.00	1291	0.45
Japan	China	4356	1.17	3385	0.34
Pakistan	India	797	3.03	94	1.44
China	India	2458	0.43	1291	0.95
China	Japan	4356	0.56	3385	1.09
Ukraine	Russia	2242	1.25	1136	1.85

Note: The affinity of India toward Pakistan is not provided because it could not be reliably computed. The same is true of the affinity of Ukraine for Russia.

Source: Calculated by Science-Metrix using data from Scopus

148 Richard C. Bush, "China-Japan Tensions, 1995-2006. Why They Happened, What to Do.," Foreign Policy at Brookings (Washington DC: The Brookings Institution, 2009); Sunil Dasgupta, "The Fate of India's Strategic Restraint," *Current History* 111, no. 744 (2012).

Intentionally or not, CERN appears in some cases to have made contributions to science diplomacy objectives in the specific context of rapprochement between countries with tense political relations. However, this reality is not always mutually shared by the partnering countries.

D.6.2. Centrality in the NPP subfield

Comparing international co-publication profiles across countries, it is also possible to characterise how "central" countries are within NPP collaboration networks — i.e. the extent to which country contributions are included in co-publications, and the extent to which these co-publications are authored together with partner countries that are themselves highly collaborative.

Table 36 presents a selection of results from the centrality analysis. Centrality scores were ranked and compared, both with the inclusion of CERN papers, and without. The countries retained below (from a population of 155 nations) had noteworthy performances either in ranking, or in changes to rankings.

Table 36 Comparison in countries' centrality in Nuclear & Particle Physics, with and without CERN papers (1996–2017)

Country	Rank in centrality without CERN papers	Rank in centrality with CERN papers	Rank changes between datasets	Centrality scores changes
Highest gains of rankins in centrality between datasets				
Qatar	87	58	29	184%
Belarus	59	32	27	494%
Georgia	58	33	25	453%
Estonia	78	54	24	364%
Serbia	51	29	22	337%
Azerbaijan	74	53	21	353%
Lithuania	76	55	21	357%
Palestinian Territory	90	69	21	52%
Armenia	41	25	16	181%
Turkey	39	24	15	150%
Highest losses of ranks in centrality between datasets				
Israel	24	40	-16	11%
Saudi Arabia	42	57	-15	-9%
Ecuador	44	60	-16	-20%
Kazakhstan	49	65	-16	-29%
United Arab Emirates	61	76	-15	-25%
Highest centrality scores				
United States	1	1	0	-43%
Germany	2	2	0	-40%
Italy	3	3	0	-26%
France	4	4	0	-27%
United Kingdom	6	5	1	-28%
Russia	5	6	-1	-32%
Switzerland	15	7	8	66%
Spain	8	8	0	-13%
China	9	9	0	-20%
Poland	10	10	0	-8%

Note: PageRank scores with and without CERN papers were normalised relative to the highest score found: that of the United States without CERN papers. Scores were compared to obtain the amplitude of change without and with CERN papers, and to obtain country rankings on centrality. Countries with fewer than 100 co-publications were excluded.

Source: Calculated by Science-Metrix using data from Scopus

The table shows that the largest changes in centrality scores (when comparing the full NPP publication set and the NPP publication set without CERN papers) for countries with relatively smaller science and innovation systems. While many of these countries have gained multiple ranks moving from one data set to the other, with correspondingly very high magnitudes of change in normalised PageRank scores,[149] other smaller science systems also saw the largest losses in ranks, albeit with restricted changes in centrality scores this time. For example, Israel goes down from 24th to 40th rank in co-publication centrality when CERN papers are added to the NPP publication set. Nevertheless, its absolute score had gone up moving between data sets, albeit at levels lower than its immediate peers.

By contrast, recognised national science systems appeared to achieve the highest levels of centrality in NPP. Given very high initial starting scores, the addition of CERN papers to the analysis, even if it considerably lowered many of these scores (with reductions between 25% and 45% of scores for the top 6 countries, notably), did not significantly reshuffle the top rankings. The United States remained the central collaborator in NPP, whereas the United Kingdom did gain one position (despite an absolute decrease in score). As to be expected, Switzerland makes it into the top 10 central collaborators when CERN papers are taken into account within the NPP data set, but not without them.

Figure 64 (without CERN papers) and Figure 65 (with CERN papers) enable a visual comparison between collaboration networks for both data sets, and associated changes in centrality. Generally, the number of edges (co-publication relations) greatly increases and densifies in moving from the first to the second figure. Figure 64 has some degree of fragmentation and isolated clusters of countries, whereas Figure 65 represents a highly integrated field where all countries are included, albeit to varying levels.

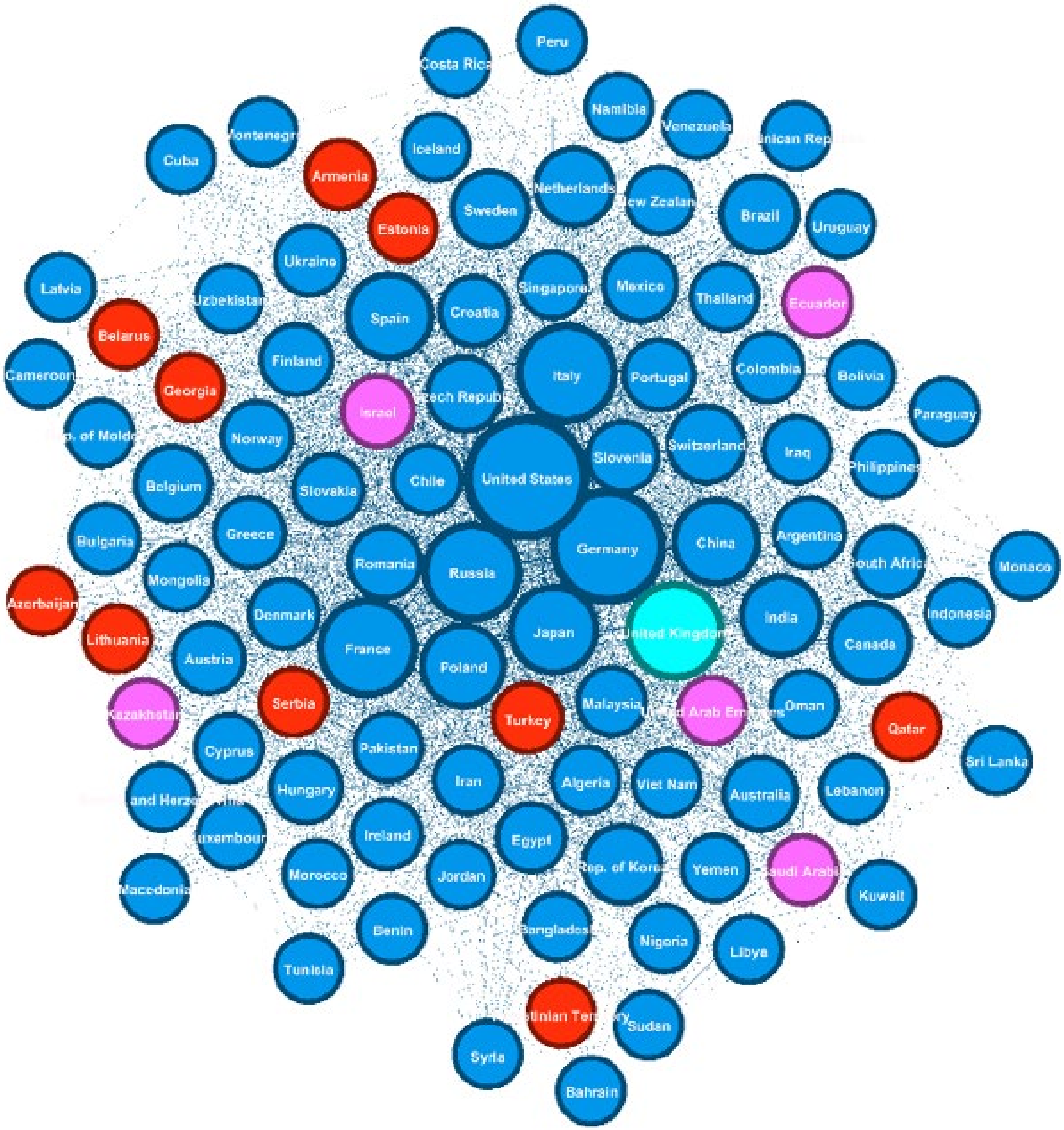
The 10 countries with the highest gains in ranks are represented in red in these graphs, while the 5 countries with the highest losses in ranks are represented in pink. The United Kingdom is highlighted in light blue. Node sizes are representative of a country's count of international co-publications.

These figures make it possible to very roughly track some of the changes noted above. For example, the Palestinian Territory's gain ranks and centrality scores are translated into movement from the periphery and isolation in Figure 64 a bit more toward the centre of the network, in the neighbourhood of other countries, in Figure 65. The same pattern is also clearly found for Serbia. The United Arab Emirates, by contrast, moves in a position of lower integration from Figure 64to Figure 65.

While patterns are more difficult to isolate for the most performing countries, a noteworthy movement came for the US, which moved from clear geometrical centrality in Figure 64 to a more peripheral position in Figure 65, although this position is still highly connected—the country does indeed retain its foremost centrality. The UK's gain of one rank in centrality in the second data set, associated with a loss in centrality score, is translated in a change in immediate neighbours in the move between data sets.

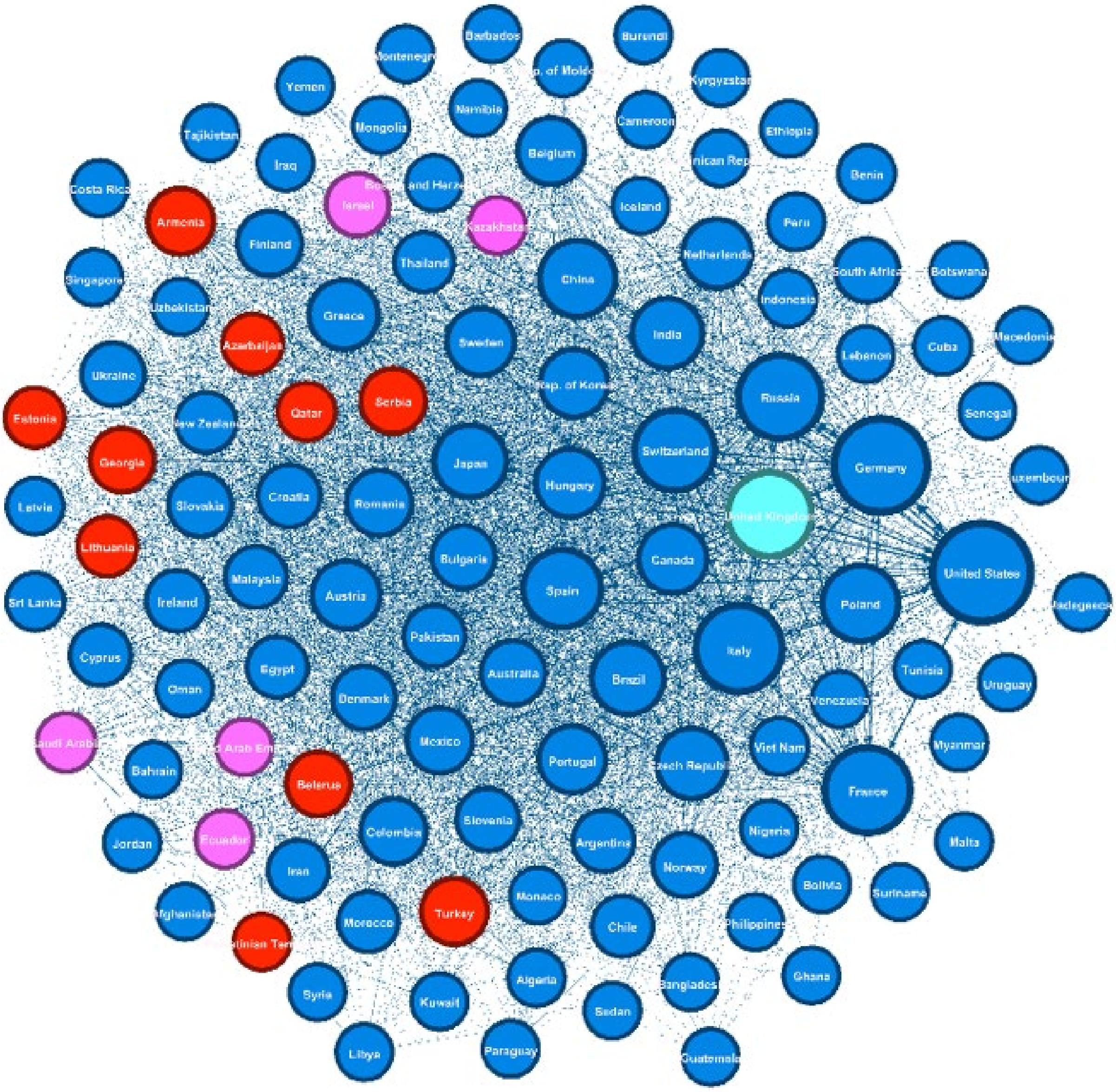
[149] Do note that magnitudes in changes here may be artificially amplified by the impossibility of conducting normalisation with a reference world level; these figures should not be used on their own and must be interpreted carefully.

Figure 64 International co-publication networks in Nuclear & Particle Physics, without CERN papers (1996–2017)



Note: The graph represents the centrality of country contributions to the NPP field as measured through networks of international co-publications. Edges represent the volume of co-publications between countries. Nodes' sizes are adjusted by PageRank score. United Kingdom highlighted in light blue. A selection of countries who moved upwards in rankings based on PageRank scores are highlighted in red. A selection of countries who moved downwards in rankings based on PageRank scores, when moving from datasets without and with CERN papers, are highlighted in pink. Calculated in full counting. Countries with co-publications with fewer than 30 other country partners are excluded.
Source: Prepared by Science-Metrix using Scopus (Elsevier)

Figure 65 International co-publication networks in Nuclear & Particle Physics, with CERN papers (1996–2017)



Note: The graph represents the centrality of country contributions to the NPP field as measured through networks of international co-publications. Edges represent the volume of co-publications between countries. Nodes' sizes are adjusted by PageRank score. United Kingdom highlighted in light blue. A selection of countries who moved upwards in rankings based on PageRank scores are highlighted in red. A selection of countries who moved downwards in rankings based on PageRank scores, when moving from datasets without and with CERN papers, are highlighted in pink. Calculated in full counting. Countries with co-publications with fewer than 30 other country partners are excluded.
Source: Prepared by Science-Metrix using Scopus (Elsevier)

Overall, centrality measurements show that CERN does contribute to a more even distribution of co-publication opportunities in the NPP subfield. Large gains in centrality scores are made by smaller science systems when CERN papers are added to the NPP publication set, although it must also be stressed that these gains are made against other smaller science systems. CERN fosters the collaborative activity of a subset of smaller national science systems, although other such systems either do not participate in or benefit from these opportunities. Ultimately, rankings in terms of co-publication centrality remained very stable for the top 15 performances, despite notable reductions in centrality scores for the most central collaborators.

Appendix E Case studies

Though presented as evidence against one of the impact areas, many of the case studies also demonstrate impact in another area as well. The table below provides an indication of the main impact area (xx) and other supplementary areas of impact (|).

Case Study	World Class Research	World Class Innovation	World Class Skills	Science Diplomacy
1. Discovery of the Higgs boson and completion of the Standard Model	xx			
2. Trapping of antimatter and wider antimatter investigation	xx			
3. Quark Matter (aka Heavy Ions and Quark-Gluon Plasma)	xx	|		
4. The search for new physics beyond the Standard Model	xx			
5. Development of crab cavities	xx	|		
6. GridPP	|	xx	|	
7. GEANT series and simulations for space and radiotherapy	|	xx		
8. Linear proton accelerators and next generation radiotherapy		xx		
9. Gaseous detectors		xx		
10. Silicon detectors and ASICs		xx		
11. Medipix Collaboration	|	xx	|	
12. CMOS image sensors – enabling cryo-electron microscopy (cryo-EM)	|	xx		
13. Radiation-tolerant ASICs		xx		
14. Medical imaging technology: PET imaging and scintillating crystals		xx		
15. Field Programmable Gate Arrays		xx		
16. AWAKE and the potential of plasma wakefields	|	xx		
17. CERN BIC – Oxford nanoSystems		xx	|	
18. CERN BIC – Camstech		xx	|	
19. CERN BIC – Croft Additive Manufacturing		xx		
20. CERN's CLOUD experiment and the role of atmospheric aerosols	|	xx		
21. CERN Supplier – Arcade UK Ltd		xx	|	
22. CERN Supplier – TG Engineering		xx	|	
23. CERN Supplier – H.V. Wooding		xx		
24. CERN Supplier – UHV Design Ltd.		xx		
25. CERN Supplier – Micron Semiconductor Ltd	|	xx	|	
26. CERN Supplier – Exception PCB		xx	|	
27. CERN Supplier – Stevenage Circuits		xx		
28. CERN@School programme			xx	
29. SESAME Light Source	|			xx

WORLD-CLASS RESEARCH

E.1 Discovery of the Higgs boson and completion of the Standard Model

On 4 July 2012, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (both of which have significant and influential UK contingents), announced the discovery of a new particle in the mass region around 125 GeV[150], later confirmed to have properties consistent with those of a Standard Model Higgs boson.

The importance of this momentous experimental discovery, destined to become one of the cornerstones of scientific knowledge, cannot be overstated. Its significance has been acknowledged in many ways, not least through the award of the 2013 Nobel Prize in Physics to François Englert and eponymous British physicist Peter Higgs. In 1964 Higgs (and, independently, Englert and the late Robert Brout) had postulated the theoretical mechanism known as the Brout-Higgs-Englert mechanism, of which the Standard Model Higgs boson is the simplest manifestation. In the words of the Nobel Prize committee, this is "a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

The discovery of the Higgs boson did not happen as a serendipitous event in CERN's distinguished history of scientific exploration, but rather it represents a crucial milestone in a long journey of discovery that has seen CERN taking centre stage for decades. CERN's state-of-the-art facilities (which are and will remain world-leading at the energy frontier for many years yet), together with other facilities around the world, are being exploited to unravel the secrets of the physical world at its most fundamental level.

The theoretical framework that particle physicists use to describe current knowledge of the properties and the interactions of the smallest known building blocks of matter, or elementary particles, is called the Standard Model of particle physics. Developed in the 1960s and the early 1970s, and built on the theoretical and experimental work of thousands of particle physicists since the 1930s, including many a generation of UK physicists working at CERN, the Standard Model describes how matter particles (quarks and leptons) and three of the four known forces (the electromagnetic, weak and strong force – but not gravity[151]) relate to one another.

The exploration of physical laws at the very small distances reveals that, rather than being an indivisible continuum, matter is composed of discrete constituents of ever decreasing size, whose existence becomes evident when physical phenomena are studied at very high energies, such as is the case at CERN's Large Hadron Collider. Beyond the realm of molecules and atoms, one discovers the existence of atomic nuclei and electrons and, inside the nuclei, of protons and neutrons. In turn, protons and neutrons, and any other hadronic matter, are composed of even smaller matter particles, the quarks (of which there are six types: "up", "down", "charm", "strange", "top", "beauty") and possibly also anti-quarks (the quarks' anti-particles). Quarks and anti-quarks are believed to be indivisible and truly fundamental elementary particles, much like the electron, the other two electrically charged leptons (the muon and the tau leptons) and the three neutrinos (the electron, the muon and the tau neutrinos). The Standard Model describes the interactions of matter particles (quarks and leptons) via the exchange of force-carrier particles, also known as "gauge bosons". These are the photon (the light particle, carrying the electromagnetic force, which is responsible for electricity and magnetism), the W and Z bosons (carrying the weak force, which is responsible for many radioactive decays and for making the Sun shine), and the gluon (carrying the strong force, which is responsible for holding things together inside atomic nuclei). The Standard Model "particle zoo" is completed by the recently discovered Higgs boson.

[150] For comparison, this is about 130 times the mass of the proton.

[151] The gravitational force has infinite range and is responsible, for example, for planetary motion. It is by far the weakest of all known forces. A valid quantum theory of gravity is yet to be formulated and gravity is not included in the Standard Model. This is not a problem for the Standard Model, as the extreme weakness of gravity ensures that its effects at the very small distances typical of phenomena involving elementary particles can be safely neglected.

Within the Standard Model, the electromagnetic and the weak forces are understood to be different manifestations of the same underlying "unified" force, known as the electroweak force. Contrary to what would be expected in a basic version of the Standard Model, where all the force carriers would all have masses exactly equal to zero, the W and Z bosons are observed experimentally to have masses nearly 100 times that of the proton. This apparent contradiction is resolved by the Brout-Higgs-Englert mechanism, which, without spoiling the good mathematical properties of the Standard Model, provides an explanation as to how particles can acquire a non-zero mass value. The Brout-Higgs-Englert mechanism postulates the existence of an invisible "Higgs field", which pervades the entire Universe and interacts more or less forcefully with different particles, whether they may be matter particles or force carriers. The more a particle interacts with the Higgs field, the greater its mass is. Particles like the photon (or, in fact, the gluon), which have masses exactly equal to zero, do not interact directly with the Higgs field, while heavy particles such as the W and the Z bosons have significant interactions with the Higgs field and consequently acquire a sizeable mass. The Higgs boson discovered at CERN's Large Hadron Collider is a direct manifestation of the Higgs field, whose existence it hence demonstrates – much like a ripple forming after a pebble has been dropped in a pond.

Over the decades the Standard Model has become established as the theoretical paradigm for particle physics, explaining most, if not all, of the available data. Its success builds as much on the wealth of precise and often ground-breaking experimental results as it does on all the key theoretical advancements that have led to its development. Starting with the first observation of weak neutral currents at CERN's Gargamelle bubble chamber in 1973, which gave the first indirect experimental indications of the existence of the Z boson, the rise of the Standard Model continued with the Nobel-prize-worth discovery of the W and Z bosons by CERN's UA1 and UA2 experiments in 1983. The Large Electron-Positron (LEP) collider, which was housed in the same tunnel as the Large Hadron Collider before construction of the latter commenced, was operational at CERN between 1989-2000. LEP collided electron and positron beams at the highest energies ever reached by an accelerator of its kind, for much of this time functioning as a "Z-boson factory" in order to probe the electroweak interaction with the highest precision possible. Paving the way for the Large Hadron Collider, it provided many key experimental results (amongst which, proof that there are three - and only three - generations of matter particles) which have consolidated the Standard Model as the default reference theoretical framework for particle physics.

With the discovery of the Higgs boson at the Large Hadron Collider, the last outstanding gap in the Standard Model has been filled. This represents a major milestone rather than an arrival point. For many years yet CERN will continue to lead at the energy frontier through the exploitation of data collected at the Large Hadron Collider and its upgrades. Precise measurements of Standard Model processes, including those involving the Higgs boson, will have to be performed in parallel with direct searches for new physics phenomena (see separate case study). Like for other ground-breaking new theories in the past, it is quite possible that the next breakthrough will emerge by shedding light on the cracks of existing theories and showing the limitations of the commonly accepted wisdom, currently represented by the Standard Model. Thanks to the Higgs boson discovery, particle physicists now have a complete theory against which to compare their data, in their quest to find solid and significant inconsistencies between experimental data and theory predictions – the unequivocal sign of a new paradigm-shifting discovery.

Supporting evidence

- Interview with Prof. Sir Tejinder Virdee (former spokesperson for CMS), Imperial College
- Case written and developed by Antonella De Santo, University of Sussex
- https://home.cern/science/physics/higgs-boson

E.2 Trapping of antimatter and wider antimatter investigation

In 1931, British physicist Paul Dirac predicted the existence of antimatter, winning him the 1933 Nobel Prize in Physics. Classical physics only allowed systems to have positive energy, but Dirac's new theory allowed for a particle now interpreted as an antimatter electron, as a counterpart to the familiar positive-energy electron. Today, it is understood that all particles have an equivalent antimatter particle with opposite charge and quantum spin. The positively charged positron, for example, is the antiparticle to the negatively charged electron. Matter and antimatter particles are always produced as a pair and, if they come in contact, annihilate one another, sometimes leaving behind pure energy.

The Big Bang should have created equal amounts of matter and antimatter. However hardly any antimatter is seen in the observable Universe. The mechanism underlying this asymmetry, i.e. favouring matter over antimatter, is called the “charge-parity (CP) violation”. The question of why there should be vastly more matter than antimatter is one of the great unsolved problems in physics, and one that research at CERN is investigating. This is being done by studying the subtle differences in the behaviour of matter and antimatter particles created in high-energy proton collisions at the Large Hadron Collider, as part of the LHCb experiment, and by investigating the properties of antiatoms at CERN’s Antiproton Decelerator.

Antimatter behaviour in the LHCb experiment

The asymmetry between matter and antimatter observed in the Universe cannot be explained by the Standard Model (SM) of particle physics. Scientists are hence looking for evidence for new physics (NP) beyond the Standard Model to explain this observation.

The Large Hadron Collider beauty (LHCb) experiment is designed to study a type of particle called the "beauty quark" (or "b quark"), which has properties highly sensitive to NP and can hence give clues to the matter-antimatter asymmetry. Quarks combine to form composite particles called hadrons - the most stable of which are protons and neutrons. LHCb recorded the particles produced by the first circulating LHC proton beam on September 10th, 2008. It concluded its operation period in December 2018 and is delivering a suite of measurements of CP violation in beauty quarks. In 2019 LHCb announced the discovery of CP violation in charm quarks, another fundamental particle species that provides an alternative laboratory to search for NP influences. LHCb will restart in 2021, after the two-year shutdown of the LHC, with an almost completely new detector to allow operation with a higher rate of proton-proton collisions and improved performance.

The LHCb experiment has investigated CP violation in beauty quarks since data-taking began, with a suite of measurements that improve our knowledge of matter dominance at the fundamental particle level. In 2019 LHCb announced the discovery of CP violation in charm quarks. Besides CP violation, the LHCb experiment has identified a range of new ‘exotic particles’ and characterised their decays. This has included the discovery of two pentaquarks (particles containing five quarks) in 2015, three tetraquarks in 2016, five baryons (particles containing three quarks) in 2017, and three additional particles in 2018. The collaboration has also reported findings that do not fit the Standard Model, providing tantalising hints at new physics beyond the Standard Model.

With eleven participating institutes, the UK is the largest contributing country to the experiment, and accounts for approximately one-eighth of its registered researchers (2016). LHCb-UK has primary responsibility for two key detector systems of the LHCb: the Ring-Imaging Cherenkov (RICH) particle identification system and the silicon vertex locator (VELO) system. Both systems identify specific types of particles from the multitude of particles produced when the LHC’s proton beams collide.

Trapping of antimatter at the antiproton decelerator

The Antiproton Decelerator (AD) slows down antiprotons, which are created when a proton beam is fired into a block of metal. These low-energy antiprotons can be used for studies of antimatter, and the “creation” of antiatoms. Since 2010, the AD experiments have published numerous measurements of antimatter characteristics, comparing them to those of matter. For example, in June 2011, the ALPHA experiment, located at the AD storage ring successfully trapped atoms made up of antimatter for over 16 minutes (300 antihydrogen atoms). This is long enough to begin to study their properties in detail. This was a world first: previously antimatter had only been held for two-tenths of a second. As well as the scientific results produced, the ALPHA experiment achieved impact via the massive media publicity it has received across the scientific and popular press. UK researchers were instrumental to the achievement. For example, the Swansea Atomic, Molecular and Quantum Physics group played a leading role in ALPHA, with the largest representation of any institution in CERN's antihydrogen experiments. Other UK collaborators involved in ALPHA included the Universities of Manchester and Liverpool. In 2012, the first measurement of the antihydrogen spectrum was published.

Supporting evidence

- Interview with Niels Madsen (ALPHA Deputy Spokesperson), Swansea University
- Interview with Tim Gershon (spokesperson for LHCb-UK collaboration), University of Warwick
- Interview with Mike Charlton (founding member of ALPHA experiment), University of Swansea
- Interview with Guy Wilkinson (founding member of LHCb, member of LHCb UK community and previously LHCb spokesperson (2014-17), University of Oxford
- Case written and developed by Antonella De Santo, University of Sussex
- http://results.ref.ac.uk/Submissions/Impact/2317
- http://alpha.web.cern.ch/collaboration
- Amole, C et al (2012) Resonant quantum transitions in trapped antihydrogen atoms. Nature 483: 439
- http://lhcb-public.web.cern.ch/lhcb-public/
- https://home.cern/science/physics/matter-antimatter-asymmetry-problem
- https://home.cern/science/accelerators/antiproton-decelerator
- https://home.cern/news/news/accelerators/discovery-new-class-particles-lhc
- https://home.cern/news/news/experiments/lhcb-unveils-new-particles-0
- http://www.lhcb.ac.uk/LHCb-UK/Welcome.html
- https://home.cern/news/press-release/cern/cern-experiment-traps-antimatter-atoms-1000-seconds
- https://home.cern/news/press-release/physics/lhcb-sees-new-flavour-matter-antimatter-asymmetry

E.3 Quark Matter (aka Heavy Ions and Quark-Gluon Plasma)

The strong force, responsible for holding things together inside atomic nuclei, is one of three fundamental forces described by the Standard Model of particle physics, which incorporates the theory of strong interactions known as Quantum Chromo-dynamics (or QCD).

At ordinary temperatures, due to the action of the strong force, quarks are confined into composite and exceedingly small[152] particles, called "hadrons"[153]. The strong force itself is not felt at large distances. At very high temperatures (of the order of one trillion degrees Celsius), hadrons "melt" into their constituents "partons" (quarks, antiquarks and gluons) and the dynamics of physical systems must be understood in terms of the strong interaction.

In the early Universe, only a few millionths of a second after the Big Bang, temperatures were indeed very high, and matter took the form of a hot "soup" of particles, dominated by quarks and gluons, called the "quark-gluon plasma". Under the action of the strong force, this state of matter is seen to behave

[152] The typical size of a hadron is a few femtometers, where one femtometer is equal to one millionth of a billionth of a meter (0.000000000000001 meters).

[153] Protons and neutrons, each containing three "valence" quarks "glued" together by the strong-interaction force-particles, the gluons, are examples of one kind of hadrons called "baryons". Other hadrons, called "mesons", each contain a quark-antiquark valence pair.

quite similarly to a perfect liquid with small viscosity (and not like a gas, as it had been initially anticipated).

Powerful particle accelerators such as the Large Hadron Collider at CERN (or the Relativistic Heavy Ion Collider, RHIC, at Brookhaven National Laboratory in the US) are used to replicate extreme conditions of temperature and pressure similar to those of the early Universe, in order to study the physical properties of the quark-gluon plasma. Very energetic beams of heavy ions (e.g., gold or lead nuclei) are made to collide head-on in particle detectors such as the ALICE, ATLAS or CMS experiments at CERN, to form microscopic "fireballs" in which all particles melt into a quark-gluon plasma.

The quark-gluon plasma is not a stable state of matter and disintegrates virtually instantaneously. Its physical properties can be investigated through the analysis of the particle debris (essentially hadrons) emerging in all directions from those same very energetic heavy-ion collisions in which the plasma is formed. Hadrons, which form from the recombination of the primary parton fragments produced in the main interaction, can sometimes emerge from collisions in narrow cones of particles known as "jets"[154].

Jets in heavy-ion collisions appear to behave rather differently from those in standard proton-proton collisions. They have to interact strongly to push through their dense surroundings and their energy may be significantly reduced ("quenched") as a consequence, in extreme cases completely extinguishing the jet. The study of jets and jet quenching in large samples of heavy-ion collisions can be used to extract information on the properties of the quark-gluon plasma.

The much greater energies available at CERN's Large Hadron Collider allow physicists to study the physics of jets and other physical phenomena in heavy-ion collisions a lot more extensively than before, in turn yielding a more detailed experimental characterisation of the quark-gluon plasma at the energy frontier – ultimately gleaning insights into the physics of the early Universe.

Supporting evidence

- Case written and developed by Antonella De Santo, University of Sussex
- https://home.cern/tags/quark-gluon-plasma

E.4 The search for new physics beyond the Standard Model

The discovery of the Higgs boson at CERN's Large Hadron Collider in 2012 confirmed the validity of the Brout-Englert-Higgs mechanism and, in so doing, filled the last remaining gap in the Standard Model's elegant theoretical construction. Far from representing the arrival point in the quest to understand the most fundamental laws of physics, the ground-breaking discovery gave a strong impulse to continue the exploration of the microscopic world of elementary particles.

The Standard Model has been probed to a very high degree of precision for a wide range of physics phenomena involving the interactions of elementary particles, nearly always returning experimental results that are consistent with theory predictions. However, for all its merits and successes, the Standard Model remains an incomplete theory, which in itself is insufficient to explain (or, in some cases, even to begin to address) several key outstanding problems in experimental and theoretical particle physics. For example, the Standard Model does not incorporate a description of gravity[155], whose existence it simply ignores, nor does it provide an explanation for the nature of so-called dark matter, the invisible matter substance that fills about one quarter of our Universe. The Standard Model also cannot explain the matter-antimatter asymmetry in the Universe and fails to describe a well-established physics phenomenon called "neutrino oscillations", whereby neutrinos belonging to different lepton

[154] Jets of hadrons collectively tend to travel in the same direction as the fragment from which they originate. They were observed in heavy-ion collisions for the firsts time at RHIC in 2003.

[155] A successful quantum theory of gravity has not been developed yet.

families are seen to change ("oscillate") into one another while travelling over a certain baseline from production to detection point[156]. Another puzzle not addressed by the Standard Model is the so-called "hierarchy problem", as reflected in the large discrepancy between the extreme weakness of the gravitational force and the comparatively greater strengths of the other three known forces[157].

In the same way that the laws of Newtonian mechanics are more than adequate to describe the everyday behaviour of not-so-fast and not-so-small objects (e.g. the orbits of planets in our solar system, the motion of a car in traffic, and so on), the Standard Model is more than adequate to describe the bulk of our knowledge of the physics of elementary particles and their interactions. However, in the same way that Einstein's theory of special relativity had to be developed to explain the behaviour of objects moving at (or close to) the speed of light, and the laws of quantum mechanics had to be unlocked in order to make sense of the surprising behaviour of microscopic physical systems, the Standard Model needs to be extended to explain certain experimental observations, or to overcome certain theoretical challenges.

Physics processes that cannot be explained using the theoretical framework provided by the Standard Model are often grouped together under the common umbrella of "beyond the Standard Model (BSM) physics". To this category belong well-established experimental phenomena, such as neutrino oscillations, but also yet-to-be-discovered new processes, often involving new elementary particles, and whose existence may be postulated by certain extensions to the Standard Model, such as supersymmetry.

Together with the characterisation of the Higgs boson's properties (and the study of neutrino oscillations), the search for new BSM phenomena is at the very top of the worldwide experimental particle physics effort. Thanks to its unparalleled capabilities, especially through the Large Hadron Collider's physics capabilities (and the CERN Neutrino Platform[158]), CERN very much leads the way in the search for BSM physics at the energy and intensity frontiers.

In some "vanilla-type" BSM scenarios, evidence for the existence of new physics may be expected to emerge as some striking experimental "signature" in data, which could in principle be used to easily set aside "signal" processes from the more conventional Standard Model "background" processes. Alternatively, in harder-to-find BSM scenarios, new physics phenomena would likely manifest themselves through a combination of less striking (and, in fact, potentially rather subtle) deviations from Standard Model expectations, whose compounded significance could ultimately also amount to a positive discovery. Either way, before any statement can be made about consistency or not between observations and theory predictions, Standard Model processes (and the detector response to those) need to be understood in great detail by physicists, often through painstakingly careful, unbiased analysis of very large samples of data.

Progress in the search for new physics is often punctuated by "null results", when good agreement between experimental findings and theory expectations is used to restrict the range of viable theoretical scenarios that remain compatible with observations. Other times, useful hints may appear as persistent "anomalies" in data collected by specialised experiments, when sizeable but not sufficiently significant discrepancies may be observed between precise experimental measurements and equally precise theoretical calculations, often of rare processes. All these results can then be considered together to guide future experimental explorations and the development of new creative theoretical solutions. As is very typical for the advancement of physical knowledge, piecing together many pieces of a complex jigsaw is just as important, and often yields similarly significant advancements, as the serendipitous direct observation of some unexpected new phenomenon in data.

[156] Contrary to one of the basic assumptions in the Standard Model, which treats neutrinos as having exactly zero mass, neutrino oscillations can only happen in Nature if the mass of at least one neutrino, however small, is in fact different from zero.

[157] Or, in other words, the smallness of the Higgs boson's mass compared to the grand unification energy scale, at which the electromagnetic, strong and weak forces are expected to become equal in strength, as in the early Universe.

[158] The "CERN Neutrino Platform", which includes the provision of a facility at CERN, was recently instituted to allow the global community of neutrino experts to develop and prototype the next generation of neutrino detectors.

Understanding the nature of **dark matter** remains one of the most intriguing challenges in fundamental physics. Dark matter is so called because, contrary to ordinary matter (protons, neutrons, electrons and so on), it does not interact via the electromagnetic force (which is mediated by the light particle, the photon) and therefore it does not "shine" through telescopes. Instead, it remains invisible over the entire electromagnetic spectrum. Its existence can be inferred indirectly from astronomical observations, such as measurements of how galaxies rotate around their centres, or the observation of gravitational effects that can only be explained if some invisible (dark) matter is present in the Universe.

From the analysis of cosmological data, we know that dark matter makes up the vast majority of the matter content in the Universe (it is more than five times the amount of ordinary matter), and about one quarter of the total energy density in the Universe.[159]

As dark matter has so far not been detected experimentally, it can be deduced that it must only barely interact with ordinary matter and radiation. The leading candidate constituent of dark matter is some new weakly-interacting massive elementary particle (**WIMP**) yet to be discovered. While several experiments are seeking to detect WIMPs directly through their interactions with (often very large) underground detectors, dark matter particles, if they are not too heavy, may also be produced in high-energy proton-proton collisions at CERN's Large Hadron Collider. The search for dark matter particles is one of the most exciting aspects of the vibrant ongoing programme of BSM physics searches at the Large Hadron Collider.

Supersymmetry is one elegant extension of the Standard Model that, as well as addressing some very interesting theoretical questions[160], could also provide a viable candidate for a dark matter particle constituent.

All known elementary particles can be subdivided into two broad groupings, depending on how they behave in the presence of a magnetic field (i.e. depending on their "spin"): fermions (which have half-integer spin values and prefer to keep in separate physical states to one another) and bosons (which have integer spin values and prefer to be in the same physical state). Supersymmetry creates a link (a "symmetry") between these two kinds of particles. For each Standard Model boson, there would be a fermionic supersymmetric partner, and for each Standard Model fermion a supersymmetric bosonic one, each with the same interactions as their Standard Model counterparts but considerably larger masses.

In many scenarios the lightest of the supersymmetric particles (often identified with a new particle called "neutralino") is quite heavy, does not decay to lighter particles, does not carry an electric charge, and interacts only weakly with ordinary matter – thus pretty much fitting the bill for being a viable particle constituent of dark matter.

Dark matter candidates may also arise in other BSM theories alternative to supersymmetry. Some of these, for example, postulate the existence of additional spatial dimensions, while others suggest the existence of a "hidden valley" where dark matter particles live having very little connections with ordinary matter. These and other theories, as well as supersymmetry, are all being studied vigorously by CERN experiments taking data at the Large Hadron Collider. If one of these theories were shown to be true, the discovery would not only herald a new age for BSM physics, but also potentially shed light on one of the biggest outstanding puzzles in fundamental physics, the origin of dark matter. This would ultimately gain us a deeper understanding of what the Universe is made of and how it is kept together.

<u>Supporting evidence</u>

- Case written and developed by Antonella De Santo, University of Sussex

[159] The remaining three quarters of the energy density in the Universe is called "dark energy", an unknown form of all-permeating energy that tends to accelerate the expansion of the Universe.

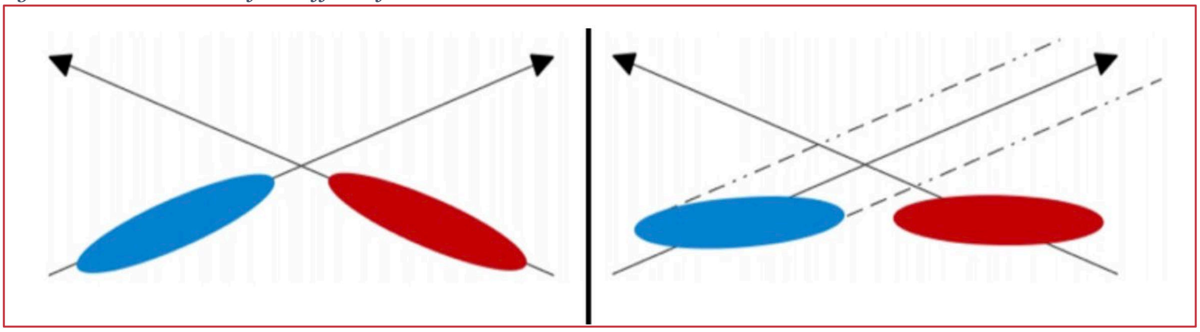
[160] For example, the hierarchy problem, or the unification at very high energies of the strength of the three forces described in the Standard Model.

E.5 Development of crab cavities

CERN's research on sub-atomic particles relies on particles interacting at extremely high energies and in quantities sufficient to allow observation of extremely rare processes. The two most important properties characterising the capability of a facility for particle physics are energy and luminosity. Energy is related to the acceleration of the beam of particles achieved by the facility's electric fields. Luminosity is a measure of the rate at which particles collide (i.e. the number of collisions that occur in a given amount of time). The High-Luminosity LHC (HL-LHC) project aims to increase the luminosity of the LHC by a factor of 10. The higher the luminosity, the more collisions, and the more data the experiments can gather to allow them to observe rare processes.

As part of the HL-LHC project, special cavities, called 'crab cavities', have been developed. The LHC's two counter-circulating beams meet at an angle at the collision point of the experiments within a so-called cavity – a metallic chamber containing an electromagnetic field. These beams are not a continuous string of particles, but are divided into chunks of a few centimetres, or 'bunches', each containing around 100 billion protons. To maximise the number of particle collisions, crab cavities were designed to tilt the proton bunches, forcing every proton of the bunch to pass through the whole length of the opposite bunch and thus increasing the probability that it will collide with another particle. This movement gave the technology its name: after being tilted, the motion of the proton bunches appears to be sideways, just like a crab's.

Figure 66 Illustration of the effect of crab cavities



Left: Illustration of the collisions in the present configuration of the LHC where the proton bunches meet with a crossing angle. Right: Illustration of the effect of the crab cavities on the bunches. After the bunches are tilted by the transverse radio-frequency field in the crab cavities, they collide head-on at the collision point. (Image: CERN,)

The two first crab cavity prototypes were assembled and tested at CERN in 2017, and on 23 May 2018, a proton beam from the Super Proton Synchrotron (SPS) accelerator was rotated for the first time, showing that bunches of protons could be tilted using these superconducting transverse radio-frequency cavities. In total, 16 crab cavities will be installed in the HL-LHC – eight each near ATLAS and CMS.

The UK, the US and CERN collaborated on the development of the crab cavities, with researchers from the UK taking a leadership role in the development and construction of this technology. This includes:

- Engineers from Lancaster University, who were involved in (in many cases led) the design of a number of sub-systems, and participated in all phases of testing from sub-systems to the final test
- Researchers at the University of Manchester and the University of Liverpool, who were involved in modelling of the beam dynamics and understanding how to measure the crabbing
- Engineers from STFC's Daresbury Laboratory, who developed the cryomodule that encloses the crab cavities and keeps them cool with superfluid liquid helium. The team was a key player at every stage of developing the cryomodule from developing basic concepts, undertaking extensive engineering analysis to developing key components such as the cold magnetic shielding.

Due to the specific and exacting requirements of this technology, the development process encouraged contributors and contractors to push the boundaries and develop new solutions to the challenges these requirements posed. In doing so, through providing technology for CERN, the UK research and engineering community was invited to participate in and conduct world class research and development.

Around 50% of the budget for the UK's work on Crab Cavities was inward investment from CERN.

Supporting evidence

- Interview with Peter McIntosh, Technical Director, (ASTeC) Accelerator Science and Technology Centre
- Interview with Rob Appleby (HL-LHC UK Spokesperson), University of Manchester
- Interview Graeme Burt (HL-LHC-UK manager and UK crab leader), University of Lancaster/ Cockcroft Institute
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E.6 GridPP

GridPP provides the very large-scale computing, storage and software infrastructure required by the Large Hardon Collider (LHC).

At the beginning of the millennium, the Large Hadron Collider (LHC) at CERN was the first project to require processing of petabyte-scale datasets (a million gigabytes), which were arising from the very large ATLAS, CMS, LHCb and ALICE experiments running at its interaction points. The scale of the data and the international nature of the LHC, led to the development of grid computing and what is now known as the Worldwide LHC Computing Grid (WLCG).

The WLCG is a global collaboration of more than 170 computing centres in 42 countries[161] linking up national and international grid infrastructures set up to store, distribute and analyse the 100 PB of data produced by the LHC at CERN and the 500 PB of processed and simulated data. The WLCG is composed of levels, or "Tiers", each providing a specific set of services:

- Tier 0 is the CERN Data Centre (the facility located at CERN is supplemented by a satellite facility at the Wigner Research Centre for Physics in Budapest). All of the data from the LHC passes through this central hub, but it provides less than 20% of the Grid's total computing capacity. CERN is responsible for the safe keeping of the raw data (millions of digital readings from across the detectors), and performs the first pass at reconstructing the raw data into meaningful information. Tier 0 distributes the raw data and the reconstructed output to Tier 1, and reprocesses data when the LHC is not running.
- Tier 1 consists of 13 computer centres (including at the STFC RAL) that are large enough to store LHC data. They provide round-the-clock support for the WLCG, and store a proportional share of raw and reconstructed data, perform large-scale reprocessing and store the corresponding output; distribute data to Tier 2; and store a share of the simulated data that Tier 2 produces. Optical-fibre links (working at 10 gigabits per second) connect CERN to each of the 13 major Tier 1 centres around the world. This dedicated high-bandwidth network is called the LHC Optical Private Network.
- Tier 2 centres are typically groupings of universities and scientific institutes that can store sufficient data and provide adequate computing power for specific analysis tasks. They handle a proportional share of the production and reconstruction of simulated events. There are around 155 Tier 2 sites around the world, including in the UK. There are 20 institutes that make up the UK's GridPP.
- Individual scientists can then access the Grid through local (Tier 3) computing resources, which can consist of local clusters in a university department or even an individual PC. There is no formal engagement between WLCG and Tier 3 resources.

This computing infrastructure underpins the analysis of all data produced by the LCH and experiments at CERN. In turn, this infrastructure contributes, and is referenced in all resulting publications.

The UK was at the forefront of the emerging Grid computing paradigm at the time, and this has now evolved into a more generic globally distributed computing infrastructure which can support many diverse communities. The UK contributes its share of the computing resources to the WLCG through GridPP. GridPP is a collaboration involving 20 different research institutions in the UK and has been supported by £115m from STFC since 2000. The project is comprised of the UK's Tier 1 facility at Rutherford Appleton Laboratory, and four distributed Tier 2 facilities (ScotGrid, NorthGrid, SouthGrid and London Tier2), and a team of computing specialists who run the software infrastructure running over these sites. The work of the WLCG has been enabled by the GridPP programme whilst the UK has benefitted by being embedded in a global effort to invent the technology.

161 http://wlcg.web.cern.ch/

GridPP comprises not only the physical-infrastructure (computing nodes, storage and networking) but also a sophisticated software-infrastructure needed to allow any international scale computing to function on over 700,000 processors worldwide. Examples of software assets "invented" for use include:

- Tools for organising and managing large internationally distributed "virtual collaborations" (VOMS)
- Services for transporting, accessing and managing Peta Byte scale data sets (FTS, XrootD, RUCIO) – i.e. large groups of researchers who are identified by belonging to a scientific project not centred on any one institute or country.
- Systems for managing submission and retrieval of complex workloads across the CPU power available across the world (e.g. DiRAC)
- A service that allows application software to be deployed, managed, and used wherever it is needed on the Grid (CernVM-FS)

To illustrate the power and sophistication of this system: a 'job' launched into the GridPP will be routed to a CPU resource somewhere/anywhere in the world that is selected based on the location of data-files needed and the capability and availability of the computational resource. The AAAI (Authentication, Authorisation, and Accounting Infrastructure) means that all access and transport issues are handled transparently, and the data accessed automatically, wherever it is located. Finally, usage is accounted for in a global system and the results returned to the originator, be they a member of a computing team carrying out large scale Monte Carlo production on behalf of an experiment taking thousands of CPU hours, or an individual's analysis running on a single data set. This is an extremey sophisticated distributed computing system, and no other science project has such a parallel.

Benefitting other sciences: For over a decade, CERN and the LHC has driven the largest scale scientific computing developments, which are now beginning to help other sciences reaching similar scales of data generation. GridPP already works with diverse communities outside the immediate LHC context, including other particle physics experiments (NA32, T2K, SNO, LuxZeplin Dark Matter Experiment and now the DUNE Neutrino experiment), PhenoGrid, and some astronomy projects (SKA and LSST). GridPP also supports other physics (e.g. the ITER fusion experiment); health (e.g. modelling disease epidemiology (EPIC), proteomics and phylogenomics, drug development); and geography (e.g. through geographic modelling of landscapes (MoSSaiC) and populations (GENESIS). A medical proton therapy project (PRaVDA) performed Geant4-based solutions on GridPP and as a result, the team has been able to move to simulations using five times more particles-per-simulation while reducing total run times from weeks to hours.[162]

The strength and expertise of GridPP has underpinned its involvement in further EU-wide activities, including:

- **EOSC-hub** is the flagship EU H2020 project for e-Infrastructure/Research Infrastructure integration and operation 2018-2020. STFC leads the task on Operational Security and continues to operate and develop the Operations Centre Database (GOCDB) and APEL accounting services. This work is also supported by **EGI** – the European Grid Infrastructure.
- **AENEAS** is the EU project to design a future SKA Regional Centre (SRC). There is much scope for LHC-SKA cooperation underlined by the formal CERN-SKA agreement. GridPP is involved here as several pieces of WLCG technology are likely to be applicable.
- **SeaDataCloud** is developing compute and storage services for the SeaDataNet ocean observation community.
- **PaNOSC** is developing distributed data services for the photon and neutron science community. STFC is funded as a third party (via EGI and facilitated by STFC's exisiting relationship with EGI). This work will provide support and some integration and development effort for the file transfer

[162] GridPP Case Study: PRaVDA. Available online: https://www.gridpp.ac.uk/researchers/case-studies/pravda/

service (FTS) that STFC currently runs for WLCG, as well as further support for the Echo petascale datastore run by STFC for WLCG.

Software re-use: The software infrastructure has also been re-used outside of particle physics, which reflects the fact that any science which grows to a scale requiring large scale distributed computing will inevitably have to invent or use WLCG-like software, e.g. the LIGO (Gravitational waves) uses CernVM-FS for the distribution of data, SKA, LSST and Lux Zeplin (dark matter) and many others use DiRAC for workload management. The VOMS service is widely used to manage identities and associate roles for members of globally distributed collaborations.

In addition to the contribution made directly to all of these projects, GridPP is embedded into a coordinated effort to create a UKRI wide common infrastructure, which will support researcher communities from a wide range of disciplines across all of UK research and innovation.

In order **to support skills development**, GridPP is actively making its resources available to schools to enable student researchers to store data and analyse results from their Medipix detector measurements (Medipix is a medical imaging development). This includes for example the Langton Ultimate Cosmic ray Intensity Detector (LUCID) project[163], a research project designed by students from the Simon Langton School for Boys (Canterbury, UK) in association with the CERN@School programme. The team behind the satellite-based LUCID experiment have run Geant4 simulations of their Medipix detectors on the Grid in order to better understand the data collected since its 2014 launch aboard Surrey Satellite Technology Limited's TechDemoSat-1.

GridPP also benefits UK businesses, through use of the GridPP infrastructure and software development.. For example, in 2007 funding was awarded to QMUL and industrial partner Econophysica to develop a powerful new trading platform for various businesses requiring massive commodities trading capabilities. As a result of this collaboration, several financial computational algorithms were adapted for Grid computing and Econophysica observed significant speed improvements for pricing derivatives. Looking back at the work achieved over this period, Dr Oleg Soloviev, CEO of Econophysica, identified that the company's association with this research and collaborating with QMUL helped to raise the profile of the company and move the company forward in the industry. In 2007, the net worth of Econphysica was <£200k, in 2016 the net worth of Econophysica was approximately £540k.

GridPP has also collaborated successfully with imense, a Cambridge start-up company developing image search algorithms. Using the GANGA interface that GridPP helped develop and the GridPP infrastructure, imense was able to process 12.4 million images in one month, with their work on the Grid leading directly to venture capital funding. Collaboration in this area is now led by a company called Camtology, which is a joint venture between imense and iLexIR, an SME with expertise in text analysis. GridPP has also supported Total Oil's Geoscience Research Centre to test the potential of Grid computing to analyse the seismic response of marine tests.

The impact of GridPP for businesses is also delivered through the development of software tools and systems. For example, when the GridPP Tier 1 storage system needed updating, RAL deployed CEPH, a free sofware storage platform to link diverse servers. The deployement of this platform required development and adaption of the software, pushing in new directions through the development of new capabilitites. CEPH is an open source software tool that is used internationally by companies and scientific research communities. As such, the capabilities driven by RAL and GridPP have also found applications for companies across the globe using this software for a range of applications. Similarly, GridPP has also been a major contributor (and release manager) to the source Quattor project, also used by commercial organisations.

GridPP has also worked collaboratively with companies within H2020 projects. Building on CEPH further, GridPP staff worked with the research arm of Seagate based in the UK to develop a multi-tiered

[163] GridPP Case Study: Case Study: LUCID. Available online: https://www.gridpp.ac.uk/researchers/case-studies/lucid/

object-based data storage system, partially funded by the H2020 Sage project. Within the HNSciCloud project, GridPP worked with commercial partners (including IBM and HPE) to develop a hybrid private/public cloud platform.

The deployement of this platform required development and adaption of the software, pushing in new directions through This work developing Ceph also resulted in an RAL contibuting to the H2020 project SAGE in collaboration with UK company Seagate Systems UK and Diamond Light Source.

Supporting evidence

- Interview and further evidence provided by Professor Peter Clarke, University of Edinburgh
- Interview with Dr Andrew Sansum, Head of Systems, Scientific Computing Department, STFC (previously Tier 1 manager and GridPP5 manager)
- GridPP Case Study: PRaVDA. online: https://www.gridpp.ac.uk/researchers/case-studies/pravda/
- GridPP Case Study: LUCID. online: https://www.gridpp.ac.uk/researchers/case-studies/lucid/
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- http://econophysica.com

E.7 GEANT series and simulations for space and radiotherapy

Geant4 is a toolkit used to simulate the passage of particles through matter. It is currently the leading toolkit for detector simulation and was specifically designed for use across a variety of different application fields. These include electromagnetic processes, hadronic processes, optical photon processes, decay processes, shower parameterisation, and event biasing techniques. The software consists of an extensive set of libraries which are object-oriented and based in C++.

Geant4 has its roots in the GEANT system ("Geometry and Tracking"), a Monte Carlo-based detector and simulation tool developed at CERN for the purposes of evaluating high energy physics experiments. Originally designed using the Fortran software architecture, research into GEANT culminated with the development of the GEANT3 model system, built in 1982. The development of Geant4 began with studies at CERN and KEK in 1993, before a formal Geant4 project began in 1994, sponsored by the CERN Detector Research and Development Committee. Geant4 saw its first beta release and subsequent public release in the second half of 1998. Since then, it has been developed further, with two or three public releases a year (along with several beta versions). Version 10.5 was released in December 2018.

Geant4 is now a world-wide collaboration of 136 scientists and software engineers who look to develop, maintain and provide support to the toolkit. CERN has played a key role, with some 35 collaborators based there. Six others are from the UK, representing organisations such as STFC, Manchester University, the National Physical Laboratory, and the Surrey-based space radiation consultancy, RadMod. Another founded the UK-based Geant4 Associates International Ltd – providing consultancy services on Geant4 and radiation simulation. Of the 39 organisations that are copyright holders for Geant4, five are also from the UK: Bath University, Imperial College London, Manchester University, the Rutherford Appleton Laboratory, and the University of Southampton.

UK-based researchers have been able to make use of Geant4 outside the particle physics domain, using the model for a range of wider applications. The University of Cambridge, for instance, has adapted Geant4 to create the programme GHOST (Geant Human Oncology Simulation Tool) which simulates radiation deposition in a patient throughout an entire course radiotherapy treatment. Using GHOST, researchers are looking to improve the modelling of late toxicity and the risk of second cancers caused by radiation exposure. It is hoped that GHOST will enable clinicians to rethink proposed treatments if the model shows a high risk of a second cancer.

Geant4 has also contributed to the development of the ESA LISA (Laser Interferometer Space Antenna) mission, which will observe gravitational waves in space. It will do so using three spacecraft separated by 2.5 million km in a triangular formation, all of which will follow the Earth in its orbit around the Sun. A team at Imperial College London used Geant4 to model the potential build-up of charged particles on the LISA spacecraft to enable the development of proofing mechanisms.

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E.8 Linear proton accelerators and next generation radiotherapy

Radiotherapy is a key aspect of cancer care, using radiation to kill cancer cells. Approximately 50% of all cancer patients could benefit from some form of radiotherapy as part of their treatment and it is estimated to contribute to 40% of cases where cancer is cured. Conventional radiotherapy uses X-rays to target and destroy tumours seated deeply within the patient's body. However, X-rays not only kills cancer cells, they also damage healthy surrounding tissues causing significant side effects.

Technology developed at CERN has assisted in the development of next-generation radiotherapy, so-called hadron therapy. In hadron therapy, cancer cells are targeted using beams of charged particles, (e.g. protons or ions rather than X-rays), with the potential to kill tumours while reducing toxic side effects. Compared to conventional radiotherapy, hadron beams cause less damage to healthy tissue they pass through to reach the tumour, and do not penetrate beyond the tumour. As this reduces the amount of radiation absorbed by surrounding tissue, the technology can greatly reduce the side effects of radiation therapy. This is especially important when treating tumours in critical areas, such as in the brain, liver, and prostate, or near the optic nerve or spine – as well as all paediatric tumours.

Accelerator technology has, and continues to, play a key role in the development of safe, effective, and affordable hadron therapy. The idea to treat cancer patients with protons originated in the USA, with the first patients receiving treatment in nuclear physics research facilities in the 1950s. However, at that time the precision of the radiation dose deposition was not precise enough to treat tumours close to critical organs such as in the brain, and hence some clinical applications were limited. Improvements in accelerator technology, coupled with advances in medical imaging and computing, made proton therapy a viable option for routine medical applications starting in the 1970s. In the early 1990s, proton facilities started to be established in clinical settings, with the hospital facility located at Loma Linda University Cancer Centre in California.

An estimated 165,000 cancer patients have been treated using hadron therapy, and the number of proton therapy centres is increasing globally. With a price tag of around £120bn per system, the cost can be prohibitively high. In order to lower the cost, and enable more widespread use to treat cancer, more compact accelerators are needed – decreasing the size and weight along with the space required to house such a facility.

Development of a linear proton accelerator for use in radiotherapy

In 1993, the TERA Foundation, an Italian non-profit institution created to develop radiotherapy techniques using hadron particles, started designing the first unit of a linear proton accelerator for treating cancer. Rather than relying on a cyclotron or synchrotron source to accelerate the protons to the high energy levels required (i.e. a circular installation), a more compact linear design would enable cancer treatment centres in urban areas to find space to build such a facility.

A first prototype of a linear proton accelerator, the linac-booster for proton therapy ("LIBO"), was designed and built under the leadership of CERN in collaboration with TERA. Operating at high frequency allowed LIBO to be more compact and shorter than the standard lower-frequency proton linacs. Following its construction at CERN, this first prototype was successfully tested in 2003. In addition to LIBO, CERN and TERA successfully cooperated on the design and tests of other proton accelerators such as the CNAO synchrotron, in Italy (first patient treated in 2011) and the MedAustron synchrotron, in Austria (first patient treated in 2016). CERN also initiated the ENLIGHT network, established in 2002 to coordinate European efforts in hadron therapy, and continues to coordinate the network (now with more than 700 participants from 25 European countries).

Commercialisation of linear proton accelerator technology – ADAM and AVO

To further develop the LIBO design into a commercially available system, a CERN spin-off - ADAM ("Application of Detectors and Accelerators to Medicine") - was founded in 2007. ADAM continued to receive crucial support from CERN, via its testing facility on the CERN site, as well as by the involvement of ADAM's management in the LHC experiment, which allowed it to draw on experience and knowledge generated.

Improving on LIBO's design, ADAM built and tested the first accelerator modules for the LIGHT ("Linac Image Guided Hadron Technology") accelerator from 2008 to 2010. LIGHT incorporates a number of technologies developed and in use at CERN, including:

- Ultra-high precision machining: CERN's CLIC (Compact Linear Collider) project had pushed the development of new machining technologies, such as tailor-made Computer Numerical Controlled (CNC) machines, to satisfy the stringent requirements of cavity machining. To achieve the required operating frequency, tolerances in the μm range are required. After machining, brazing at high temperature is needed to finish the product. LIGHT was then able to make use of the technology and know-how related to the design, high precision machining, brazing and RF tuning of accelerating structures.
- High frequency RFQ (radio-frequency quadrupole): CERN's experience in the design of RFQs for the LINAC4 project led to the optimised design of a more compact RFQ for the LIGHT prototype (with a much higher frequency than that used for LINAC4). This novel RFQ reaches the same radio frequency gradients as used by X-ray linacs (5 MeV over 2 metres).
- System commissioning: CERN's experience in the beam dynamics studies and commissioning of linacs represented a valuable input for the commissioning of the LIGHT system.

In 2013, Advanced Oncotherapy (AVO), a UK company, acquired ADAM to continue development of the LIGHT system for commercialisation. The company now has around 90 staff across the UK, Switzerland and the US and a market capitalization of £76.85m. In 2018, AVO established an assembly and testing centre for the LIGHT system at STFC's Daresbury Laboratory. Following verification and validation of the first system, it is now being installed in in Harley Street, London (within the space of two traditional terrace houses). The site is expected to be ready for installation by 2019, and following regulatory approval and commissioning, the first patient treatment is expected by the end of 2020. While development of LIGHT is carried out at AVO's CERN facilities (ADAM), the company signed a contract with the STFC in 2018 to establish a UK assembly and testing centre for the LIGHT system at the Daresbury Laboratory in Cheshire. The full LIGHT system will first be assembled, tested, and submitted for regulatory approval at the Daresbury Laboratory site, before it is relocated and installed at Harley Street.

The relative ease of installation combined with a cheaper production process could give AVO's LIGHT system a competitive edge against cyclotrons, synchrotrons, and more conventional LINAC systems - and allow it to secure a substantial share of the global proton therapy market. Proton therapy currently represents only 1% of all external radiotherapy systems installed worldwide and in 2017, only 0.1% of all cancers treated worldwide were treated using particle therapy (proton therapy or carbon therapy). Despite high treatment costs, recent forecasts project that the global proton therapy market will grow from US$0.9bn in 2017 to reach between US$2.33 and $4.3bn by 2030 with between 900 and 1,300 particle therapy treatment rooms opens to patients worldwide.

Delivering improved cancer therapy to UK patients

There are over 300,000 new cases of cancer diagnosed in the UK every year. Of those around 4 out of 10 people will have radiotherapy as part of their treatment. Annual NHS costs for cancer services are £5bn, but the cost to society as a whole, including costs for loss of productivity, is £18.3bn.

In 2013, the Government committed £250bn capital investment for UK's first NHS proton therapy centres. This includes the buildings and PBT cyclotron and gantries, providing 6 NHS treatment rooms (3 at each centre). The first centres is located at The Christie in Manchester, and started operation in December 2018, and the second is at University College London Hospital will be operational from 2020. The two centres will be able to treat up to 1,500 patients per year at half the cost of what the NHS is currently paying for this treatment. Roll out of the therapy option is also supported by an education programme delivered by Health Education England to ensure supply of trained professionals.

Supporting evidence

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E.9 Gaseous detectors

In particle physics, gaseous detectors are used for the observation of ionising particles. The latter interact with a detecting gas, a mixture of a noble and a quenching gas, which ultimately produces a signal that can be detected by sensing electrodes. Similar methods are also applied in nuclear- and astrophysics. Prior to the use of gas-based methods, detection systems such as bubble and spark chambers, flash tubes, and scintillation counters were used. These, however, relied on relatively simplistic photographic methods which held back the discovery of new particles and other phenomena that are often based on extremely rare particle interactions.

French physicist Georges Charpak revolutionised particle detection with his invention of the multiwire proportional chamber (MWPC). This particle detection system was able to record millions of tracks from particle collisions, which was a major improvement over prior techniques that could only capture one or two tracks per second. Later, Charpak also developed the Micromegas (Micro-MEsh Gaseous Structure), which was based on the MWPC. Through these efforts, Charpak was the first to introduce modern electronics, transistor amplifiers in particular, into particle detectors systems, which allowed them to be connect to a computer for the purpose of data collection. Charpak would ultimately be awarded the Nobel prize for physics in 1992 for his work on particle detectors, especially the MWPC.

Over time, MWPCs were gradually replaced by Gas Electron Multipliers (GEM), another type of gaseous ionisation detector. Compared to MWPC, GEM detectors excelled in terms of performance and rate capability at a low cost of production and operation. Within CERN, GEM tracking detectors have since been used for the LHCb, COMPASS, and TOTEM experiments. Nevertheless, GEM detectors were still based on working principles similar to those of the MWPC. Indeed, many modern particle physics experiments still use detectors based on the principles of Charpak's multiwire proportional chamber (MWPC). As particle detectors have become more complex and capable of generating more data, researchers have also developed software to interpret the signals and recreate them in 3D space. These event displays are still being used in experiments for visualising geometry, developing algorithms and detector monitoring in (e.g. in the LHC CMS experiment). Ultimately, the technologies based on MWPC principles have contributed to several important discoveries in particle physics such as the charm quark, the W and Z bosons, and the gluon.

The invention of the Micromegas and GEM detectors cleared the way for new Micro-Pattern Gas Detectors (MPGD) with higher levels of spatial resolution and rate capability, large sensitive area operational stability and radiation hardness. Similarly, Macro-patterned detectors (THGEN) have since been developed as well for applications with large-area coverage and moderate spatial resolutions. Although silicon detectors have now superseded gas detectors for some applications, highly integrated amplification and readout electronics have allowed for the design of gas-detector systems with similar channel densities as modern silicon detectors.

Recently, gaseous detectors have also been implemented in the ATLAS experiment aimed at the observation of highly-massive particles using high-energy accelerators. One of the subsystems of the ATLAS Inner Detector is the Transition Radiator Tracker (TRT), which is also a type of gaseous detector. The ATLAS experiment contributed significantly towards the discovery of the Higgs boson. The UK is involved in the ATLAS collaboration through 14 universities and the Rutherford Appleton Laboratory.

Within the UK, the technology detector group at RAL has also been developing gas-based radiation sensors for over 30 years, the majority of which is directly based on the MWPC. These have been developed for a wide range of applications for high energy particle physics, as well as medical physics. Finally, beyond the field of particle physics, MWPC-based techniques have found applications in the fields of medicine and biology, and material science. With regards to medical science, these have been implemented for imaging ionizing radiation. X-ray and γ-ray imaging in particular. They have also been used as detectors in X-ray crystallography by replacing the X-ray film, which allows for new studies in protein structures. Furthermore, it has been applied in low energy neuron imaging to study structures in molecular biology. Other applications include positron cameras for γ-ray detection. An example of this is clinical trials that were carried out by RAL using a MWPC positron camera at the Royal Marsden Hospital.

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E.10 Silicon detectors and ASICs

Silicon detectors and high-density readout electronics are now crucial for particle physics experiments, and have had a large impact on other scientific fields and applications outside particle physics.

Particles containing charmed quarks were discovered in 1974. Their properties included very short lifetimes which could be measured using detectors with spatial resolution of a few µm. Silicon was suitable for electronic detectors which could be read out under computer control. Segmented reverse-biased diode devices robust enough to operate for long periods were needed, which could be manufactured at an affordable price. MOS techniques, inspired by the semiconductor industry, achieved this. Companies like Hamamatsu Photonics (HPK, Japan) and Micron Semiconductor (UK) began to produce sensors for CERN, and later US, experiments.

In the 1980s many experiments studied charmed particles using “telescopes” of silicon microstrip detectors, arranged in a longitudinal array with sensors transverse to the incident beam. They enabled the tracking of charged particles, with trajectories reconstructed and projected back to the interaction point, where it was then possible to identify tracks which originated after the interaction vertex as a consequence of a charmed quark decay.

It was also realised that silicon diodes of a few cm2 area could be used for scintillation light detection from crystal and plastic scintillators, and that these could be used to inexpensively instrument calorimeter detectors, to measure charged and neutral particles up to very high energies. This allowed new types of calorimeter to be produced using compact, inexpensive sensors which could tolerate the magnetic fields used in many experiments, unlike photomultipliers.

As detectors became more ambitious, complementary electronics were developed to amplify the small ionisation signals from the silicon. High density was required, to instrument growing numbers of channels, initially in the tens of thousands, with low power to avoid generation of heat and electronic noise. Application Specific Integrated Circuits (ASICs) were mandatory for vertex detectors at colliding beam experiments, where several layers of highly segmented silicon microstrips were packed into a few centimetres of radial distance, near to the beams. Similar electronics was also required for calorimeters, to permit amplifiers to be embedded within detectors and transmit signals to remote data acquisition electronics.

Silicon vertex detectors were installed in several CERN LEP experiments. The first HEP ASIC was an NMOS circuit developed at Stanford with CERN collaboration, fabricated in a research lab, and soon followed by CMOS versions designed at Rutherford Appleton Lab for the DELPHI and OPAL experiments. ASIC design for particle physics came of age during the 1990s as experience increased and modern commercial manufacturing processes became accessible. In Europe this was aided considerably by the Europractice consortium which was set up to train ASIC engineers, and provide access to commercial foundries and sophisticated software design tools.

Charged Coupled Devices (CCDs), also based on MOS technology, were pioneered for particle physics in early CERN experiments, and later used on a larger scale in the SLAC SLD experiment. CCDs provide precise 2D spatial measurements in the plane of the sensor but are not easily adapted to very high rate experiments, and are sensitive to radiation damage. They are much used for astronomy and R&D has expedited development of new devices by a UK manufacturer, EEV.

Microstrip detectors are planar devices providing 1D spatial measurement; sensor sizes are set by the size of silicon wafers. Early on, pixel detectors which would provide 2D data were envisaged, but hard to develop because a matching array of amplifiers was required, connected individually to each pixel. Individual ASICs are restricted in size to a few cm2, and working die are selected by testing prior to wafer dicing. Hence construction of pixel detectors requires assembling ASICs onto the surface of the sensor, with interconnection by metallised bumps between them. This was a challenge for many years because of the high bond density. However, pixel detector electronic design began during the 1990s, led originally by the CERN MEDIPIX project.

From 1990, experiments were designed for the CERN Large Hadron Collider. Radiation levels generated by proton collisions at enormous collision rates were to be unprecedented. It was not known if detectors would survive, yet vital to measure particles close to the interaction points. Particle trajectories over typically a metre distance were measured, so detectors were to be large, with many millions of channels, and very low cost per channel.

Investigations over about ten years, by international CERN R&D projects, demonstrated that silicon would function in the LHC, provided sensors could be operated at high voltage and low temperature. In fact, silicon was shown to be superior to any alternative material. Radiation-tolerant ASICs, which are discussed separately, were also essential to construct the detectors.

The LHC also saw the first generation of pixel detectors, placed very close to the collision point, deployed in experiments. The high density bump-bonding was provided by a number of companies, as well as some in-house systems.

Avalanche photodiodes were developed for the sensing of scintillation light in the CMS electromagnetic calorimeter, which has about 80,000 crystals, each with two photosensors. This was a remarkable achievement by the manufacturer HPK, since avalanche devices are intrinsically unstable. To manufacture them with a high degree of uniformity and with good breakdown characteristics had originally been thought to be almost impossible.

Another type of avalanche device was invented at the end of the 1990s, often called the Silicon Photomultiplier, or SiPM. This is a pixellated sensor which experiences a local electrical breakdown, or uncontrolled charge multiplication, when a charged particle is detected in a pixel. There is a short recovery time to stabilise the pixel behaviour, when the device is locally insensitive, but with sufficient segmentation the detector can offer close to 100% sensitivity. SiPMs have been taken up for many applications and may replace photomultipliers at much lower cost, typically where light can be concentrated onto the small surface area of the device.

Another pixel detector concept is for sensors and electronics to be constructed on the same wafer, in a standard commercial electronic fabrication process. Such devices, Monolithic Active Pixel Sensors (MAPS), are similar to photosensors used in digital cameras and could allow large detecting areas at low cost. Such detectors are being used in the ALICE experiment at CERN which is a significant step forward.

The next generation of silicon microstrips and pixels is under development for upgrades of the LHC experiments at the end of this decade. They must tolerate much higher levels of radiation and will use a different type of silicon and continue the evolution from those currently in use.

Over almost 40 years, silicon detectors have evolved from simple, small area diodes to huge systems, measured by channel count. This has been driven the requirements, and efforts, of particle physics aided serendipitously by the evolution of the electronics industry. They are used increasingly in other applications, such as pixel detectors for synchrotron x-ray crystallography.

Major developments have taken place in Europe, for CERN, and US projects have often relied on European expertise; UK groups have been very active. Scientists working at CERN have played influential roles, including evaluating radiation tolerance of many sensors under a wide range of conditions.

As well as HPK, there are several European companies providing detectors on a smaller scale, some founded specifically to target particle physics applications.

Gaseous detectors were partly displaced by silicon, especially for modest sensor areas where high spatial precision is the goal. However, silicon developments also stimulated this activity, with similar assembly technologies, and providing readout ASICS.

Supporting evidence

- Case study developed in collaboration with Geoff Hall, Imperial College London

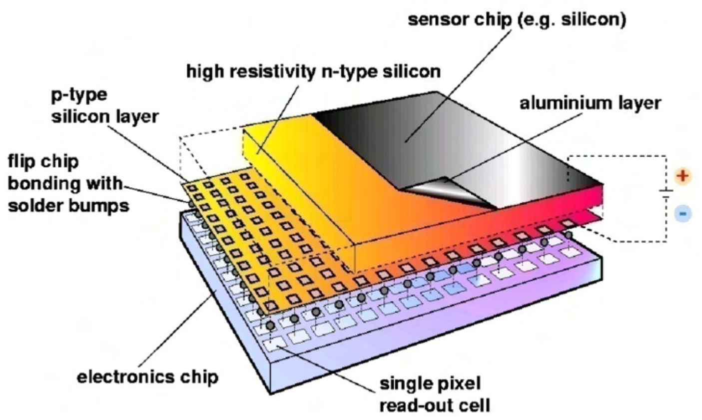
E.11 Medipix Collaboration

Medipix is a family of read-out chips for particle imaging that were developed by the Medipix Collaborations (CERN, plus other partners) and which can be used for a range of applications. The original concept of Medipix is that it works like a camera, detecting and counting each individual particle hitting the pixels when its electronic shutter is open. The chips are hybrid pixel detectors, consisting of two thin layers of an absorbent material (e.g. silicon or Gallium arsenide). In the case of the silicon detectors, incoming particles create electron-hole pairs in the pixelated silicon sensor layer; the resulting charge is transferred to, and recorded in, the second layer, an array of readout electronics channels. This enables capturing of high-resolution, high-contrast, noise free images, making the chip uniquely suitable for imaging applications.

Hybrid pixel detector technology was initially developed to address the needs of particle tracking for CERN. In the 1990s, a University of Glasgow team led by Professor Kenway Smith was actively involved in the development of hybrid pixel detectors for the LHC. The primary aim was to develop a 2D detector capable of time stamping high energy physics events at the expected collision rate of the LHC. In the course of this research, it became clear that such a technology could also be useful for other applications, such as medical imaging. This is when the Medipix collaboration was born.

The initial partners of the Medipix collaboration were CERN, the University of Glasgow, the University of Freiburg (Germany) and the INFN of Pisa and Napoli. They re-designed the Omega3 particle tracking chip, which had been developed at CERN for the then future LHC machine, incorporating its front-end circuitry into the Medipix-1 chip. Medipix-1 was submitted to fabrication in 1997 and demonstrated the potential of the technology in single photon counting X-ray imaging.

Figure 67 Structure of a Hybrid Silicon Pixel Detector



Source: Professor Michael Campbell

Over the years, the collaboration has been through iterations and reconstitutions to further develop this technology and take it to new fields. As the cost of developing and prototyping these devices is challenging, each collaboration allows the partners to focus their efforts on developing chips with new features to support new applications. These collaborations are purposefully very open, seeking to encourage partners to contribute to and benefit from the development and application of the technology, on the provision that results are made publicly available.

This process has allowed for:

- The Medipix2 collaboration, formed in 1999, which produced a chip with improved spatial resolution (Medipix2), and the first Timepix chip, a modified version of Medipix2 with the additional functionality of time or amplitude measurements. Initially composed of 13 European research institutes, the collaboration expanded over time to reach a peak of 17 member institutes, including two from UK – the University of Glasgow and the Medical Research Council's (MRC) Laboratory of Molecular Biology (LMB) in Cambridge.
- The Medipix3 collaboration, formed in 2005, which produced the Medipix3 and Timepix3 chips which not only counts photons but also determines their energy levels. Medipix3 chips allows 'colour' X-ray imaging. The Timepix3 chip is no longer a camera, but sends data off-chip as soon as radioactive particles are detected.
- The Medipix4 collaboration, formed in 2016, which aims to design a pixel read-out chip capable of spectroscopic X-ray imaging at rates compatible with medical CT scans ('Medipix4'), and an updated Timepix chip with higher spatial and timing precision ('Timepix4'). These chips are also tile-able and can be stacked side by side. This collaboration includes the University of Oxford and the STFC's Diamond Light Source Detector Group.

Figure 68 The Timepix USB interface

Source: Professor Michael Campbell

The Medipix technology is one of CERN's most successful examples of knowledge transfer. Each collaboration has triggered a significant number of commercial activities in a range of application areas, including medical imaging, space dosimetry, education, and material analysis. For example:

- The technology has been applied in X-ray computed tomography (CT), in prototype systems for digital mammography, in CT imagers for mammography and for beta- and gamma-autoradiography of biological samples.
- Timepix is being exploited for radiation monitoring in NASA's Orion rocket, while at the International Space Station the chips themselves are plugged into computer USB ports to deliver data directly to the Earth based support team (Figure 68).
- Timepix has been used as part of the CERN@School project to develop a kit of teaching materials and tools for schools to allow students to undertake ground-based experiments (see CERN@School case study).
- Medipix2 and the Medipix3 chips are both being used by UK based company Malvern PANalytical for commercial X-ray of materials analysis, with applications for pharmaceuticals, evaluation and synthesis of new materials, and the detection of counterfeit drugs. Similarly, Czech company InsightArt s.r.o. has adopted the Medipix technology to perform detailed X-ray scans of artworks for authentication purposes.

The Medipix detectors have also played a role in supporting UK research communities to conduct world class research. For example, research from Imperial College London is currently seeking to demonstrate the theory of the Breit-Wheeler process, a process postulating that it should be possible to turn light into matter by smashing two particles of light (photons) together to create an electron and a positron. This experiment uses Medipix detectors and STFC's Central Laser Facility.

Photon counting systems have been widely adopted at synchrotron light sources over the last 15 years. In addition to other applications for synchrotrons across the globe, Medipix chips have also been the focus of development for the Diamond Light Source, which has developed two systems using Medipix chips. The Merlin system is a compact, LabView based readout designed for the for the application of Medipix3 and Timepix3 chips. The Merlin system supports the development of detectors for time resolved experiments, and is now operating on five different beamlines. The EXCALIBUR detector is a Medipix3RX-based system for application in the Coherent X-ray diffraction, and is operating on one beamline. In doing so, these chips are therefore supporting a key piece of research infrastructure in the UK that underpins a wide scope of academic and industrial research.

The applications of the Medipix chips are also expanding into other research areas through UK participation. For example, researchers at the University of Oxford's high energy physics department are currently working with the University's chemistry department to highlight the applications for mass spectrometry.

Hybrid pixel detectors developed within the Medipix Collaboration were the first 'direct' detectors used at the MRC-LMB on a 12 kV electron microscope. MRC-LMB's participation in the collaboration since 1999 was very useful for understanding the detector requirements for electron microscopy. Establishing that hybrid detectors were not suitable for work at higher energies later led to the development of CMOS sensors.

The Medipix Collaboration has also supported a UK based company, Quantum Detectors, based at the Harwell Science and Innovation Campus. The company was founded in 2007 to promote a wider exploitation of detectors developed for synchrotron radiation. One of Quantum Detectors' products, the Merlin photon counting detector system, has been licensed from Diamond Light Source. This product is based on the Medipix3 ASIC and was adapted for transmission electron microscopy applications (MerlinEM) in collaboration with the University of Glasgow. The company has been delivered to synchrotron facilities and universities across the globe, and now around half of their sales include Medipix Chips.

Supporting evidence

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E.12 CMOS image sensors – enabling cryo-electron microscopy (cryo-EM)

Electron microscopy (EM) is used as a tool for obtaining high-resolution structural information, including in the biological sciences. Electron and ion microscopes use a beam of charged particles instead of light, and electromagnetic or electrostatic lenses to focus the particles.

In 2017, British biochemist Dr Richard Henderson was one of the recipients of the Nobel Prize in Chemistry, for pioneering work with cooled electron microscope technology – so-called electron *cryo*-microscopy (cryo-EM). This allows researchers to freeze-*trap* biomolecules or macro-molecular complexes *during reactions* and to visualise their structure and shape at atomic or near-atomic resolution.

Working at the MRC Laboratory of Molecular Biology in Cambridge, Dr Henderson *and colleagues*, developed the electron camera systems necessary for this 'resolution revolution', able to operate both, at high speed and at high resolution (unlike alternative technology in use – photographic film and charge-coupled device (CCD) cameras). Unlike the 'incumbent' for structural studies, X-ray crystallography, cryo-EM does not depend on the slow and arduous process of growing crystals of the molecule to be investigated. This not only reduces the time and risk associated with molecular structure determination, it also allows working with samples that cannot be isolated in sufficiently large quantities for crystallisation – representing substantial benefits for researchers in biochemistry, e.g. in the development of pharmaceuticals. It therefore requires less material, less purity and less stability than other methods.

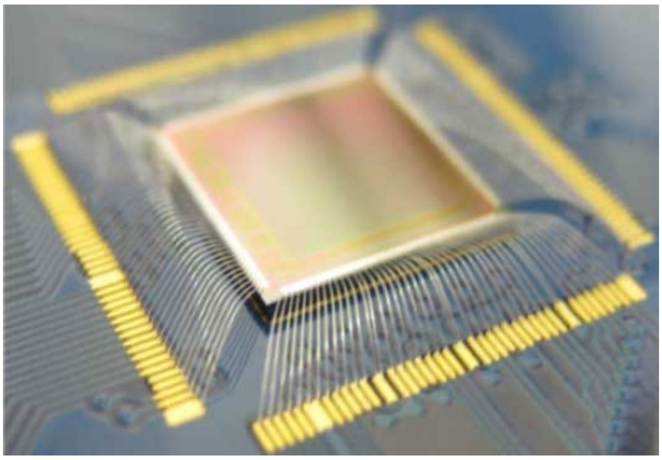
To greatly improve cryo-EM's resolving power, a collaboration between Dr Henderson *and colleagues*, engineers at the Rutherford Appleton Laboratory (the STFC CMOS Sensor Design Group) and scientists at the Max Planck Society, replaced existing detectors in the microscope with modern CMOS image sensors. Notably, the establishment of the CMOS Sensor Design Group was in large part driven by requests to develop ASICs for particle physics experiments at CERN.

Complementary metal–oxide–semiconductor (CMOS) technology is commonly employed in the computer chip design industry and broadly used today to form integrated circuits for a broad range of applications. A CMOS sensor is an electronic chip that converts photons to electrons for digital processing (i.e. the analogue-to-digital conversion occurs on the chip itself). These sensors are used to create images in digital cameras, and can also be found in astronomical telescopes, scanners and barcode readers. Advances in microelectronics technology, combined with the ability to use the industrially available CMOS process, have allowed an increasingly large number of components to be packed into relatively small areas – leading to high functionality of the chips.

A key problem in the use of CMOS sensors for EM was the need for chips that could withstand the direct exposure to the beam of high-energy electrons, without incurring radiation damage in the device. This is where knowledge and experience from the development of radiation-hard sensors for CERN's LHC programme played a key role. The STFC CMOS Sensor Design Group was able to apply the expertise it had gained working with CERN in the design of large area, radiation-hard sensors to produce the first high-resolution CMOS devices for cryo-EM. A general-purpose CMOS sensor developed by the group was used in 2003 in an electron microscope at the MRC-LMB, and, for the first time, an electron was directly detected by this type of sensor electrons were directly imaged in an electron microscope*.

The success of the trial led to a partnership between the MRC LMB, RAL and Max Planck with FEI, a US supplier of microscope systems, to build an optimised electron direct detection CMOS camera. Following the success of this prototype, work began in 2008 to design a full-scale sensor for presentation to market in 2009, funded solely by the electron-optics company. The sensor utilises novel, patented CMOS image sensor architecture for direct detection of electrons. Problems overcome to create the sensor included single electron sensitivity, spatial resolution, radiation hardness and sensor size. The final, full-scale 16 Megapixel sensor is able to record images faster than video rates, with very good radiation hardness and single electron sensitivity. In 2012, the first camera with a CMOS image sensor was released onto the TEM market, the FEI FALCON I. Today, these sensors are an integral part of all of FEI's flagship transmission electron microscopy products and are found in a wide range of the world's leading electron microscopes.

Figure 69 CMOS sensor



Source: STFC

The CMOS direct electron detectors are also revolutionising the field of structural biology and accelerating discovery, e.g. for the development of drugs. In 2018, a study reported that cryo-EM was used for microcrystal electron diffraction of powders of small organic molecules to determine their structure (i.e. without the need to grow crystals). Techniques routinely used to date have been in place since the 1960s; the use of cryo-EM will potentially be the next big advance in the field and become a superior routine analytical technique for chemists.

The UK has thus positioned itself as a global leader in the cryo-EM field. This is further supported by the establishment of the Electron Bio-Imaging Centre (eBIC) at the STFC's Diamond Light Source, in collaboration with Birkbeck College London and the University of Oxford. The facility was the result of a £15.6m grant from the Wellcome Trust, the Medical Research Council (MRC) and the Biotechnology and Biological Sciences Research Council (BBSRC). During the set-up phase, eBIC began by offering time on a single FEI Titan Krios microscope equipped with the latest generation of direct electron detectors. The facility now offers five cryo-electron microscopes. In 2018, the facility entered into an agreement with FEI/ThermoFisher, which will further expand eBIC's cryo-EM offerings by providing two new dedicated microscopes and professional cryo-EM services designed exclusively for the pharmaceutical industry. The additional advanced instruments will help position the UK as a global leader in providing large-scale industrial access to cryo-EM for drug discovery research.

Supporting evidence

- Validation and clarification provided by Dr Wasi Faruqi and Dr Richard Henderson, MRC Laboratory of Molecular Biology
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E.13 Radiation-tolerant ASICs

The CERN LHC experiments required detectors to tolerate high radiation levels, especially close to the colliding proton beams. During the 1990s, it was gradually established that so-called "radiation hard" electronic technologies developed for military and space applications were expensive and relatively antiquated, and would be problematic. Following intensive R&D, CERN engineers demonstrated in 1997 that an alternative solution was to use commercial state-of-the-art CMOS technology and special transistor design techniques to ensure circuit performance. CMOS foundries offering 0.25 µm feature size transistors achieved low unit costs because they handled large numbers of wafers and provided reliable implementation of circuit designs using well understood manufacturing processes.

The first major ASIC using a 0.25 µm process was the APV25 developed by Imperial College and the Rutherford Appleton Laboratory for the CMS tracker; this is the largest silicon microstrip system yet built with 9.3 million channels covering a surface area of about 200 m2. The APV25 has since been used by several other experiments worldwide. Subsequently, most ASICs requiring high radiation tolerance in LHC experiments were designed in the same process. The Beetle ASIC, used in several detectors in the LHCb experiment, originated in the same CERN R&D project as the APV25 and was later further developed by collaborating teams. ASICs for all of the pixel detectors used the same technology and were also developed by multinational teams.

The next generation of silicon microstrips and pixels is currently under development for upgrades of the LHC detectors in 2024-26; they must tolerate much higher levels of radiation and new ASICs are required. Technologies have evolved considerably since 2000; finer feature manufacturing processes are available (130 nm and 65 nm, compared to 250 nm of the first generation) which are more expensive but allow higher density, and thus smaller, circuits. While ASIC transistor sizes in use in HEP have reduced substantially, they still lag far behind the most advanced commercial circuits.

Much of the higher density is utilised to integrate greater digital functionality into the ASICs, so greater complexity and longer data storage times are possible, as well as higher throughput of data. These allow more intelligence to be installed on the detector, which requires great care in the overall electronic design, both to manage the complexity and also to avoid dangers of unexpected unwanted features, especially in a radiation environment which can alter the behaviour of the circuits.

The radiation exposures experienced at the LHC are not identical to those in military and space applications. Nevertheless, this is a sensitive area and exports of components manufactured in these technologies are subject to government controls. This would be hard to manage without the infrastructure, and legal and contractual support provided by CERN. Frame contracts have been negotiated via CERN with several foundries, which is important since, despite the large size of experiment systems, the volume of business generated by particle physics (and spin-off applications) is insignificant compared to commercial applications, for whom foundries process hundreds of thousands of wafers each month.

Low unit costs for the electronics were vital to construct detectors with vast numbers of channels. ASICs are also essential to meet the high spatial density and low power requirements. The investment needed to design, manufacture and bring ASICs to maturity, which usually requires multiple design cycles, is significant and, as circuits become more complex, rely heavily on consortia of engineers and physicists from different institutes distributed widely geographically to provide the effort needed. This is a new style of working, requiring careful management to succeed, but of a kind which is natural in the CERN environment.

Beyond CERN and particle physics, there is growing demand for radiation-tolerant electronics in the space sector. It is interesting to compare particle physics with space science which has had a more conservative approach to integrating new technologies. Since space missions are lengthy and cannot afford electronic failures, they usually adopt a procedure of procurement of electronics from commercial vendors, working to tight specifications, followed by careful qualification of the product under the conditions, including irradiation, expected. This is a lengthy and expensive process and not conducive to implementing state-of-the-art components. In the past, radiation-hard parts, such as memories, lagged far behind currently available units.

Particle physics, on the other hand, might take more risk in exploiting the latest developments. Caution is certainly exercised, but it is usually possible to replace detectors or repair faults, even if that is at the cost of experiment downtime and financial penalties. The benefit, of course, is much more productive experiments.

While space technology remains conservative, it does seem that suppliers have followed recent trends in particle physics electronics and are profiting from using similar approaches. Today, some radiation-tolerant ASICs developed for CERN applications are able to meet space specifications at an affordable price while achieving high performance. The TimePix detectors, for instance, are being used by NASA aboard the International Space Station.

Supporting evidence

- Case study developed in collaboration with Geoff Hall, Imperial College London

E.14 Medical imaging technology: PET imaging and scintillating crystals

As beams collide inside CERN’s detectors, billions of particles interact every second and create new particles that decay in complex ways. To create a record of these "collision events", sophisticated detector technology is needed to register each particle's passage and convert the paths and energies into electrical signals. CERN has been pushing the frontier of detector technology in order to register ever-smaller and more elusive particles, and these technologies have found applications outside of CERN. For example, detection systems are a key component of medical imaging systems.

Positron Emission Tomography (PET) is a medical imaging technique used to observe metabolic processes in the body to assist in the diagnosis of disease. PET scanners work by detecting the radiation (gamma rays) given off by a radioactive substance, called a radiotracer, injected into the body. As the radiotracer accumulates to varying degrees across different parts of the body, e.g. in cancerous tumours, an isotope in the tracer will decay and produce antimatter particles called positrons, which will annihilate an electron (its antimatter counterpart) in the body and release a pair of photons that fly in opposite directions. The ring-shaped PET detector surrounding the body detects the photons and uses their positions to reconstruct a 3D image of the target area. This image reveals information about the tissue by mapping the tracers concentrated there. Today, 40 million people undergo medical diagnosis involving radio-pharmaceuticals every year, many by means of PET.

While PET was not invented at CERN, the work carried out by two CERN scientists, Alan Jeavons and David Townsend, made a major contribution to its development. Current high-performance clinical PET scanners comprise more than 20,000 individual detector elements and these detectors were initially developed as particle detectors for experiments at CERN. In the mid-1970s, Jeavons developed a new detector, based on a high-density avalanche chamber, to take PET images, while Townsend developed the software to reconstruct data from the detectors and turn them into an image.

Today, PET scans are often combined with computerised tomography (CT) scans to produce more detailed images. This is known as a PET-CT scan. Initial diagnosis and staging of tumours are commonly based on morphological changes seen on CT scans. However, PET can differentiate malignant tissue from benign tissue and is a more effective tool than CT in the search for metastases. By merging the two it is possible to view morphological and physiological information in one fused image. Work at CERN contributed to the development of algorithms and software for image reconstruction, and to a new scanner design, the Advanced Rotating Tomograph (ART) scanner. The ART scanner is a prototype of the 'PET part' of a combined PET-CT scanner, and was developed at CERN from 1989 to 1990.

The combined PET-CT scanner has proven more accurate than either scanner independently and is one of the most effective imaging tools in oncology. In 2016, the global PET-CT scanner device market was valued at USD$1,454 million, and is estimated to reach USD$2,108mnby 2023, growing at a CAGR of 5.0% (2017-2023). Furthermore, the combined PET-CT scanner has shown significant promise in reducing the cost of cancer treatment through earlier diagnosis and improved staging to determine the appropriate treatments, as well as improving patient quality of life.

Detector technology developed at CERN also continues to improve PET technology. PET uses scintillating crystal detection systems – similar to the electromagnetic calorimeter (ECAL) detectors in CERN's CMS experiment. High-energy photons generated in collisions at the LHC, as well as during the decay of the PET radiotracer, are converted into visible light when they interact with a 'scintillating material' inside the scintillation detector. This visible light in turn is converted to an electrical signal with the help of photodiodes.

The Crystal Clear Collaboration, also known as "Crystal Clear" or "CCC" was created in 1990, with the objective of developing new inorganic scintillators suitable for crystal electromagnetic calorimeters of LHC experiments. Crystal Clear is involved in:

- Investigating scintillator materials for high energy and nuclear physics, astrophysics, dark matter search, beam diagnostics, medical imaging and other industrial applications
- Development of new crystal production methods
- Development of ionising radiation detectors in particular for applications in high energy physics and medical technologies

From 1990 to 1994, the CCC identified and characterised three candidate scintillators with potential for use in the LHC. Of these, lead tungstate was chosen by CMS and ALICE as the most cost-effective crystal suitable for LHC conditions. While lead tungstate is not commonly used for PET, this work has progressed the general understanding of scintillating materials.

The collaboration has continued to develop novel medical imaging devices based on scintillating crystals, drawing on technology and expertise developed while working on the CMS detector. For example, the ClearPET project developed a non-invasive PET technique to image animals for dynamic studies with high spatial resolution. ClearPET has since been licenced to Germany company Elysia-Raytest. To develop ClearPET further, in 2002, the CCC launched the ClearPEM (Positron Emission Mammography) project to develop a dedicated breast PET scanner. ClearPEM can detect cancer lesions as small as 1.3 millimetres (typical clinical PET scanners image at 4mm), potentially leading to earlier detection and subsequent lower breast cancer mortality. The system's photodetector, i.e. the device that converts light from the scintillating crystals into electrical signals, is the same avalanche photodiode as the one developed for the CMS ECAL. The ClearPEM system is currently being translated to the clinic and has gone through successful clinical trials in hospitals across several European countries.

The CCC also developed an international network to coordinate and cross-fertilise global research on scintillators and their applications. Today, a global scientific community of around 300 people comes together every two years at the 'SCINT conferences' to present their work and discuss progress in the field. The CCC also initiated the European COST Action Fast Advanced Scintillator Timing (FAST) (2014-2018) to bring together European experts from academia and industry to collaborate on scintillator-based detectors with improved time precision.

Work by researchers around the world seeking to improve PET technology continues, informed by CERN's technology development. For example, in 2009, particle physicist Paweł Moskal of Jagiellonian University in Kraków, Poland, introduced a system that uses inexpensive plastic scintillators instead of the (expensive) inorganic scintillators currently used for detecting photons in PET systems. The detector is based on technologies employed in the ATLAS, LHCb, KLOE, COSY-11 and other particle-physics experiments, and has the potential to enable more cost-effective whole-body PET imaging.

Supporting evidence

- Additional information provided by Professor Harry Tsoumpas, University of Leeds
- https://crystalclear.web.cern.ch/crystalclear/
- https://cms.cern/content/medical-imaging
- https://cerncourier.com/crystal-clear-celebrates-25-years-of-success/
- https://fast-cost.web.cern.ch/fast-cost/
- https://cerncourier.com/j-pets-plastic-revolution/
- https://cerncourier.com/clearpem-clarifies-breast-cancer-diagnosis/
- https://arxiv.org/abs/1710.11369
- http://www.world-nuclear.org/information-library/non-power-nuclear-applications/radioisotopes-research/radioisotopes-in-medicine.aspx
- https://home.cern/about/updates/2017/12/forty-years-first-pet-image-cern
- http://cds.cern.ch/record/132740/files/CM-P00059721.pdf?version=1
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- Fischer, B.M., Siegel, B.A., Weber, W.A. et al. Eur J Nucl Med Mol Imaging (2016) 43: 1749. https://doi.org/10.1007/s00259-016-3414-5

E.15 Field Programmable Gate Arrays

An application-specific integrated circuit (ASIC) is an integrated circuit built for a specific application or purpose. They are essential for on-detector readout because these circuits must be customised for defined sensor requirements, as well as to provide specific functionalities, such as analogue-to-digital conversion, and data storage, reduction and transfer, which are all highly dependent on the overall detector design and objectives. ASIC development thus requires significant investment, and time.

By contrast, off-detector data processing is now entirely digital and can usually be best provided by reconfigurable, commercially available logic in the form of Field Programmable Gate Arrays (FPGAs). FPGAs are programmed to achieve the functionality required, which therefore can be provided at lower total cost and in much less time than designing an equivalent ASIC.

There are several types of application for which FPGAs are well suited. One example is networking and real-time data flow management, such as in telecommunications, and data-routing applications in CERN experiments. Data acquisition and triggering is another important case. High-energy Physics (HEP) experiments require triggers to select rapidly in real-time the most promising collision events which might contain new or interesting types of physics, and these triggers should be flexible, to adapt to changing experimental conditions, and extremely fast. They must process, in parallel, large volumes (10-100 Tbps) of incoming data from multiple streams in identical ways, before combining results from several systems to refine the selection process further.

Traditional CPUs have insufficient speed and bandwidth to handle the first level of trigger selection at the LHC, but FPGAs are well suited for such tasks. Trigger and networking functions generally require large, powerful FPGAs, with significant resources, such as DSPs and memories, and many high-speed input and output interfaces, typically connected to fibre-optic links. Other applications may use smaller, less expensive parts, for a wide variety of control and monitoring purposes.

Programming FPGAs is different to programming CPU since the code, or firmware, must represent the intrinsic parallelism which is not present in CPUs and so not present in high-level software. Visualising parallelism is a specialised skill, which is challenging to apply to trigger algorithms and particle reconstruction. In recent years, firmware expertise in the particle physics community has increased a lot, but still relies heavily on experts for critical applications. Traditionally, firmware is written in hardware description languages (HDLs) but commercial tools have evolved to allow efficient conversion of software to HDL, so applying FPGAs to such problems should become easier and more accessible. This also opens up new applications.

While consumer boards containing FPGAs are often suitable for development, HEP applications usually require complex boards targeting high-throughput and low-latency, typically featuring many optical receivers and transmitters, power supplies and support electronics. Designing them is a specialised task, which requires experienced engineers and is time-consuming. Particle physics applications have evolved towards generic, highly flexible, hardware which can therefore be deployed in multiple applications, freeing intellectual input to be applied to the functionality.

Since the late 1990s, the LHC experiments have used FPGAs, which have grown exponentially in numbers and capability. UK groups have contributed extensively to both hardware development and to building and programming systems. This trend continues as the experiments are upgraded, and is also leading to new working methods, with more extensive collaboration between individual groups to benefit from sharing workloads and avoiding duplication, as well as easier operation and maintenance of installed systems.

External collaborations are extending these developments to other communities. For instance, the data processing and distribution model used at CERN will be adopted for the Square Kilometre Array (SKA) project. SKA is the world's largest radio telescope project, expected to generate an exabyte of raw data daily, creating major challenges in transferring data from multiple antennae, and amalgamating data for analysis. CERN is to collaborate with the SKA project to solve the problems of the acquisition, storage, management and distribution of data, as well as its analysis.

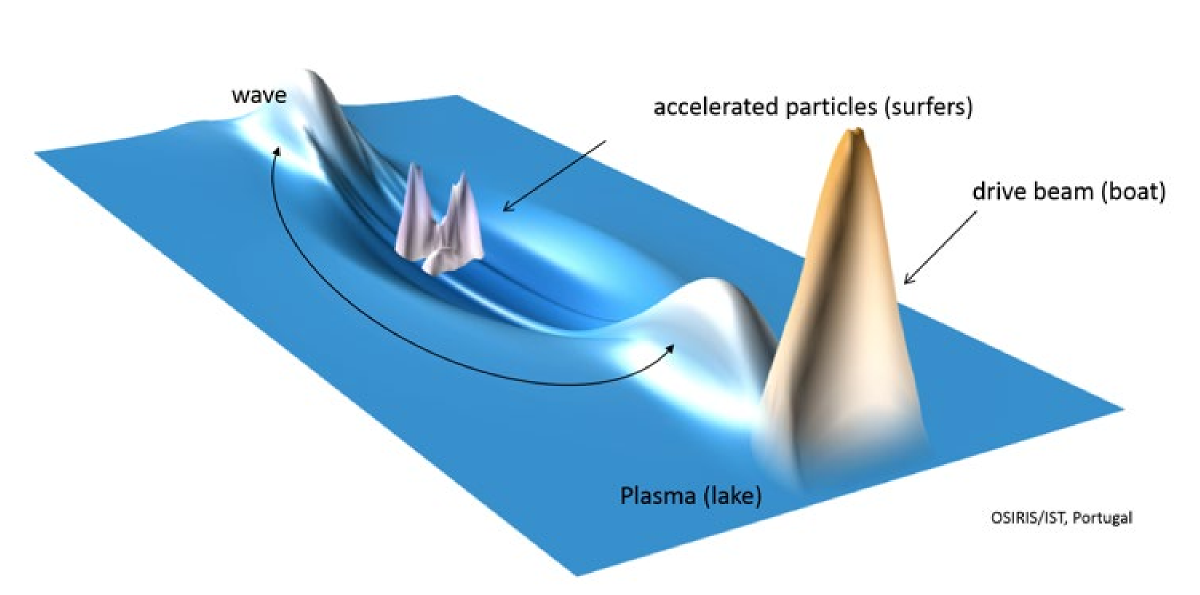
Supporting evidence

- Case study developed in collaboration with Geoff Hall, Imperial College London

E.16 AWAKE and the potential of plasma wakefields

The Advanced Proton-Driven Plasma Wakefield Acceleration Experiment (AWAKE) is a proof-of-principle accelerator R&D project based at CERN. It investigates the use of protons to drive plasma wakefields for accelerating electrons to higher energies than can be achieved using conventional technologies. While it is likely that many years of development will still be needed, the use of plasma wakefields has the potential to drastically reduce the distance needed to accelerate particles to the required energy, and would thus be a smaller - and hence lower cost - alternative for future accelerators, e.g. compared to projects currently in planning such as the CERN Compact Linear Collider (CLIC) or the International Linear Collider (ILC). Plasma-based accelerator technology could also one day lead to vastly smaller synchrotron light sources which probe the structure of e.g. proteins and table-top accelerators of lower energy for use in hospitals or industry.

Traditional accelerators use what are known as radio-frequency (RF) cavities to kick the particle beams to higher energies. This involves alternating the electrical polarity of positively and negatively charged zones within the RF cavity, with the combination of attraction and repulsion accelerating the particles within the cavity. By contrast, in wakefield accelerators, particles are accelerated by "surfing" on top of a plasma wave (or wakefield) which contains similar zones of positive and negative charges. This requires two different beams: the beam of particles that is the target for the acceleration, known as the 'witness beam', and the beam that generates the wakefield, known as the 'drive beam'. AWAKE is the first experiment to use protons for the drive beam, as these can penetrate deeper into the plasma than previously used drive beams of electrons and lasers, due to the possible higher stored energy in a proton bunch. Proton drive beams can therefore accelerate their witness beams for a greater distance, allowing them to attain higher energies. CERN is uniquely positioned in enabling this research: AWAKE gets its drive beam protons from the Super Proton Synchrotron (SPS), which are then injected into AWAKE's 10-metre-long plasma cell.



Source: AWAKE experiment webpage

The AWAKE project was approved in 2013, and the first proton beams were sent to the plasma cell towards the end of 2016. Originally a collaboration of nine institutions, the project now involves 18 institutes, including six from the UK (the Cockcroft Institute, the John Adams Institute for Accelerator Science in Oxford, Lancaster University, the University of Liverpool, the University of Manchester and University College London).

Only five years after CERN approved the project, the AWAKE collaboration successfully accelerated witness-electrons for the first time in May 2018. Over a length of the plasma cell (10 metres), electrons 'rode' the plasma wave and were accelerated by a factor of around 100, to an energy of almost 2 GeV (billion electronvolts). The strength at which an accelerator can accelerate a particle beam per unit of length is known as its acceleration gradient and is measured in volts-per-metre (V/m). By accelerating electrons to 2 GeV in 10 metres, AWAKE has demonstrated that it can achieve an average gradient of around 200 MV/m. For comparison, the advanced conventional technologies considered for the next generation of electron accelerators promise gradients in the range of 30–100 MV/m.

AWAKE is a promising first step towards the development of future high-energy particle accelerators using plasma wakefields; the collaboration now aims to achieve 1000 MV/m, as well as address other requirements, such as the intensity and quality of the accelerated beam and the distance over which acceleration can be sustained.

It is hoped that the AWAKE project can be developed into a useable technology for accelerating electrons to high energies for future particle physics experiments which would not otherwise be possible. The findings and outputs of the AWAKE project will help the appropriation of plasma accelerators for a range of other applications, such as medical treatment and diagnostics, security scanners and the study of advanced materials. In these cases, conventional accelerators have already proved beneficial however supply has been limited by the cost and size. Though it will be some time before this manifests, the UK's involvement in the AWAKE project supports future development and exploitation.

Plasma acceleration is currently done at laser laboratories such as CLF and Strathclyde SCAPA, as well as various university groups. There are however new facilities also starting up all over the world (often including UK research groups). For example, UK involvement in the AWAKE project has also supported subsequent UK involvement in DESY's plasma acceleration facilities. The UK's future strength and prominence in the plasma acceleration field is supported not only through the participation in AWAKE, but also through collaborations with other UK groups working in conventional accelerator physics, who are also in turn benefiting from CERN.

Supporting evidence

- Interview with Matthew Wing (Deputy spokesperson, AWAKE experiment), University College London/DESY
- https://home.cern/news/news/experiments/awake-successfully-accelerates-electrons
- Adli et al (2018) Acceleration of electrons in the plasma wakefield of a proton bunch. Nature 561: 363–367; https://home.cern/news/news/experiments/awake-successfully-accelerates-electrons
- https://awake.web.cern.ch
- https://greybook.cern.ch/greybook/experiment/detail?id=AWAKE
- https://awake.web.cern.ch/learn-more-general-public#overlay-context=learn-more

E.17 CERN BIC - Oxford nanoSystems

Established in 2012, Oxford nanoSystems is a nanotechnology business that produces coating technologies to improve heat transfer in components used in industrial, transport and electronics platforms. It has developed nanoFLUX, a structured metal surface which enhances heat transfer in two-phase systems. The company sees nanoFLUX as having potential applications in refrigeration and waste heat energy, automotive heat management and energy recovery, and heat dissipation in electronics.

Based at the Harwell Campus, Oxford nanoSystems first became aware of CERN BIC as they were based in the same building as scientists working on cooling systems for the ATLAS detectors in CERN. Following some initial conversations with staff there, Oxford nanoSystems was keen to explore the potential of using nanoFLUX as part of the ATLAS cooling system, prompting them to join the BIC in January 2015. In so doing, they became the first company to join CERN BIC's base at Harwell.

The company primarily drew on CERN BIC to access advice and facilities of CERN and CERN research groups. The programme provided advice and support from a world class thermodynamicsist who helped the company to ensure they were interpreting data correctly and consequently allowed them to make quick modifications to the technology. Engagement with BIC also gave the company access to specialist equipment, namely 3D printing at Harwell, and testing facilities at the University of Manchester linked to a CERN-research group. The CERN BIC support also included funding provision to Oxford nanoSystems, the company using this to buy parts and to bring in additional staff.

Company representatives have spoken of how CERN BIC has played an important role in enabling the company's progression and growth. They added that the knowledge gained through their interaction with CERN BIC and the CERN associated researchers has particularly helped the speed of the company's growth. Access to leading knowledge and facilities has helped the company develop and refine their product at a rate that would not have been possible without BIC support. Originally, the company planned to develop coatings for use in the metre-long titanium tubes that feature in CERN. Although, this end goal has not yet materialised, Oxford nanoSystems has directly applied the knowledge and experience gained to their other product areas, as well as giving them the capabilities to develop much larger nanoFLUX systems than those they previously developed. The company also remains in ongoing dialogue with CERN to provide them with cooling solutions for ATLAS.

Prior to joining the CERN BIC, Oxford nanoSystems was a 2 person firm operating from a 300 sqft lab just before their work with the BIC, Oxford nanoSystems is now a 14 strong company based in a 8,000 sqft facility. Since graduating from CERN BIC in February 2016, the company has continued to grow and has secured financial backing from two major Oxfordshire investors. The technology will also continue to be applicable to a wide variety of applications. They for instance are working with fridge manufacturers to produce more compact refrigeration devices which in turn will provide more space for food storage; they are investigating the technology's use on geothermal systems to enable more effective heat transfer; and believe that nanoFLUX has real potential in cooling data-processing hardware.

Supporting evidence

- Interview with Dr Alexander Reip, CEO, Oxford NanoSystems
- https://www.cernbic.stfc.ac.uk/Pages/Oxford-nanoSystems.aspx
- https://oxfordnanosystems.com/
- https://stfc.ukri.org/about-us/our-impacts-achievements/case-studies/stfcs-support-for-start-ups-accelerates-business-growth/

E.18 CERN BIC - Camstech

Founded in 2014, Camstech is an early stage company that develops novel biochemical sensing technologies for life sciences research, and also for applications in biotechnology and medical diagnostics.

The company's engagement with CERN BIC initially came via one of the firm's founder's links to CERN: Alex Efimov, Camstech's CEO, was previously a CERN-based physicist. His knowledge of the facility helped him see the potential of CERN's major array detectors (which detect collisions between particles) in developing more effective biosensors. In particular, the company identified CERN intellectual property which could help them scale up and manufacture their biosensors more cost effectively than compared to standard processes. In 2015, Camstech licenced technology that CERN was using as part of its Large Hadron Collider upgrade and subsequently in March 2016, entered the CERN BIC at Harwell.

Company representatives noted that being part of CERN offered a number of advantages. Securing the IP licence was particularly important as it helped put the firm in a better position to realise its vision and bring sensors to market. In addition, the company has valued some of the wider advice and guidance provided by the CERN BIC. For instance, they welcomed CERN BIC's advice on how to position the company so that it could optimise technology transfer and progress up the TRLs most effectively. Engagement with CERN BIC also helped give the company better knowledge of the support and facilities that STFC could also provide.

While they are not actively pursuing the technology licenced from CERN, prioritising other research projects instead, they still believe that it offers real commercial potential and it remains a solution that the company is actively looking to pursue in the medium term. Indeed, they are looking to raise additional funding that will help them maintain the research's momentum.

Nevertheless, the company believes that their participation in CERN BIC has already led to real and tangible benefits. In light of their early work on the CERN-linked biosensors, the company adapted some of their other solutions and approaches to other research projects, helping them secure additional funding. For instance, their experiences of using CERN helped encourage a switch from more electron-based detection mechanisms to optics-based ones instead. By changing this approach, Camstech was able to secure additional funding (£100k) from Innovate UK to develop miniaturised optics for in-body measurements, and also obtained NIHR grant money to extend this project by a further year. One representative also added that were it not for the support provided by CERN BIC, Camstech would not have applied for North Wales photonics Launchpad funding either.

Since graduating from CERN BIC, Camstech has now moved to Daresbury. Consultees were clear that without their involvement CERN BIC, the company could not have made the progress that it has.

Supporting evidence

- Interview with Pankaj Vadgama, Founder and Co-Director, Camstech
- https://www.cernbic.stfc.ac.uk/Pages/Camstech.aspx
- http://camstech.co.uk/

E.19 CERN BIC - Croft Additive Manufacturing

Croft Additive Manufacturing is an SME that specialises in the additive manufacturing (3D printing) of complex metal components. Its particular focus is on the use of selective laser melting, a powder based fusion process that constructs components through the layering of metal powder.

In 2013, Croft Additive Manufacturing was the first company to join the CERN BIC at Daresbury. Prior to this relationship, the company had already developed a new metal additive manufacturing (AM) technology to help produce filter technologies for their sister company, Croft Filters. The company felt that their production method could also be used to produce filters for use in vacuums. They approached CERN to help them test and validate this theory, drawing on its knowledge of how parts and materials operate during the de-gassing process that helps make them vacuum ready. By understanding whether their AM developed parts operated properly in vacuums, Croft Additive Manufacturing would then be able to sell them as being vacuum ready.

Through their engagement with CERN BIC, Croft Additive Manufacturing accessed CERN technologies, expertise and facilities, and also received £40,000 of funding. Company representatives have spoken of their involvement in CERN BIC as having been beneficial. Of direct relevance to their AM process, consultees highlighted how working with CERN experts helped the company validate the vacuum readiness of their parts. The company said it was pleased with the outcomes from their CERN project, saying that the results would go a long way to convincing potential customers of their products' vacuum readiness. Although Croft Additive Manufacturing has relatively few current vacuum customers, and the test results are not directly relevant to the company's current manufacturing processes, they still believe the experience has been worthwhile. Consultees said that they now knew that they could build good quality vacuum products if ever needed.

The company has seen some intangible benefits from their engagement with CERN BIC. Company representatives for instance spoke about the reputational benefits of working with CERN, particularly having their technologies validated by them, which Croft Additive Manufacturing continues to benefit from. Indeed, one of Croft Additive Manufacturing's clients initially approached the company after seeing them profiled on STFC CERN publicity. The links to CERN have also provided opportunities to meet others and raise the company's profile. They for instance, have been able to visit CERN, and have exhibited at CERN-organised events and workshops. Some STFC research groups have also approached the company to build parts for their own experiments.

The consultees also spoke about the benefits of CERN BIC's Darebsury location. It gave them the opportunity to interact not only with those linked to STFC and CERN, but also with end-researchers based on the wider campus.

The relationship has been mutually beneficial to both the company and CERN. Croft Additive Manufacturing has benefitted from knowledge on how to work in vacuums while the consultee believed that CERN had benefited from gaining new expertise in the additive manufacturing process.

Company representatives attributed the business' development to their involvement with CERN BIC, noting that it had accelerated the company's progression in its first couple of years. For instance, engagement with CERN BIC helped improve Croft Additive Manufacturing's profile and reputation, in turn helping them secure an Innovate UK grant.

Supporting evidence

- Interview with Neil Burns, Founder and Co-Director, Croft Additive Manufacturing
- https://www.cernbic.stfc.ac.uk/Pages/Croft-Additive-manufacturing-.aspx
- https://www.croftam.co.uk/

E.20 CERN's CLOUD experiment and the role of atmospheric aerosols

Experiments at CERN are investigating the role of cosmic rays and atmospheric aerosols in cloud formation, an important factor affecting climate change.

Clouds are made of microscopic droplets of liquid water or, in some cases, of small ice crystals. They form when water vapour condenses on tiny solid or liquid particles, known as aerosols, which are present throughout the atmosphere. These can be natural or man-made so-called *direct* aerosol particles arising from Earth's surface, such as dust from deserts or salt crystals from the oceans, or carbon from combustion. Aerosols also form *indirectly* in the atmosphere from the condensation of trace vapours such as sulphuric acid, which derives largely from fossil fuels. Once these particles grow above a certain size (50–100 nm), water vapour can condense on them to form cloud droplets.

Atmospheric aerosols and their effect on clouds are recognised as the largest source of uncertainty in climate projections over the 21st century. They affect the Earth's climate directly, with dark aerosols, such as black carbon or dust, absorbing sunlight (a warming effect), while light-coloured aerosols, such as sea spray or sulphates, reflect sunlight back out to space (a cooling effect). Aerosols also affect climate indirectly through their role in cloud formation. The number of concentrations of aerosols present in the atmosphere affect not only the amount of cloud cover but also characteristics such as cloud lifetime and reflectivity, as well as the vertical development of convective clouds. The radiative forcing of the climate by these indirect aerosol effects is larger than the direct effect, and more difficult to quantify.

Despite its importance for climate, aerosol formation is poorly understood. Measuring the underlying microphysics in controlled laboratory conditions is important for a better understanding of atmospheric aerosol. The Cosmics Leaving Outdoor Droplets (CLOUD) experiment at CERN recreates a realistic atmospheric environment and is the first, and thus far the only, facility in the world capable of measuring these processes under controlled conditions. Conceived and led by Jasper Kirkby, a British researcher based at CERN, the CLOUD detector was completed in 2009 and the first experiments began that year. It is now a collaboration of scientists from 18 institutes in nine countries, including the University of Leeds from the UK. The construction, governance and operation of the CLOUD experiment draws heavily on the CERN model of scientific collaboration.

Figure 70 The CLOUD experiment simulates the effects of cosmic rays on atmospheric aerosols and clouds. Fish-eye view of the inside of the CLOUD chamber from the lower manhole, showing the fibre-optic UV lights and transparent high voltage electrodes.

Photo: Maximilien Brice, CERN http://cdsweb.cern.ch/record/1221293?ln=en

At the heart of the experiment is a stainless-steel chamber, surrounded by instruments that continuously sample and analyse the gases and particles inside. The chamber is filled with synthetic air made from liquid nitrogen and liquid oxygen, and the temperature is controlled to any tropospheric temperature in the range -70°C to 40°C. Small quantities of other gases such as sulphur dioxide or organic compounds are added and, after switching on one of CLOUD's five different light sources to simulate sunlight, aerosol particles are formed and characterised. CLOUD is the first experiment to reach the technological performance and ultralow contaminant levels necessary to be able to measure aerosol nucleation and growth under controlled conditions in the laboratory. In addition, and underlying its original design at CERN, CLOUD can investigate the influence of cosmic rays on aerosol-cloud processes. A beam of particles from CERN's Proton Synchrotron is passed through the CLOUD chamber, providing an artificial source of "cosmic rays". This allows the beam's effects on aerosol production or on liquid or ice clouds inside the chamber to be recorded and analysed.

CLOUD is now recognised as the world's leading experiment to measure aerosol production under tightly-controlled atmospheric conditions in the laboratory. Its results comprise the most comprehensive laboratory measurements of atmospheric aerosol nucleation and growth so far achieved. CERN technical know-how has been crucial for the reaching the unprecedented performance of the CLOUD chamber and its gas system, and continues to play a key role in further developing the detector to meet new experimental challenges.

In 2016, CLOUD announced the discovery that biogenic vapours emitted by trees and subsequently oxidised in the atmosphere can form aerosol particles in the absence of sulphuric acid[i]. The new mechanism implies the presence of a ubiquitous source of biogenically-driven aerosols alongside the largely anthropogenically-driven aerosols with sulphuric acid. The effect is to raise the baseline aerosol state of the pristine pre-industrial atmosphere and reduce estimates of anthropogenic aerosol radiative forcing and their uncertainties.

In 2016, data collected by CLOUD was used to build a model of aerosol production based solely on laboratory measurements (led by researchers at the University of Leeds) - using CLOUD-measured nucleation rates involving sulphuric acid, ammonia, ions and organic compounds. Although sulphuric acid had long been known to be important for nucleation, the results showed for the first time that observed concentrations of particles throughout the atmosphere can be explained only if additional molecules - organic compounds or ammonia - participate in nucleation. The results also show that ionisation of the atmosphere by cosmic rays accounts for nearly one-third of all particles formed, although small changes in cosmic rays over the solar cycle do not affect aerosols enough to influence the Earth's polluted climate significantly.

CLOUD's unique contributions thus allow the representation of aerosols in climate models to be based on experimental measurements rather than *ad hoc* parametrisations. CLOUD results are now being implemented in the global climate model of the UK Met Office, which is one of the major models that inform the Intergovernmental Panel on Climate Change. This is helping to clarify the role of aerosols and clouds in partially offsetting global warming from greenhouse gas emissions, thereby reducing the uncertainty in projected warming during this century.

A sound understanding of how aerosols respond to the complex system of inorganic and organic gas emissions and other environmental factors will help to predict more accurately how these factors affect climate for future emission scenarios – and help provide a sound scientific basis for policy decisions. The potential value of such improvements is vast. For example, the Met Office recently estimated that its climate change information would bring £2.95bn in value to the UK over the next 10 years.

Supporting evidence

- Interview with Jasper Kirkby, CLOUD Spokesperson, CERN
- https://home.cern/science/experiments/cloud
- http://cloud.web.cern.ch/cloud
- Dunne, EM et al (2016) Global atmospheric particle formation from CERN CLOUD measurements. Science 10.1126/science.aaf2649; https://home.cern/news/news/experiments/cloud-experiment-sharpens-climate-predictions
- http://cloud.web.cern.ch/content/aerosols-0
- http://cdsweb.cern.ch/record/1257940/files/SPSC-SR-061.pdf
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- IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. https://www.ipcc.ch/report/ar5/wg1/
- London Economics (2016) Met Office General Review 2016. Available online: https://londoneconomics.co.uk/blog/publication/met-office-general-review-march-2016/

E.21 CERN Supplier – Arcade UK Ltd

Arcade UK Ltd is a company specialising in heating, ventilation, and air conditioning (HVAC). Between 2011 and 2015, Arcade delivered around 17 contracts to CERN valued at over £1.7m. These contracts included supplying the heating and ventilation systems for a number of experiments, including the CMS experiment, as well as smaller projects such as improvements to the cooling systems for a server room and the installation of redundant pumps and ventilation for parts of the LHC (e.g. ALICE experiment).

While these contracts are for fairly standard HVAC products and services, these projects have had a significant impact on the business, with the initial contracts supporting the expansion of the company's engineering team and providing valuable revenue. Moreover, working at CERN has enabled Arcade to demonstrate a full range of design and installation specialisms working for high-profile customer. In this vein, working for CERN has positively impacted upon the reputation of the company and provided assurance to other customers with equally high standards. For example, CERN work has provided assurance of the quality of the products supporting Arcade UK to successfully secure contracts in the defence sector, such as a large contract for BAE Systems to work on their submarines.

Working with CERN has also raised their experience of working with large systems and complex project management structures. This knowledge and familiarity of working with such systems and management styles has also positively impacted their future capacity to bid for and manage such projects.

Supporting Evidence

- Interview with Mike West, Managing Director, Arcade UK Ltd
- https://stfc.ukri.org/innovation/tender-opportunities/business-success-at-international-facilities/
- http://www.arcade-uk.ltd.uk/arcade-provides-unique-design-and-installation-systems-at-international-scientific-base/

E.22 CERN Supplier – TG Engineering

TG Engineering is a world class supplier of fully integrated, high specification modular clean room assemblies, precision machined components and engineering solutions to leading edge industries. In 2012, it acquired NTE Vacuum Technology, a manufacturer of vacuum chambers/vessels, pipework, ultra-high vacuum systems and vessels, cryostats, precision machined components, with a strong track record of supplying to CERN. It was whilst working with CERN and other research facilities in the mid-1980s that NTE Vacuum developed the required skills and then continued to improve the performance of its chambers/vessels to the point where it was the number one choice for many companies, both in the UK and abroad. Between 2010 and 2014, NTE supplied 9 contracts valued at over £170k. As such, it has a history of supplying both standard machine components as well as vacuum chambers and vessels.

As a small company, TG Engineering are better placed to provide bespoke products. While the components it now supplies to CERN are in most cases fairly standard, they often require tight tolerances and in some cases materials that are less common. As such, each product requires a different approach and a different set of skills, some of which are developed through delivering CERN projects.

In one such project, NTE Vacuum delivered a tubular pulled port system, the production of which required the company to develop and master a new welding process. One big advantage of this system was the production of Tee pieces with ports of either the same tube diameter or smaller. The subsequent welding of tubes to Tee piece can then be achieved with full penetration butt welds without the use of any filler wire. This feature is particularly important for CERN, as they often require a grade of stainless steel for which no filler wire is available. The welding of these tubes involves a tungstem inert gas process, which prevents oxidisation of the inside of the fabrication and produces a clean, smooth, full penetration weld that is essential for ultra-high vacuum components. The welding process took a lot of development but was eventually mastered, this enabled NTE to take a big step forward in the production of specialised UHV chambers & vessels.

For TG Engineering, the working history with CERN has benefits for the reputation of the company and the products. Indeed, representatives from the company noted that much of their business came through word of mouth recommendations and the association with the CERN brand had a positive impact on the perception of the company and its products.

Supporting Evidence

- Interview with and additional information provided by Thomas Rak, TG Engineering
- http://tgengineering.com/

E.23 CERN Supplier – HV Wooding

HV Wooding is a manufacturing company that provides a wide range of services covering design assistance and prototyping through to the assembly and testing of finished products. A supplier to CERN, HV Wooding has provided a range of products including yoke and collar magnet parts, busbars, and machine parts. Since 2011, it has delivered 28 contracts for CERN worth £1.4 million.

Prior to working with CERN, HV Wooding had not undertaken large scale scientific work. A previous client of the company initially recommended HV Wooding to CERN. As part of the upgrade to the Large Hadron Collider, CERN was looking for a new method of manufacturing magnetic yokes, stainless steel collars and filler components for a prototype focussing magnet (quadropole). Working with experts at CERN, HV Wooding developed a new manufacturing method using laser cutting and wire erosion, a process the company had not extensively used before. Through working with CERN, HV Wooding has developed some of the build components for the quadropoles.

Company representatives have spoken about their CERN work creating several benefits. As already described, HV Wooding had not previously worked on large scale scientific work. The CERN contracts also helped open new markets for the company. CERN responded positively to HV Wooding's work and their reputation has subsequently spread by word of mouth. The company secured similar contracts with other science facilities including the Brookhaven National Laboratory in the US, the Rutherford Appleton Laboratory in the UK, and facilities in France. To that end, company representatives said that the CERN contracts, plus others secured following it, have helped consolidate their existing export activity. They also added that there were strong reputational benefits from working for CERN.

Company representatives also highlighted the skills and expertise gained from their CERN contracts. They noted the close working relationship they had with CERN's Technology Department, frequently liaising with them to develop the magnetic yokes which provided valuable feedback and knowledge. HV Wooding noted that they applied this knowledge to other contracts. Working on the CERN contracts and with the staff there has also helped give the company greater confidence in their work. It has been demanding and required HV Wooding to deliver high quality outputs, thereby providing valuable experience and expertise. As such, the contracts have supported improvements to the price points and the saleability of their products.

Interviewees also identified financial benefits associated with their CERN work. The absence of the CERN contracts would have had commercial implications for the company as it would have been much more difficult to enter the scientific markets without them. Furthermore, to help fulfil the initial contracts with CERN, the company invested in two machines with limited applications for other customers. Without the initial CERN work, HV Wooding would not have made this investment. Financially, the company would not have suffered too badly without their CERN contracts, but they would have lost all of the significant reputational and brand value benefits associated with the work.

Based on the knowledge gained, the reputational benefits for the company and the support these contracts provided for accessing new markets, company representatives estimated these benefits were worth £600,000 to the company.

Supporting evidence

- Interview with, and survey responses from, Alan Crow, Technical Support Manager, H.V. Wooding
- https://www.hvwooding.co.uk/precision-engineering-news-uk/assembled-part-at-cern-manufacturing-magnet-components-for-cern

E.24 CERN Supplier – UHV Design Ltd.

UHV Design Ltd is a manufacturing firm based in the UK specialising in the design and manufacture of manipulation products suitable for use in Ultra-High Vacuum environments.

Over the past decade UHV Design's involvement with CERN has been relatively modest, with most orders received being for standard products or variants thereof. In 2017, however, CERN approached UHV Design with a particular request for a customised version of their magnetically coupled Linear PowerProbe that could also operate remotely in vacuum. The products hitherto used at CERN all used edge welded bellows assemblies which are subject to unpredictable failure leading to loss of vacuum with potential catastrophic loss of service. Furthermore the bellows assemblies are prone to shed particulates into the beam leading to a degradation of beam quality.

UHV Design collaborated with CERN's engineers in the development of a customised fail-safe Linear PowerProbe which, due to the use of a magnetically coupled bellows-free actuation, guarantees vacuum integrity for the lifetime of the device. Furthermore, the additional challenges associated with the design of a mechanism capable of working under ultra-high vacuum conditions for potentially millions of cycles required that the design had to be adapted in order to reduce the contact areas between moving parts, whilst requirements for cleanliness prevented the use of lubricants. This bellows-free solution brings together creative design, smart materials selection and precision operation. Having successfully passed the prototype testing phase at CERN, UHV Design has recently received a confirmed order for a quantity of these devices and orders for further quantities are expected over the coming years.

Furthermore, it is envisaged this new design could improve the operability of beamlines around the world and reduce unscheduled downtime due to loss of ultra-high vacuum conditions. As such, UHV Design is in a strong position to work with those sections of the global synchrotron and linear accelerator community who have in interest in moving away from the use of bellows in critical areas. In this sense, association with the CERN brand bolsters the reliability and reputation of this product and of the company. While their exposure to this particular market segment is still developing, this piece of development work has further widened the product range which UHV Design can offer this market in the future.

<u>Supporting evidence</u>

- Interview with and survey responses from Patrick O'Hara, UHV Design Ltd
- https://physicsworld.com/a/uhv-design-advances-bellows-free-drive-for-critical-beamline-applications-at-cern/

E.25 CERN Supplier – Micron Semiconductor Ltd

Micron Semiconductor Ltd is a world leading manufacturer of silicon detectors for a range markets, including High Energy Physics, Space, Nuclear and Medical Research and OEMs. Micron Semiconductor has been working with CERN for close to 30 years and, as an SME, has largely focussed on supplying CERN experiments with small volume orders. Over the past 10-15 years, this has involved developing and supplying new P-Type and N-Type Silicon Pixel detectors for various upgrades, including ATLAS, LCHb and CLIC, amongst others.

Micron Semiconductor have strong relationships with the Liverpool- and Glasgow-based university research groups involved in the ATLAS experiment. This relationship has involved the iterative and collaborative design of pixel detectors, with the university groups providing their design requirements and empirical observations and Micron Semiconductor providing manufacturing expertise. As such, the company works with the researchers to outline what design characteristics are both suitable for their needs whilst being manufacturable.

In doing so, Micron Semiconductor have been challenged to provide novel designs and processes to meet the exacting and particular requirements of the experiments. This paid research and development has been beneficial for the company as it removes some of the risks and the time that would be required under other circumstances. Such projects have been beneficial in pushing the design and processing limits of the company. This is very beneficial because it supports Micron Semiconductor to push the design and processing limits of their products. Micron Semiconductor are considered to be one the world's best in this area due to their work with CERN experiments.

This early development work is expected to come to fruition soon, as Micron Semiconductor are currently in the tendering process to supply large quantities of detectors. Indeed, applications for these tenders are underpinned by this long standing relationship and development work with CERN.

The relationship with CERN research groups has also supported the development of skills through CASE studentships, where Micron Semiconductor hosts PhD students from UK universities working with CERN and supports their projects by conducting practical work on testing devices. Indeed, Micron's Head Designer is a CERN trained researcher who previously participated in a CASE studentship. As such these collaborations also provide a pool of possible future highly skilled staff in the future.

The vast majority of their work in high-energy physics and their work providing pixel detectors is with CERN, as this represents a very particular niche market. While these development have fed into other markets to a small extent (e.g. pixel detectors for medical applications), it is difficult for Micron Semiconductor to determine the influence of this previous work.

Supporting evidence

- Interview with Amanda Boothby, Finance Director, and Mark Bullough, R&D Manager, and Susan Walsh, Head of Design, Micron Semiconductor
- https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=31755
- P.p. Allport-J. et al. (2014) Nuclear Instruments & Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors & Associated Equipment

E.26 CERN Supplier - Exception PCB

Exception PCB Ltd is printed circuit board (PCB) manufacturer that has delivered over 700 contracts to CERN valued at around £900,000. The contracts have benefited the company through improvements to efficiency and productivity, as well as improvements to the quality of the products themselves. More broadly, the relationship with CERN has facilitated sales to other CERN suppliers and stimulated the adaptation of their business model to fill a niche in the market.

Exception PCB have supported CERN by supplying a range of products and services, ranging from R&D studies and support, through pre-production runs to medium volume production runs. As such, while some contracts include fairly standard products, there are technically challenging projects too. This has included the supply of PCBs for the CERN data servers, covering 200-250 different projects alone.

Exception PCB also have a good working development relationship with CERN, meeting with them twice a year to support the design process and ensure that what they have designed is possible to manufacture.

The majority of their business is directly with CERN, though they have also worked as contractors for other companies supplying CERN, including Norcott Technologies and Micron Semiconductor. Reflecting this, representatives from Exception PBC attend the STFC-supported bi-annual delegation to CERN to strengthen their relationship with CERN, as well as taking the opportunity to meet with other customers and suppliers. This has brought them into contact with several new customers across Europe.

As CERN is at the leading edge of the technology development, Exception PCB have also benefitted from the lessons from CERN's own PCB Development Lab. The technically challenging projects are those that can't be put through mainstream manufacturing processes because of their small size, and very particular characteristics.

One particular project supporting R&D was joint funded by CERN and Exception PBC for the development of a PCB with challenging physical geometries and very tight margins. While it was possible to image the layout of the PCB, the choice of materials for this PCB was less familiar for Exception PCB and is more fragile than other materials. As such, when undertaking depth drilling of the boards, the tolerances were much tighter resulting in a higher risk of the boards breaking. While working this material was not entirely new for Exception PCB, it did require a degree of upskilling and adaptation on behalf of the company. It is expected that CERN will require 400-500 boards per year of this type, and Exception PCB expect to supply these contracts in the future. The new processes developed as part of this project have since been integrated into other work conducted by Exception PBC.

As there are a number of departments across CERN requiring electronics, Exception PCB have received fairly regular income and have benefited from strong relationships and positive reputation across different departments. This trust now means that CERN staff approach Exception PCB directly to support their own development processes to take the PCBs to a manufacturable state. Off the back of this type of work, Exception PCB have established an internal group, Integrated Design Support, to provide support to CERN and other customers to trial and explore new ideas and push the boundaries of what is possible. This allows the company to explore new opportunities, undertake reciprocal learning with CERN, as well as positioning them to deliver contracts in the future. In this way CERN has provided Exception PBC with steering to find their niche market and competitive edge.

The company usually has a view on when CERN will be tendering (as a result of collecting quotes), allowing Exception PCB to better forecast and schedule their order books. Many of the CERN orders are random and need to be turned around quite quickly. In response to this need, Exception PBC have adapted their business model to provide quicker lead times to their mass manufacturing competitors.

Supporting Evidence

- Interview and survey responses from Mike Devine, Technical Sales Director, Exception PCB Ltd
- https://epcbonline.com/

E.27 CERN Supplier – Stevenage Circuits

Stevenage Circuits supplies all types of printed circuit boards (PCBs) and have a long and involved relationship with CERN experiments. The contracts delivered to CERN account for less than 5% of their business and tend to be high-value contracts for small quantities. These contracts often involve delivering products with challenging specifications, as the researchers and engineers working at CERN push the technical boundaries in their designs. As such, the work often requires Stevenage Circuits to adapt to meet these challenging briefs, pushing their products to the leading edge of the technologies.

Stevenage Circuits worked with the University of Liverpool to develop the LHCb VELO readout hybrids. The processes developed have been noted as being 'ultra-reliable' and have since been extended to other projects including the ATLAS tracker upgrade. In support of this upgrade, Liverpool University was responsible for the design and production of barrel hybrids. Stevenage Circuits supplied all of the strip barrel hybrid substrates, working in collaboration with the ATLAS-UK designers to modify the designs to ensure high reliability/yield at low costs. This upgrade was based on the same design rules of the LHCb VELO Hybrids, extending the ultra-reliable processes for this ATLAS tracker upgrade.

For example, the collection from silicon circuit boards, requires gold wire bond pads have to be very small and perfectly positioned. Given the density of these bond pads on a board, it was necessary for Stevenage Circuits to adapt their process to allow for this. The firm then document these development processes, ready to apply for equivalent customers should they have similar issues or requirements.

The company's relationship with Liverpool University has also supported other development projects, including those to explore the use of materials the company is already familiar with but in different ways. For example, researcher at Liverpool are already using flexi-materials to make rigid printing circuit boards to produce a thin product that meets their requirements. In the process, they are learning about what happens to materials when you rigidise them, to which Stevenage Circuits have supported experiments and supported product development.

Supporting evidence

- Interviews with Dave Charlton & Mike Fairclough, Business Development, Stevenage Circuits

- Gateway to Research, Research Grant Capital Equipment, Project Reference: ST/L00335X/1
- Gateway to Research, 2012 Consolidated Grant Supplement, Project Reference: ST/M001474/1

WORLD-CLASS SKILLS

E.28 CERN@School programme

Following on from initial school visits to the CERN facility, the CERN@school initiative was developed in the UK, providing equipment and support to schools to enable them to engage and participate in scientific experiments. The success of this initiative has also led to the formation of the Institute for Research in Schools (IRIS), which provides teachers and schools with opportunities to work on cutting-edge, original research from within a school setting. As well as enthusing students and developing knowledge, this work has directly contributed to scientific progress and discoveries.

Traditionally in the UK, the teaching of physics had been based on a theorist pedagogy. Students were taught about scientific discoveries, but the curriculum generally only covered those discoveries which had been made up to the 1930s. However, physics is a dynamic area, with new discoveries being made all the time – and these were not being reflected in the A-level curriculum. One teacher, Dr Becky Parker MBE, was inspired to expand the curriculum to include more recent discoveries in particle physics. She secured funding from the Wellcome Trust and one of the exam boards to develop this, as well as additional support from the Open University and the Institute of Physics. In developing this new curriculum, she visited CERN, and then took a group of 50 school children there to gauge interest. She then successfully persuaded the exam boards to include particle physics in the A-level curriculum. This is something that students have indicated they found 'practical' and an example of 'real science'.

Since then, thousands more UK students have visited CERN. The feedback from these visits is extremely positive, with 89% of teachers rating their visit 4/5 or 5/5, and 100% of teachers intending to bring another group to CERN [CERN data]. However, with the opening of the LHC, there was concern as to how to maintain interest for school trips, as these visits would no longer be able to take children to the subterranean level. Dr Parker consulted with CERN about this and, working with academics and research groups at CERN, they decided to create something schools could do, either in conjunction with their visits to CERN and/or back at their schools in the UK. From this, CERN@school was born. Initially funded by the UK Space Agency and Kent County Council, it has been funded by STFC since 2010.

CERN@school

Initially, CERN@school was based around the Timepix hybrid silicon pixel detector, the data from which can be used to visualise ionising radiation in a very accessible way (further details below). Broadly speaking, CERN@school consists of a web portal that allows access to data collected by the Langton Ultimate Cosmic ray Intensity Detector (LUCID) experiment in space and the student-operated Timepix detectors on the ground. Educational resources are provided by CERN for teachers to use with LUCID data and detector kits in the classroom. This initiative was one of the first uses of the Timepix detector technology in open space. Students and teachers were supported to either contribute to large international scientific collaborations or to devise their own research projects. This has been different to other radiation experiments as, with these detectors, radiation can actually be seen and visualised.

CERN@school provides schools with this Timepix detector technology and they use it to make research-grade measurements of ionising radiation. Students are able to make a direct connection between what is being done with a remote instrument and the instrument they control themselves. Schools have to plan and design their use of the equipment and in effect submit a bid for the use of the detectors. The popularity of the CERN@school programme is evident from the number of schools submitting bids to participate. Also, feedback from schools shows that the waiting time for a detector is one of the main frustrations of the programme. Schools would like to have the detectors on site more frequently and for longer time periods.

The CERN@school programme has allowed students to take measurements from satellites in space, monitor radiation levels on the international space station and hunt for exotic new particles in the data from the LHC, undertaking genuine scientific research for themselves. They have worked alongside companies like Rolls-Royce and Surrey Satellite Technology, as well as NASA and CERN.

Initially, CERN@school comprised just ten detectors being used by schools in Kent. That number has now grown to 40, to which schools have access on rotation for six weeks at a time. To date, over 20,000 students in more than 460 schools, from across the UK, have participated in CERN@school projects. These projects have been published in multiple peer-reviewed journals, something not regularly achieved by UK school children in the past.

Resources are provided to aid students and teachers in the running of these research groups in schools. For example, guidelines are provided to schools setting out how to run weekly collaboration meetings where results are shared and progress updates are given, so encouraging and facilitating schools to collaborate across a network, and share ideas and results.

Schools are free to design their own programmes using the detectors provided. This has enabled them to design experiments based on the specific interests and specialisms of the teachers and students involved. In addition, some have been used as part of a series of educational demonstration workshops across multiple schools, while two of the detectors have also been deployed to the Daresbury and Rutherford Appleton Laboratories for use in their outreach and public engagement events.

Since 2014, CERN@school has run an annual research symposium, where teachers and students from across the UK present results from their research projects. This has grown year-on-year, with the most recent symposium being too large for all the delegates, and two satellite groups joined the symposium via video conferencing. In attending these symposia, and other academic conferences, and presenting their work and their findings, students are given a genuine taste of the scientific process, of developing and conducting unique experiments, of reporting their findings and of the nature of professional scientific collaboration.

In addition to this annual symposium, in January 2019 ten teachers running CERN@school research projects are speaking at The Association of Science Education Conference, where the keynote speech is about CERN@school. These teachers are showcasing the research they are undertaking and discussing how it impacts more widely on their schools.

Since its inception, over 20,000 students across more than 460 schools have participated in CERN@school research projects.

<u>Institute for Research in Schools (IRIS)</u>

The success of CERN@school led to the formation of the Institute for Research in Schools (IRIS) in 2016. This charitable trust has the aim of developing a wide range of research fields within which schools and teachers can participate in authentic research. This is intended to inspire the next generation of scientists (students reported that before participating they "had no idea what scientists *actually did*"). CERN@school, which is now overseen by IRIS, has made science less about theoretical learning – deploying a more activist pedagogy, where neither students or teachers know the answers in advance.

CERN@school (and latterly IRIS) have also coined the term 'teacher scientist'. Teachers involved in the programme are no longer teaching scientific theories in the abstract. They are working on cutting edge scientific research, something usually reserved for practicing scientific researchers. This has enhanced teachers' knowledge of the subject, making them better teachers and providing a new level of career development. These teachers are given the opportunity to move on from being effective teachers of curriculum materials to ones who are inspirational, expert teachers. As well as enhancing their subject expertise, these teachers are also leading the development of others and sharing knowledge. Participating teachers have specific areas to follow up in their continuing professional development (CPD), which include sharing their learning more widely with colleagues and other schools.

CERN@school and latterly IRIS have also taken much needed steps to encourage and retain physics teachers. More widely, there has been concern around the retention of science teachers for some time, as over half of all STEM teachers leave the profession within five years. But in one study where 1 in 12 teachers who did not participate in STEM learning CPD left teaching the following year, this reduced to 1 in 30 for those who did engage in STEM-specific CPD[164].

One early IRIS project linked schools with Tim Peake's mission on board the International Space Station. NASA is working to better understand and monitor radiation exposure to crew members during long duration space exploration missions on the journey to Mars. The TimPix initiative is making the data which was taken during Tim Peake's stay on the station available to teachers and students. Using the Timpix technology first deployed by CERN@school, the IRIS TimPix projects offers students the opportunity to analyse space radiation data and take part in authentic space station research. This work is undertaken in collaboration with CERN, and also receives funding from the ESA and the UK Space Agency. Following the success of work of UK schools on the TimPix initiative, US schools were signed up to undertake a US version of this project. So, the UK initiative was beneficial to NASA in helping NASA to detect and monitor the effects of radiation on the body and to understand better what it needs to do to protect astronauts during a future manned mission to Mars. In addition, it paved the way for US schools to become involved in this initiative, raising the international profile of the collaboration between CERN and UK schools.

More recently, a group of UK students have discovered a rare evolved star as part of the IRIS cosmic mining project. The students have been working with STFC scientists at the UK Astronomy Technology Centre (UKATC) to select potential targets for pointing the James Webb Space Telescope (to be launched in 2021). They sifted through data from the Spitzer Space Telescope, which has observed tens of thousands of points of potential interest, creating vast amounts of astronomical data. The students presented their findings at the Royal Astronomical Societal in 2019.[165]

The success of IRIS has seen a two-way impact, as scientists who have been collaborating with schools are now motivated to find new ways to participate in school science, and are independently identifying opportunities to utilise schools in their work. Most recently, IRIS has set up the first large-scale school genome decoding project, in which students from 60 schools are working with scientists from the Wellcome Trust and European Biometrics Institute to find, identify and label all the genes in the DNA of a global parasite (the human whipworm). This is the first time school students have worked directly with scientists to help curate an entire genome, and will directly help scientist to find new ways of treating and preventing this infection.

The Genome project is just one example of where schools initially working with CERN has had leverage in other fields. Currently IRIS is running seven projects in schools, which span chemical, physical and mathematical sciences, biological and ecological sciences and social and behavioural sciences. IRIS is also supporting a further four research projects that are being led by partner institutes and universities, giving school children and teachers an insight into the world of science and scientific careers beyond the school experience.

The satisfaction students gain from participating in innovative new science alongside their learning is evident in their feedback. One of the teachers involved with CERN@school stated this work had "increased my enthusiasm for physics, and has helped me ignite a passion for STEM in my students". And within one month of their engagement, 93% of students said they were more interested in science.

Supporting evidence

- Interview with and additional data provided by, Becky Parker, Director of IRIS
- Interview with Michael Campbell (Spokesman of Medipix collaboration), CERN
- http://www.researchinschools.org/CERN/home.html

[164] https://wellcome.ac.uk/press-release/cpd-improves-science-teacher-retention

[165] Further details: https://stfc.ukri.org/news/uk-student-scientists-discover-rare-evolved-star/

- STFC Public Engagement Case Study of the CERN@school programme, 'You're never too young to be a researcher'. Available: https://stfc.ukri.org/files/youre-never-too-young-to-be-a-researcher-the-cern-school-programme/

SCIENCE DIPLOMACY

E.29 The synchrotron-light for Experimental Science and Applications in the Middle East (SESAME)

The SESAME synchrotron light source is an excellent example of science diplomacy and showcases the critical role CERN plays in fostering cooperation across political, religious and cultural divides. It is widely cited as an example of science for peace and inspired several other major cooperative initiatives.

The genesis of the new light source is one of the most well-documented examples of CERN's support for international relations, with several papers and book chapters providing a moving account of its development.[166][167] We have used this material to compile a brief overview of that history, picking out just one or two of the key milestones; as such our account is heavily abridged. The full story is very well worth reading, and underlines the critical importance of scientific communities in being able to keep open communications and rebuild bridges.

The SESAME synchrotron

SESAME is a "third-generation" 2.5 GeV synchrotron light source located in Jordan. The Synchrotron-light for Experimental Science and Applications in the Middle East (SESAME) was opened officially on 16 May 2017 and is the Middle East's first major, international research centre. It is a cooperative venture by scientists and governments of the region set up on the model of CERN (European Organisation for Nuclear Research) and developed under the auspices of UNESCO, following formal approval in 2002.[168] It is an autonomous intergovernmental organisation at the service of its Members, the composition of which is remarkable: Cyprus, Egypt, Iran, Israel, Jordan, Pakistan, the Palestinian Authority and Turkey. The list of 17 Observers is also notable in terms of both the geographical extent and the geopolitical dynamics; it is a manifestation of world-wide support for SESAME: Brazil, Canada, China, EU, France, Germany, Greece, Italy, Japan, Kuwait, Portugal, Russian Federation, Spain, Sweden, Switzerland, the UK and the USA.

SESAME will both:

- Foster scientific and technological excellence in the Middle East and neighbouring countries (and prevent or reverse the brain drain) by enabling world-class scientific research in subjects ranging from biology, archaeology and medical sciences through basic properties of materials science, physics, chemistry, and life sciences
- Build scientific and cultural bridges between diverse societies, and contribute to a culture of peace through international cooperation in science

As an intergovernmental scientific and technological centre of excellence open to all scientists from the Middle East and elsewhere, SESAME will serve as a propeller for the scientific, technical, and economic development of the region and will strengthen collaboration in science.

The origins of SESAME

The origins of SESAME have many sources but are widely considered to relate in particular to the ambitions of Abdus Salam, a Pakistani physicist and Nobel Laureate, who argued there was a need for an international synchrotron in the Middle East as long ago as the 1980s.

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[166] The original chair of the SESAME Interim Council, Herwig Schopper, wrote a 40-page paper published in 2017, entitled, The light of SESAME: A dream becomes reality, RIVISTA DEL NUOVO CIMENTO Vol. 40, N. 4 2017.

[167] See 'Science Beyond Boundaries: SESAME and the International Cooperation,' Chris Llewellyn Smith, Chapter 26 in the International Cooperation for Enhancing Nuclear Safety, Security, Safeguards and Non-proliferation–60 Years of IAEA and EURATOM: Proceedings of the XX Edoardo Amaldi Conference, Accademia Nazionale dei Lincei, Rome, Italy, October 9-10, 2017. Editors: Luciano Maiani, Said Abousahl and Wolfango Plastino, Springer, 2018.

[168] Decision of the UNESCO Executive Board, 164th session, May 2002

Salam's idea was nurtured at CERN within the Middle East Scientific Cooperation (MESC) group, headed by Sergio Fubini. MESC's efforts to promote regional cooperation in science, and also solidarity and peace, started in 1995 with the organisation in Dahab (Egypt) of a meeting at which the then Minister of Higher Education of Egypt, Venice Gouda, and Eliezer Rabinovici (MESC coordinator and professor at the Hebrew University, Israel) issued an official statement in support of Arab-Israeli cooperation.

The MESC group was also instrumental in persuading the German government to consider donating the components of the soon to be decommissioned Berlin synchrotron (BESSY 1) to SESAME. Herwig Schopper (a former CERN Director General) brought the plan to the attention of the DG of UNESCO, who convened a meeting in 1999 of all delegates from the Middle East and other regions, which resulted in an agreement to move forward with the project and the creation of an Interim Council (of SESAME members). Schopper was appointed as chair and oversaw the development of design studies and the competition to host the facility, which Jordan won. UNESCO formally approved the proposals in 2002.

Herwig Schopper's written account of the process is a fascinating story about the importance of CERN's constitution and reputation in securing support for the project within the international community and the eminence and social capital within the region of the scientists driving the project.[169]

Regional cooperation

The synchrotron is only just beginning its experimental programmes, so there is not much science to report on yet. However, there are many references in the various accounts of the SESAME story that point to the furtherance of scientific cooperation across the region, which emerged through the development of the proposals for the new light source and the targeted training and capability building that has been underway for more than a decade.

> *SESAME was opened on May 16th, 2017 … My next dream is for it to produce top quality science … No matter what's going to happen, just the fact that all of us, Iranians, Israelis, Jordanians, Egyptians, Pakistanis, Palestinians, could work together for twenty years proved that it's possible, no matter what the leaders say. I believe that scientists in different countries took their leaders to a place they never expected to be. I don't think anybody in Jerusalem or Tehran thought this was going to happen. But up until now even when they realise where they are they did not yet blink. They didn't run away. They may, eventually, because anything is possible in my region. But we have shown it's possible.*

DANCERS AND LONE WOLVES: Conversation with Eliezer Rabinovici[170]

UK involvement

The UK involvement is evident at a number of points. Initially as one of the observer countries within the Interim Council, it provided political support for the project as well as making more practical contributions in the form of beamline equipment (contributions in kind) and training / capability development of future SESAME researchers.

Sir Christopher Llewellyn-Smith agreed to become president of the SESAME Council, following the opening of the main building in November 2008, taking over from Herwig Schopper. Llewellyn-Smith has written several articles and a book chapter (2018) describing the experience, which again

[169] The original chair of the SESAME Interim Council, Herwig Schopper, wrote a 40-page paper published in 2017, entitled, The light of SESAME: A dream becomes reality, RIVISTA DEL NUOVO CIMENTO Vol. 40, N. 4 2017.

[170] http://scgp.stonybrook.edu/archives/24915

underwrites the critical importance of the international scientific community in finding a way through political crises.[171]

Llewellyn Smith's appointment was in recognition of his relevant experience as a former CERN Director General that had overseen the development of early proposals for the LHC and the inclusion of Japan and the USA as observer countries. His personal contributions are widely credited with getting SESAME to the stage where it was able to begin its scientific programme, finding a way through multiple political incidents and related funding crises that characterised the 10 years between the opening of the main building and the first experiments beginning.

The critical importance of this extended period of diplomatic stewardship to the realisation of the project was attested to when Sir Christopher was named personally in the AAAS 2019 award for science diplomacy as one of five people that made SESAME possible.[172] The AAAS press release underlines the exceptional nature of the community's achievements in the realisation of the project.

For over a decade, SESAME's vigorous training programme has been building scientific capacity in the region and nurturing a community of scientists who will visit the facility in order to carry out research. Llewellyn Smith (2018)

"SESAME is a remarkable example of how scientists can unify in the pursuit of knowledge, even among nations with longstanding political tensions," said AAAS CEO Rush Holt. "The scientific enterprise in and of itself can promote peace and foster international collaboration."

"In recent years, there is hardly a more shining example of science diplomacy than SESAME, which demonstrates the power of science to build bridges in the face of geopolitical tensions," said Mahlet Mesfin, deputy director of the AAAS Center for Science Diplomacy.

[171] See 'Science Beyond Boundaries: SESAME and the International Cooperation,' Chris Llewellyn Smith, Chapter 26 in the International Cooperation for Enhancing Nuclear Safety, Security, Safeguards and Non-proliferation–60 Years of IAEA and EURATOM: Proceedings of the XX Edoardo Amaldi Conference, Accademia Nazionale dei Lincei, Rome, Italy, October 9-10, 2017. Editors: Luciano Maiani, Said Abousahl and Wolfango Plastino, Springer, 2018.

[172] Christopher Llewellyn Smith, Eliezer Rabinovici, Zehra Sayers, Herwig Schopper and Khaled Toukan received the 2019 AAAS Award for Science Diplomacy. https://www.aaas.org/news/architects-cooperative-middle-eastern-research-center-receive-2019-aaas-award-science

technopolis group

Appendix F Parameters used for monetising benefits

The following sub-sections present further details of parameters used in the calculations of monetised benefits (see Section 10). The final sub-section provides additional explanation of an alternative approach used by Florio et all (2017) to estimate a valuation for CERN by wider society.

F.1 Willingness to Pay of UK science and engineering community

The average number of academic staff (2014-2017) has been used to arrive to grossed-up estimates of the willingness to pay of the scientific community, based on HESA data.

Table 37 Academic staff, by cost centre

Academic year	Group 1: Physics	Group 2: Other relevant fields*
2014/15	5,070	19,250
2015/16	5,185	19,625
2016/17	5,175	19,750
2017/18	5,385	21,055
Average	5,203	19,920

Source: HESA data * General engineering; Electrical, electronic & computer engineering; IT, systems sciences & computer software engineering and Mathematics

F.2 Value of the production of knowledge

To estimate time dedicated to research, we conducted a follow-up survey with 50 scientists. They stated in the first survey that they read and reference / cite CERN publications at least several times each year. Fifteen answered our follow-up survey. They estimated they dedicate between 70% and 100% of time to research, or an average of 73% and a median of 80%. We have used this in our calculations.

Table 38 Time dedicated to research

	Mean	Median	Min	Max
Time dedicated to research	73.3%	80.0%	70%	100%

Source: Technopolis (2019) (n=15).

Productivity

We have measured 'productivity' based on (1) number of UK researchers & staff members and (2) number of all UK scientists (including CERN Researchers - Scientists, not employed by CERN, carrying out work / experiments at CERN, UK Staff members (research physicist and scientific & engineering work categories only), Fellows present at CERN, Students Present (Technical and Doctoral) at CERN on the CERN Studentship Programme). Results are presented in the table below and the range from 0.60 – 0.72. We have used Productivity 2 (mean), with two years of lag in our estimates. The two years of lag means that the number of scientists in 2015 are associated to the number of publications in 2017.

Table 39 Productivity: Number papers per scientist (based on data for the period 2010-2017)

	Same year comparison		Two-year lag **	
	Mean	Median	Mean	Median
Productivity 1: Number of papers with at least one UK author / number of UK researchers & staff	0.64	0.68	0.72	0.71
Productivity 2: Number of papers with at least one UK author / number of all UK scientists**	0.60	0.64	0.67	0.67

Source: Prepared by Technopolis using information provided by CERN and Science Metrix * Time t-2 scientists & time t publications, e.g. 2015 scientists & 2017 publications. **Including: CERN Researchers - Scientists, not employed by CERN, carrying out work / experiments at CERN, UK Staff members (research physicist and scientific & engineering work categories only), Fellows present at CERN, Students Present (Technical and Doctoral) at CERN on the CERN Studentship Programme

Salaries

We have obtained information on salaries from two different sources:

- Information on CERN salaries. They range from £35,252 to £92,493 depending on the Grade and status (staff or fellow) as shown in Table 40. This equates to a (weighted) average of £63,864.
- Information on UK salaries for academics based on information published by Times Higher Education in 2016 and Glassdoor). They range between £44,995 and £114k, with the average salary for a Professor in the UK being £79,030, as shown in Table 41.

We have used those two averages in our estimates, to provide a lower and an upper bound. We have also adjusted the values of salaries over time (for the period 2009-2018), using national statistics on average annual salary growth.

Table 40 Annual salary (in £) – CERN (2019)

	Grade 1	Grade 4	Grade 7	Average (Grade 1 & 7)
Staff	35,235	59,373	92,493	63,864
Fellow	40,761	64,017	72,702	56,732

Source: https://careers.cern/salary-conditions-and-career-progression, which provides information on monthly remuneration net of tax in CHF. Calculations assume 12 months of income and 0.75 CHF to GBP (March 2019)

Table 41 Annual salary (in £) – UK academics

	Average	Range	Source	Reference year
Professor	£79,030	£51.7-£97.0	Times Higher Education	2015-2016
Other senior staff (academics)	£82,506	£55.6 -£185.3	Times Higher Education	2015-2016
Professor	£75,548	£60k to £114k	Glassdoor	2019
Physicist	£44,995	£30k to £74k	Glassdoor	2019

Source: Glassdoor, Times Higher Education (www.timeshighereducation.com/sites/default/files/breaking_news_files/uk_university_salaries_2015-16.pdf)

F.3 Wage premia

The table below show the information on salaries collected for the estimation of the value of skills. The information on salaries for software engineers was used as a proxy for the salary in industry. Salary on academics, depending on their level of seniority was obtained from Prospect.ac.uk.

We have also adjusted the values of salaries over time (for the period 2009-2018), using national statistics on average annual salary growth.

Table 42 Salaries (2019)

	Academia*	Industry (e.g. software engineer)**	Industry (e.g. financial analyst)**
Entry level	£41,709	£ 40,050 (5yr change: +4%)	£ 40,229 (5yr change: +4%)
Mid-career (senior)	£55,998	£ 64,536 (5yr change: +22%)	£ 49,808 (5yr change: +11%)

https://www.prospects.ac.uk/job-profiles/higher-education-lecturer, ** A software engineer, with 3 years of experience (entry level) or 9 years of experience (mid-career), with experience in C++ programming and a PhD.

F.4 Inflation

Final estimates on cost and benefits have been adjusted by inflation and expressed in terms of 2018 real prices, using a GDP deflator (see table below).

Table 43 GDP deflator

Calendar year	GDP deflator at market prices (2018=100)	Value of £1 in Year X, expressed in 2018 real prices
2008	84.8	1.18
2009	86.161	1.16
2010	87.48	1.14
2011	89.16	1.12
2012	90.55	1.10
2013	92.239	1.08
2014	93.821	1.07
2015	94.229	1.06
2016	96.168	1.04
2017	98.289	1.02
2018	100	1.00

Source: ONS (February 2019)

F.5 Valuation from the wider society

Florio et al used a contingent valuation approach (consistent with the NOAA 1993 protocol) to determine social preferences for the non-use value of the LHC as discovery device, a public good with unknown practical use, proxied by WTP.

The author polled the public (1,027 university students across four countries, including approximately 200 in the UK in 2015) on their willingness to pay for LHC research activities (offering options of €0, €0.5, €1 or €2 per year, for 30 years)[173]. A two–page description of CERN and a two-minute video visualising what particle physics research at CERN consists of were provided to interviewees[174]. A minority (27%) was unwilling to pay anything. A grossing up of the balance arrived at a figure of €3.2bn (for 30 years). A separate analysis of just French respondents in 2018[175] computed a figure of €4 per person per annum as the maximum amount taxpayers would be willing to pay for the construction of a new particle accelerator at CERN. (This compares with the actual French national payments, which amounts to around €2.7 / person each year).[176]

An estimate of €4 per person per annum (for 10 years) would equate to £1,209.1m in the UK (based on a tax-payer population of 30.3 million and an exchange rate of 0.85). This final figure accounts for inflation.

It is difficult to tell what people (in this case, students) were included in this valuation, which means the approach may already capture some of the estimates presented in the table at the start of this section. That depends on their level of awareness of CERN (even after the information and video was provided) and what they regard as important. However, this estimate should probably be taken as an all-encompassing measure, that is supposed to account for all measured and unmeasured benefit.

[173] Forecasting the socio-economic impact of the LHC: a cost-benefit analysis to 2025 and beyond

[174] Some questions were asked before the provision of information material and some were asked afterwards. This permitted before/after comparisons and the assessment of real (i.e. not biased) awareness about CERN.

[175] Scientific Research at CERN as a Public Good: A Survey to French Citizens, 22 August 2018, Massimo Florio (University of Milan) and Francesco Giffoni (CSIL – Centre for Industrial Studies and University of Milan)

[176] https://cerncourier.com/lhc-upgrade-brings-benefits-beyond-physics/

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