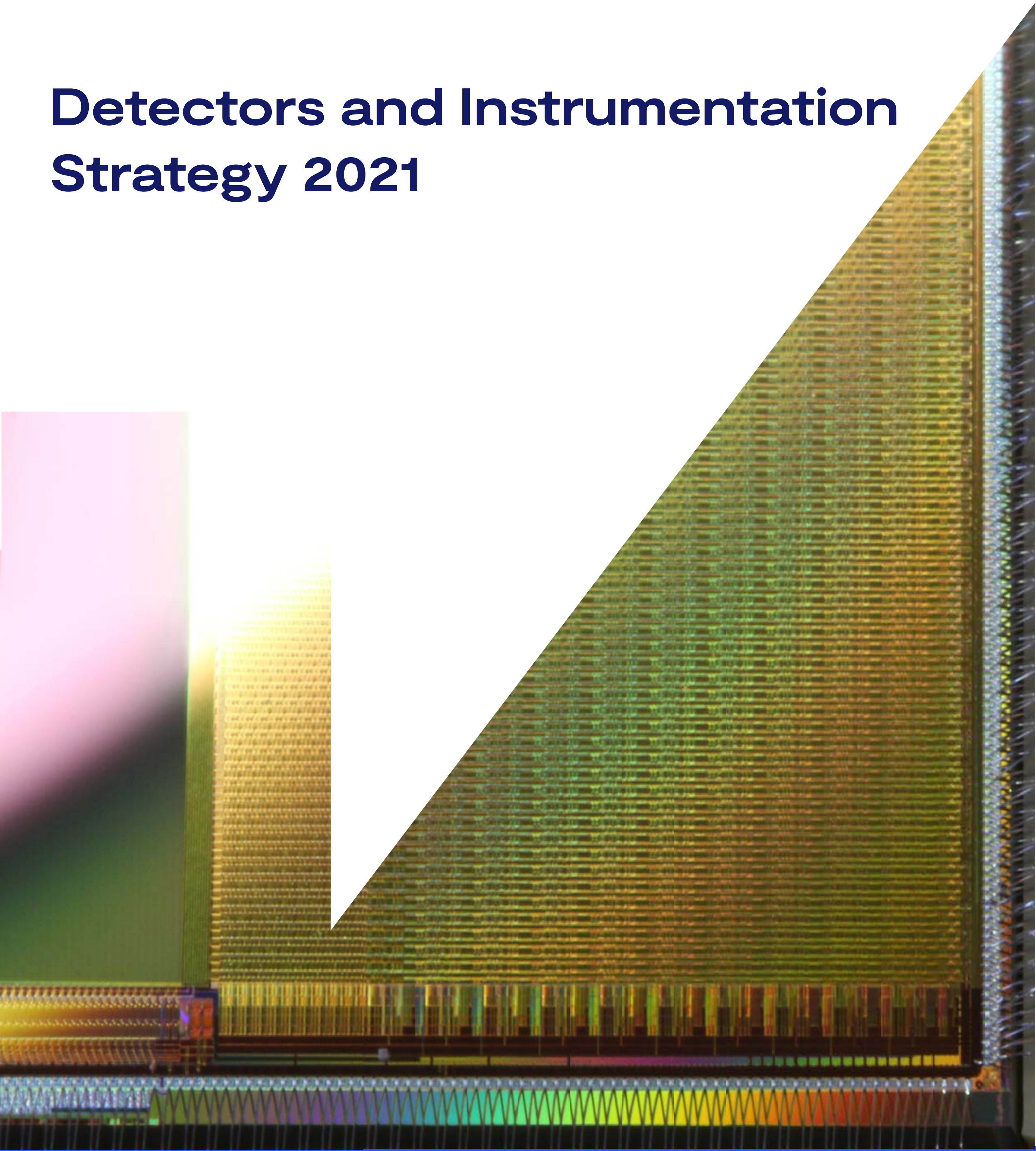
Science and Technology Facilities Council

Detectors and Instrumentation Strategy 2021



October 2021

Foreword

By Professor Mark Thomson, STFC Executive Chair

Detector technologies and instrumentation are at the heart of much of the Science and Technology Facilities Council's (STFC) operations in our core science areas and at the national and international facilities. It is our ability to sense the natural world, from fundamental particles to gravitational waves, that enables us to understand how our world functions.

STFC's national laboratories and the science communities that we work with have a fantastic track record of world-class developments in detector science and technology. This includes key elements of the massive ATLAS and CMS detectors at the Large Hadron Collider (LHC) at CERN and the Nobel Prize winning developments in cryo-electron microscopy. There are also many examples of how this expertise and knowledge is being applied to benefit the whole of society including new medical imaging systems and remote sensing to monitor how our environment is changing. We recognise that our future investments in world-leading research infrastructures will only deliver their planned outcomes if they are properly instrumented.

Building on the findings of the 2019 Detectors and Instrumentation Strategic Review, this strategy sets out how STFC aims to support and enable the next generation of detector technology research and applications. Our approach is to coordinate and foster collaborations and knowledge exchange that will be able to benefit research priorities across STFC and more widely across UK Research and Innovation (UKRI). An important element of the strategy is to strengthen the pool of technical skills that underpin all areas of detector and instrumentation research, development and exploitation.

We look forward to working with our colleagues and stakeholders across all the UK science and technology communities including academia, industry and our international partners as we begin to implement the measures set out in this strategy.

Executive summary

STFC's mission of investigating fundamental science questions depends on utilising a wide range of advanced detector technologies and instrumentation systems that can image the world by detecting and sensing a wide spectrum of photon wavelengths, particles and phenomena of interest. The instrumentation technologies we need are also applicable to many of UKRI's wider research programmes. Therefore, possessing a leading instrumentation capability is recognised as a critical enabler for STFC. This strategy sets out how we will identify, prioritise and address key instrumentation development challenges across its science areas.

Optimised instrumentation systems are vital to our work. They help to deliver the full scientific potential of our facilities and science programmes and also maximise the return on our science investments. These systems also bolster the UK to secure partnerships and leadership positions in international projects and enable STFC's skills to be applied across the wider UKRI science portfolio and industry. The performance of our instrumentation solutions shapes many science experiments and can define the success of major science programmes. It is critical that we plan long term and prepare for tomorrow's programme by investing today in the detector technologies and instrumentation skills that will be needed for future science and innovation challenges.

This strategy builds upon our current national capability in detectors and instrumentation in our national laboratories and facilities, academic research communities and industry. The central theme of the strategy is to establish a coordinated approach that will foster collaborations, help build skills and technical capability and identify high priority technical challenges for focussed attention. The hub and spoke model is recommended where the hub acts as a central resource that is also well connected into all the expertise on the many aspects of detectors and instrumentation that exist across the UK.

Enhancing skills progression, identifying gaps, succession planning issues and promoting career development opportunities are important themes of the strategy so that the expertise that is critical to success across all the instrumentation dependant research areas is strengthened and retained. This covers the whole skills spectrum including apprenticeships, technician training, doctoral training and fellowships to ensure we have the researchers and project leaders of the future.

Many of STFC's technological challenges are also very relevant to industrial applications in fields such as security and medical imaging. This strategy explains how this will be managed and optimised to deliver value to the UK economy.

In each section the opportunities and actions for STFC, our partners and other stakeholders are identified and listed. Progress in putting the strategy into action will be overseen by a detector's strategy implementation group with representation from across the STFC communities and the wider UKRI detector interests. This group will work with the Detector Hub to help steer the various areas of activity including helping identify funding opportunities and reporting on impacts made and outcomes achieved.

Contents

1) Introduction, vision and goals

Science, research and innovation lie at the heart of the UK's continuing prosperity. Our ability to develop new ideas and translate these into innovative and commercial applications is also central to achieving the government's ambitious industrial strategy and ensuring the UK's competitiveness as a global player in driving innovation.

STFC combines leading researchers from academia, government and industry, to investigate and understand the Universe from the largest astronomical scales to the tiniest constituents of matter. Creating and providing access to large scale scientific and technical facilities equipped with instrumentation to image and map data, lies at the heart of this remit. A critical component underpinning these unique scientific assets are our detector and instrumentation systems.

Detector developments and their enhancements have not just led to increased scientific discovery improving our understanding of fundamental science such as investigating the nature of matter, the interactions in drug molecules and material properties. They have also created tangible assets that lead to new techniques, methods and devices. Applications range from the everyday visible imaging cameras, to improved microscopes, medical imaging systems and security scanners. This development process creates valuable Intellectual Property (IP), creating opportunities for licensing and spin-out companies thereby driving an innovation ecosystem around our campuses, programmes and clusters that enables the transfer of our technologies between disciplines and on into new commercial applications.

Developing advanced technologies is recognised as one of STFC's key Strategic Themes[1]. Within this theme, the need to develop sensors and other detector related instrumentation is identified as critical across almost all aspects of our science, technology and innovation activities. The breadth and diversity of these needs were clearly illustrated in a recent strategic review[2], which provided a comprehensive snapshot of detector and instrumentation technologies, applications and future needs across the full spectrum of science and technology areas. Whilst focussed on the areas of particular relevance to STFC, the review also covered some topics important to the wider UKRI-supported science communities. The review findings have therefore provided an excellent steer for developing this strategy.

This document outlines a framework in which specific detectors and instrumentation challenge priorities can be defined, communicated, tracked and revised as our scientific landscape evolves. Working with our advisory boards including Science Board (SB), Technology and Accelerators Advisory Board (TAAB) and STFC's Centre for Instrumentation (CfI), a current list of instrumentation priorities will be maintained and periodically updated. This process will help shape current funding mechanisms to match the identified priorities and recommend additional resources to be sought as appropriate.

This prioritisation process will also enable STFC to identify skills shortages and potential succession planning issues in the future. This will help to build and maintain the correct teams within academia and the national facilities and laboratories, making sure they are matched to

1. https://stfc.ukri.org/files/delivery-plan-2019/
2. https://stfc.ukri.org/files/corporate-publications/detectors-and-instrumentation-a-strategic-review/

the emerging UKRI needs. To coordinate this, and to benefit the whole community, a hub and spoke model is proposed with a central Detectors Hub overseen by a mix of STFC, academic and industrial staff. The hub will work with our advisory boards to track, prioritise and manage identified instrumentation challenges, form networks of experts, share knowledge and foster stimulating opportunities for helping detectors specialists to grow their skills and experience.

Vision

Detectors and instrumentation are at the forefront of enabling progress in all STFC's core research areas and at our national facilities that support research across much of the wider UKRI remit. The performance requirements for detector components and systems are constantly increasing as new techniques are developed. This requires a long-term plan to ensure that future detector needs for STFC, partners, stakeholders and science communities can be effectively met. The formation of UKRI provides an opportunity to more closely link STFC's detector developments to those of researchers across UKRI's research disciplines, so that synergies can be realised, and silos of similar research activities avoided.

Our vision is to establish an overarching framework so that future detector and instrumentation needs can be effectively identified and progressed in a coordinated manner. Also, to create a stronger community of detector specialists spanning across the science communities, national laboratories and industry that can foster the growth of talent and skills. This will ensure that there is a pipeline of new expertise that will be needed to support the needs of future major research infrastructures, help drive innovation that can exploit the investment in detector and instrumentation technologies and keep the UK as a partner of choice with our international peers in these key disciplines.

In delivering this vision, we will adopt the following guiding principles. We will:

- Prepare for and support the needs of the next generation of research infrastructures that will require state of the art detection and instrumentation to help them realise their full potentials. Working with the research communities and the private sector, we will maximise the value to wider society from the investments in detectors and instrumentation
- Maintain and grow a detectors capability that is driven by the ambition of STFC and UKRI's diverse communities of researchers and innovators to ensure state-of-the-art provision is available across the spectrum of detection scales that are needed by our communities
- Through a strong detectors programme, support and enable breakthroughs in subjects across UKRI and help accelerate the development and deployment of current emerging technologies such as quantum systems for fundamental physics and imaging of ultrafast processes in atoms and living cells and organisms
- Create effective implementation and governance arrangements that can inform prioritisation of STFC's future needs and opportunities, support funding opportunities and track and report achievements and outcomes across a 10 – 20 year timeline

Instrumentation development goals

The UK has many talented development teams throughout our research communities in academia and industry. With the growth of development opportunities in priority areas throughout UKRI science, the opportunities for new projects are abundant. The challenge today is to identify those critical to STFC's programme and prepare the UK teams to align their work and lead, invest and deliver progress in the priority areas.

Delivering leadership

Leadership in this field is vital to deliver the full potential of our national science facility investments by enabling them to optimise their performance and operations to maximise our scientific output. Internationally, engagement in this field enables early access to scientific data, enables UK scientists to secure project leadership positions, steer international teams and thereby maximise the impact of our national investments. An important priority for STFC and our partners, stakeholders and science communities is therefore to steer investment to ensure that the necessary detector capabilities are developed in a timely way and are in place with capacity to meet the science programme priority needs both for today and in the future.

Delivering investment

Development investment is needed because complete instrumentation solutions are generally not available from industry in the form of off-the-shelf products, so STFC supports the research, development and application of customised detector systems, that are optimised to meet the needs of our evolving science programme. These solutions often depend on access to leading industrial semiconductors and other advanced engineering technologies that are expensive to access and have to be highly customised for each application. This involves significant investment of time and money, so must be prioritised and balanced with the ongoing science programme.

Priority focus

This strategy sets out a framework for how STFC will approach prioritisation, and how we will maintain and develop the most important detector capabilities needed to deliver its future scientific research and innovation programmes. In parallel, detector technologies that have been developed for the core sciences will also be applied to wider UKRI research applications within our society and the economy. Past examples of these extended benefits include disruptive technologies applied to medical imaging, industrial screening and security systems. To maximise that impact, STFC's innovation programme will work to actively foster this exploitation with technology licensing, spinouts and other business opportunities.

In this strategy we summarise how this detectors capability fits into the overarching STFC strategy and how we identify the instrumentation needs of our programme today and into the future. We also summarise the current funding mechanisms and sources that drive today's developments, discuss how skills and careers in this area are developed and maintained and how we work through partnership with our universities, academic teams and national laboratories. In each area, key actions are highlighted that STFC commits to follow to ensure this discipline is managed appropriately and balanced with the needs of the ever-changing UK science programme.

We are also aware that the UK is a recognised top destination in Europe for venture capital investment, with inward investors attracted by our talented and diverse workforce as well as our cutting-edge technologies and services. By committing to invest in research and development (R&D) to 2.4% of GDP by 2027, the UK is expected to increase public funding for R&D to £22 billion per year by 2024-2025 to progress towards this goal. We see instrumentation and detector systems as investment opportunities, so IP protection and management are recognised as factors for the strategy. These targets are summarised in a recent UK government policy paper “UK Research and Development Roadmap”[3].

Strategic themes

Our vision will be delivered through six high-level, inter-related strategic themes that will form a coherent approach to maintain and strengthen the national capabilities in detectors and instrumentation.

1. Instrumenting large scale science and multidisciplinary facilities.
   We will follow a strategic approach that embraces all the sensing requirements and techniques and technologies that STFC’s science programmes and facilities rely upon.

2. Delivering tomorrow’s instrumentation.
   We will follow a systematic approach to capturing future requirements across all the STFC science areas drawing upon horizon scanning and roadmap activities.

3. Building national capability.
   We will create a national focus for the UK’s detector communities and capabilities. This will take the form of a hub and spoke approach that will effectively link together all the groups in higher education institutes (HEIs), national laboratories and industry and the partnerships that exist around our international collaborations.

4. Advancing key detector technologies.
   We will create a cadre of Theme Champions who can help coordinate activities in particular sensor and technology areas that are identified as priorities and help share knowledge and identify synergistic opportunities.

5. Resourcing the development programme.
   We will seek to secure recognition of detector and instrumentation needs and opportunities in the breadth of UKRI and other funding schemes and support the development of high-quality applications for detector projects.

6. Recognising the importance of detectors and instrumentation skills.
   We will seek to secure opportunities for detector specialist career path development through established schemes such as fellowships, the Technicians Commitment, and apprenticeships.

The Advanced Gamma Tracking Array (AGATA) spectrometer. Construction at Daresbury Laboratory.

3. https://www.gov.uk/government/publications/uk-research-and-development-roadmap

Strategy map

STFC is an inherently multidisciplinary, diverse science organisation located at six UK sites, which sponsors many researchers throughout the UK in academic centres that have a long history of delivering world-leading instrumentation. STFC's mission, focussed on three themes of discovering the secrets of the Universe, developing advanced technologies, and solving real-world challenges all rely on the continued success of these sites.

STFC's strategy is summarised in the map illustrated below. This illustrates how STFC's mission fits within the wider UKRI strategy and identifies the key goals that STFC promotes to deliver this.

UKRI Vision
UK is a world leader in research and innovation

UKRI Mission
To maximise the UK's R&D contribution to knowledge and ideas, quality of life and prosperity for everyone

UKRI Values
We are collaborative partners; we are innovative, creative and catalysts; we act with integrity and we focus on excellence

STFC Vision
The UK is a world-leader in fundamental science, with large-scale national facilities and research and innovation campuses that are the envy of the world

STFC Mission
Discovering the secrets of the universe, developing advanced technologies, and innovating to solve real-world challenges

STFC's Customers, Communities and Stakeholders
Expect excellent research outputs, a streamlined funding system, impartial advice and high quality environments in which to solve research and innovation challenges, inspire and engage the public

STFC Goals

World-Class Research
We will champion UK global leadership in research to understand the universe, its fundamental constituents, and their interactions

World-Class Multidisciplinary Facilities
We will ensure our national laboratories and international facilities deliver world-leading science

World-Class Innovation
We will be innovative across all of our activities, developing advanced technologies and creating new business opportunities

World-Class Skills
We will utilise our national laboratories and Science Programme to develop a pipeline of skilled engineers, technicians and scientists

Operational Excellence
We will ensure that STFC is a modern and effective organisation that values our staff and delivers for our stakeholders

STFC Aims

To deliver our goals, we will:
1. provide **high-quality strategic leadership for UK frontier research** in particle physics, nuclear physics, astronomy, space science and particle astrophysics;
2. actively position our national laboratories and large-scale facilities as **world-class centres of excellence in fundamental science, engineering and technology**;
3. provide effective **management of UK participation in world-leading international facilities**, maximising the benefit to the UK;
4. catalyse the development of **next generation technologies** and accelerate the growth of the **skills base to exploit them**;
5. position our **national laboratories and campuses at the heart of the UK multi-disciplinary research and innovation landscape**;
6. exploit our national laboratories, campuses and Science Programme as **an interlink ecosystem for innovation in science and technology**, accelerating commercialisation and broader societal and economic impact;
7. provide campus-wide leadership to ensure that **Harwell and Sci-Tech Daresbury are national beacons of excellence in science and technology** that maximises the benefits to our academic, industrial and regional stakeholders;
8. deliver a world-class programme to **develop the skills at all levels needed by UK research and industry** to maximise UK leadership in frontier research, leading edge science, and new disruptive technologies;
9. maximise the **cultural impact of our inspirational science programme** to encourage the public to explore science and technology, encouraging the next generation to purse careers in STEM subjects.

Enablers

As an organisation we will:
1. value our people and champion ED&I across all of our activities;
2. operate with transparent and robust governance and management processes;
3. engage effectively with our national and international communities and stakeholders;
4. make the most effective use of resources;
5. operate a healthy, safe, modern and sustainable working environment;
6. continuously improve.

Figure 1 STFC strategy map (2020)

In following table, we illustrate how detectors and instrumentation developments are relevant to each of these goals and are therefore closely aligned to enabling the success of STFC. Key risks associated with failing to prioritise this field are described in Annex 1.

STFC goal	Instrumentation deliverables	Examples of impacts
World-class research	Imaging and data capture throughout our discovery programme. Reliable and robust radiation hard systems. Disruptive semiconductor imaging. Quantum sensors. Data acquisition, trigger processing and storage.	The discovery of the Higgs boson, the particle that is thought to communicate mass, has helped theorists understand how matter interacts and the universe was formed. In astronomy the study of gamma rays enables us to peer into the hearts of solar flares, supernovae, neutron stars, black holes and active galaxies.
World-class multidisciplinary facilities	Technologies matched to the needs of tomorrow's facilities. Ultrafast imaging systems for photon science applications. Extreme dynamic range requirements for high power systems. High technology system assembly centres equipped to contribute internationally.	High framerate systems combined with high power sources enable the imaging of chemical and biological processes in real time. High dynamic range systems enable the scientists to record and understand rare and weak phenomena.
World-class innovation	Applying technologies across UKRI. Supporting industrial partners with innovation programmes. Active management of IP, patents, licensing and spin-out foundation. Supporting proof of concept studies.	Realising the full potential of forming UKRI. For example, radiation hard detectors developed for particle physics have transformed cryo-electron microscopy. Sensors developed for particle physics systems have been developed to create linear scanning systems for security and food production.
World-class skills	Public engagement – promoting science as a career path. Online lectures and media engagement. Doctoral training pathways. Post-doctoral support with fellowships. Supporting leadership posts in academia.	Inspiring the next generation to invent disruptive technologies and systems. Linking academia with world-wide consortia increasing the knowledge and awareness of science. Tackling the lack of diversity in science by promoting an equal, diverse and inclusive culture.
Operational excellence	Delivering wider economic impact through business growth. Efficient use of our science facilities, maximising potential. Continuous improvement methodology applied to share learning between disciplines.	Securing leadership positions in key international projects. Delivering innovation for the UK economy and stimulating high technology industries to set-up and grow in the UK.

Table 1: The role of instrumentation in delivering STFC's Goals

2) Instrumenting large scale science and multidisciplinary facilities

What we sense

The full electromagnetic spectrum is of interest to STFC, from high energy gamma rays through to low frequency radio wave sensing. In addition, electrons, muons, neutrons and charged particles are imaged across our community of researchers.

In astronomy, the study of gamma rays enables us to peer into the hearts of solar flares, supernovae, neutron stars, black holes, and active galaxies, whilst in nuclear physics their tracking permits the study of short-lived radioactive nuclei. X-rays are also critical to our imaging of materials and biological processes, with higher energy X-rays being required to penetrate dense materials and soft X-rays to image living cells. Ultraviolet (UV), visible and infrared (IR) imaging devices are used across many of our facilities, with microwave and radio astronomy critical for imaging the cosmic microwave background that allows us to look back at how the very first stars and galaxies formed just after the big bang and to study the vast magnetic fields which permeate the cosmos.

The use of photon and neutron scattering and spectroscopy techniques in our facilities enables us to study basic microscopic information on the structure and dynamics of organic and inorganic materials. These studies are transforming our understanding of technically important materials such as plastics, proteins, polymers, fibres, liquid crystals, ceramics, hard magnets and superconductors, as well as to our understanding of fundamental phenomena such as phase transitions, quantum fluids and spontaneous ordering.

In particle physics, our detectors are revealing how photons and the full family of sub-atomic particles interact with the mysterious Higgs boson, which gives mass to everything in our Universe. With the recent addition of gravitational waves and other quantum phenomena, what we detect is a wide and continuously evolving field.

How we sense

From direct ‘imaging’ of radiation with classical camera systems to tracking high energy particles through multiple layers of segmented detectors, many methods have been developed to measure, classify and store scientific data. As research infrastructures and scientific techniques have developed, this has led to growing requirements for high dynamic range systems capable of sensing from a single particle to 10^5 particles in each image pixel. Many investigation techniques also require energy measurement along with position and time, demanding complex spectroscopic analysis systems. The latest generations of scientific facilities are now substantially increasing throughput, demanding higher speed systems that produce data at an unprecedented rate. New technologies are needed to capture, process and export the information captured by the sensing elements.

To cover the wide range of energies and techniques, a number of sensing materials and techniques must be employed. High resistivity silicon systems are now widely used wherever possible, but their limitations with material geometry and stopping power mean that a whole family of other materials are required to cover the full range of science. They include high purity germanium for high energy tracking systems in nuclear physics to cadmium telluride, gallium arsenide and other semiconductor sensors for other high energy systems. Matching their dynamic range, data collection time and frame rate all dictate many architectures and measurement approaches.

The longevity of the systems is also critical in many fields. For example, in space it is critical to have high reliability, the ability to withstand both vacuum and the harsh radiation environment and also the ability to withstand launch stresses. In particle physics the ability to withstand the accumulated radiation dose acquired over many years of operation in powerful accelerators such as the Large Hadron Collider is another critical need. Therefore, the operational environment is a key element of the requirements capture for each application.

Managing future data volumes

The increase in framerate, pixel count and beamline brightness, along with the development of high speed data link technology, have conspired to create sensors and systems that can each generate many hundreds of gigabytes per second leading to an avalanche of data that require computing and power to manage, process and store.

With the increasing need for research facilities to be more environmentally sustainable in their operation, the option of simply scaling computing resource is not practical, so there is a parallel need for the productive use of increasingly complex data reduction methods to seamlessly integrate data, algorithms, and computing resources in an efficient way. This is relevant as this discipline will have to evolve and work closely with our computing colleagues as they approach the challenge of Big Data throughout the development path.

Summary and way forward

In the following sections we describe how STFC commits to review its programme and capabilities and, from those, identify the development needs required to deliver our detector and instrumentation needs of tomorrow.

In this strategy we review the current UK and international facility roadmaps and consider where specific technology advances are needed to deliver these plans. Each of these advances is captured as a ‘challenge’ and analysed to identify the key performance issues that require addressing. Capturing these benefits in the form of required ‘key results’ will enable us to communicate common goals across STFC’s national laboratories and facilities and our wider academic and commercial partners.

The following sections go on to explain how the priorities are identified, analysed, reviewed and managed. Funding opportunities within STFC, UKRI and the wider European system are also summarised and matched. Where specific needs are identified that can’t be supported by these routes, STFC’s Advisory Boards can make recommendations to STFC’s executive board to address and seek additional funding sources.

3) Delivering tomorrow's instrumentation

Preparing for tomorrow's STFC instrumentation systems requires long term planning, appropriate funding mechanisms and a matched human and capital investment portfolio within academia and industry over sustained periods. With support from its advisory panels, academic partners and national laboratories this need is addressed by a process of requirements capture, categorising and mapping development needs and implementing, via various funding routes, programmes that are reviewed and managed.

Requirements capture

We know the demand for bigger, faster and lower noise imaging systems is stronger than ever. For example, the new advanced free electron lasers and updated storage rings all have large area imaging requirements and will deliver significantly higher instantaneous sample flux. They therefore require systems with higher dynamic range, increased sensing resolution, higher pixel density, and novel functions such as in-pixel memories and ultrafast imaging and readout.

To deliver this, STFC must invest in the development and application of new sensing materials, readout electronics, advanced interconnect and data acquisition systems. One key theme for STFC is semiconductor devices, based on silicon and other materials. Advances in these detectors will make it possible to achieve high spatial resolutions, in order to, for example, measure elementary particles more precisely, or to record diffraction patterns produced by complex systems at synchrotron radiation sources that would otherwise be missed.

Given the long development time required to build capability, construct prototypes and demonstrate instrumentation solutions, a long forward look is required. UKRI's research infrastructures programme[4] is currently developing a view of the future facility needs of the UK's research and innovation activities. In parallel, STFC regularly reviews its own local and national programmes through periodic reviews. These inputs are required to deliver both UK national and STFC's international needs.

UK large-scale facility planned investments

STFC science facilities span six sites here in the UK. These are the result of many years of significant investment from the science budget. Whilst internationally our sources might not all be the most powerful, by optimising our instrumentation and detector systems we can still lead the science by maximising the performance and value of these investments.

The majority of STFC's science facilities have international partners and we have a reputational responsibility to manage and operate these facilities at their maximum efficiency. These arguments all point to leading instrumentation technology, optimised and matched to each facility.

The table opposite summarises the status of examples of new, and upgrades to existing, UK research infrastructures.

4. https://www.ukri.org/wp-content/uploads/2020/10/UKRI-201020-UKinfrastructure-opportunities-to-grow-our-capacity-FINAL.pdf

Construction phase	Detailed planning	Case preparation
EPAC	DIAMOND II	VULCAN 2020
RFI	ISIS ENDEAVOUR	HiLUX
NQCC		UKFEL
		ISIS II
		IMAGING (NMR/MRI/RUEDI)

Table 2: Examples of potential future large UK multidisciplinary research infrastructures with significant detector and instrumentation needs

International large-scale facility plans

The table below shows examples of new and planned international research infrastructures with STFC involvement, along with their current status. A strong presence in instrumentation capability is a recognised route to secure leadership roles in the international consortia behind these projects. Early understanding of the instrumentation needs of each facility or programme early will enable the UK to develop the appropriate skills and facilities to maximise the impact of the UK from both academia and industry.

Construction phase	Detailed planning	Case preparation
ESS	HL-LHC CERN	FCC CERN
DUNE/LBNF	HYPER-KAMIOKANDE	ELECTRON-ION COLLIDER
SKA		EUROPEAN SOLAR TELESCOPE
FAIR		EINSTEIN TELESCOPE

Table 3: Examples of potential future large international research infrastructures all with significant detector and instrumentation needs

Internationally, CERN is our largest overseas investment and presents an excellent opportunity for UK scientists, where instrumentation skills are needed to lead and shape the future experimental programme. Investing today in preparatory steps for high luminosity running for example, puts the UK groups in a strong position to influence and lead the experiments as that programme develops.

By reviewing and analysing the UK and international plans for new research infrastructures and projects in this way, priority challenge areas for instrumentation development can be identified.

Mapping technology requirements

Instrumentation development occurs in the fields of sensing materials, modelling, readout electronics and application specific integrated circuits (ASICs), system interconnect, powering, data transmission, analysis and software. These must be developed to approach a set of instrumentation challenges that we can then apply to our science programme. One of the key strengths of STFC is its multidisciplinary remit – so we can exploit developments for one area across all of our disciplines and maximise the value and impact of our knowledge and skills.

The image below illustrates how our portfolio of experiments and programmes have a common set of instrumentation challenges. By analysing the plans from the infrastructure road-mapping exercise we can refine and manage this list of priorities. With the assistance of our Advisory Boards we will then identify challenge leads and promote the need within the STFC network.

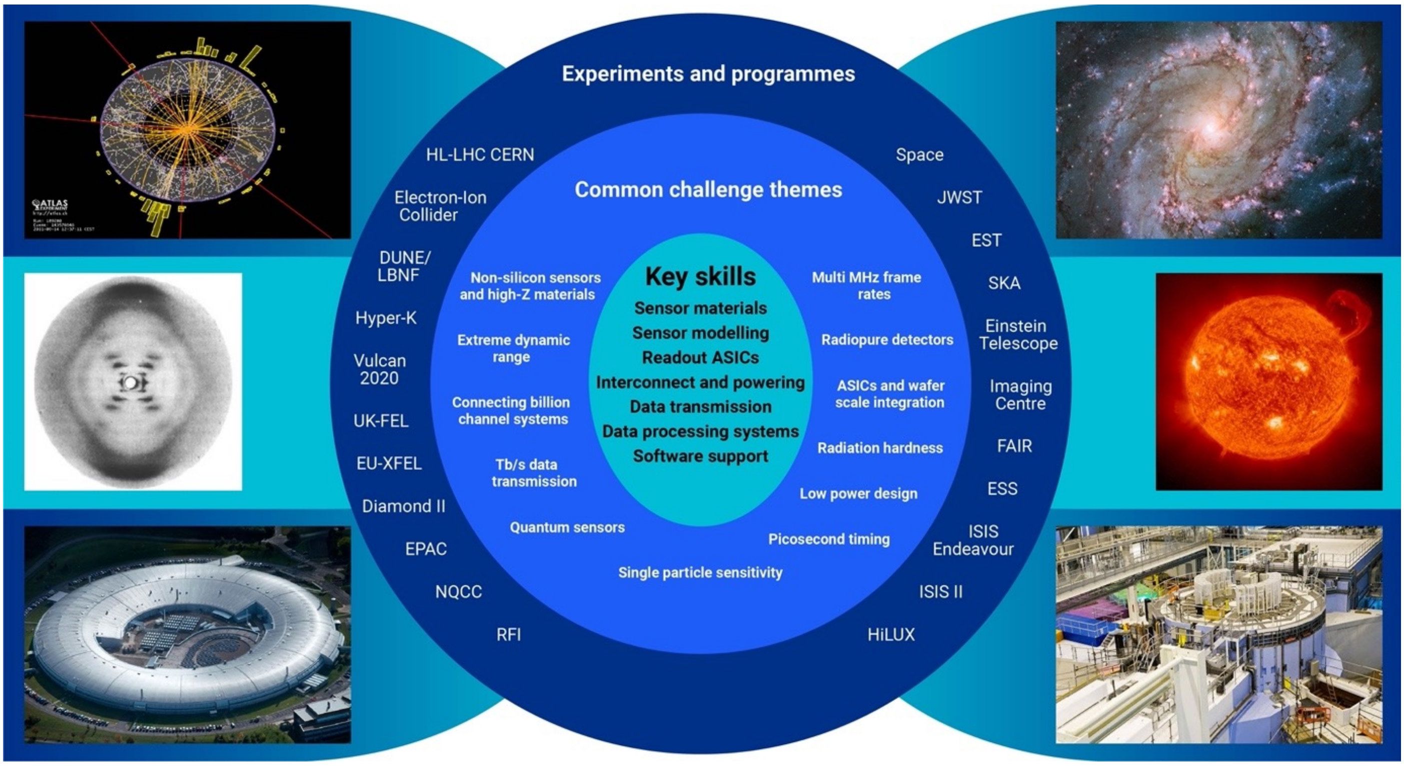


Figure 2: How key skills relate to our instrumentation challenges that deliver STFC science needs

For example, in Figure 2, the challenge of 'extreme dynamic range' systems are identified. This is relevant to nuclear physics, so impacts on FAIR, as well as XFEL, UK-FEL and Diamond, all of which must cope with extreme dynamic range images.

Implementing priorities and the importance of skills development

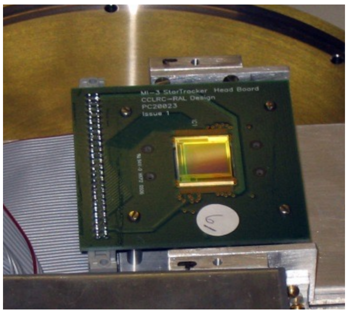
To realise the full potential of the UK in this field we must recognise that long term underpinning research activities are supported as well as specific projects, and that investment is targeted appropriately mindful of the parallel need for capital investment in assembly and test.

With limited funding available from the core programme, full use must be made of other sources. By championing key challenges (see section 5), this review process will provide a way to inform and support bidding into other development funds.

In addition to our technical challenges we must also work to ensure that career paths are maintained and supported. Through strong public engagement and pushing science throughout our diverse economy, we must also work to develop the leaders of tomorrow.

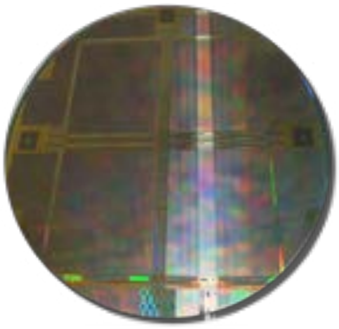
Innovation example: Cryo-electron microscopy

Electrons have been used for bio-imaging purposes alongside photons since before 1950. However, because of their damaging effect on image sensors, until 2010, direct electron imaging had to be done with primitive photographic film or indirectly with phosphor plate technology. In 2003, staff at the Rutherford Appleton Laboratory (RAL) as part of the Centre for Instrumentation development programme, built an imaging device for spacecraft applications based on radiation hard design methods developed earlier for the LHC. At that time, working with visionary physicists at the MRC in Cambridge, the star tracker device was also evaluated in this application and found to survive such high energy electron imaging.



2003 - RAL Star Tracker ASIC

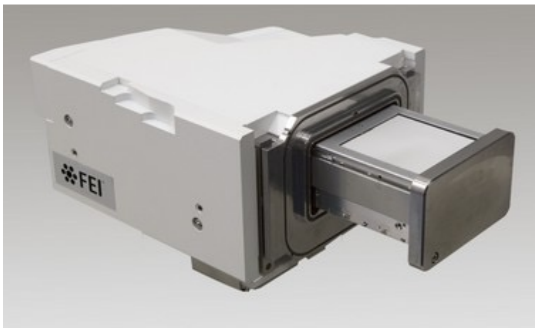
This proof of concept work was then combined with the latest in developments in stitched large area sensors that was also active at RAL at the time. This led to the first megapixel imaging sensor specially optimised for electron imaging. This component was then subsequently commercialised by Thermo Fischer Scientific (then FEI) and led to four generations of their 'Falcon' imaging cameras. This product contributed to the world-wide disruptive advance in cryo-electron (Cryo EM) microscopy that was recognised with a Nobel Prize for Professor Richard Henderson at the Laboratory of Molecular Biology (LMB) in 2017.



16 Mpixel STFC sensor wafer

STFC, working with the Rosalind Franklin Institute on the Harwell campus, is developing a new generation of wafer scale sensors to apply this technology to a new class of lower energy microscopes with the aim of substantially reducing the cost of ownership of such Cryo-EM technology whilst maintaining imaging performance. The current cost of Cryo-EM is prohibitive and limits the uptake in this revolutionary technique.

This example illustrates how instrumentation skills and technology developed for one science can have a direct impact in another. Since the formation of UKRI in 2018, STFC has been seeking to maximise such opportunities and deliver disruptive technology developments in new fields across the full breadth of UKRI.



The FEI Falcon camera series launched in 2011

Summary and actions

1. Engage with roadmap exercise to identify lead STFC projects and programmes.
2. Identify priority instrumentation challenge priorities and share with Advisory Boards.
3. Annually present to Science Board, Technology and Accelerators Advisory Board (TAAB) and Centre for Instrumentation (CfI) boards the current set of challenges, update retiring challenges or adding any new ones.

4) Building national capability

Increasing the capacity in this field, in which the UK already has a reputation for innovation excellence that is reflected in a flourishing industry base, is an important aim. To address the identified instrumentation challenges, we must combine all the skills and strengths of our network of our academic teams, international collaborations, national laboratories and UK industry in a coherent way. The national laboratories support the UK-based facility needs and also provide a centre for test, assembly and characterisation facilities for the wider international programmes. Here we summarise the UK academic landscape, the industrial capabilities, some of the key international collaborations we are engaged in and summarise the national laboratory focus.

The UK academic landscape

STFC engages with academic groups throughout the UK and supports them across the full STFC science programme. To succeed, we must capitalise on this existing infrastructure and align developments to provide a focus push the boundaries of instrumentation design, working with all the leading UKRI science communities to address the next big science challenges. The academic groups STFC currently engages with in instrumentation development are shown in the image below.

Figure 3: Key academic centres that are invested in the STFC instrumentation developments

Industrial engagement

The successful supply of instrumentation depends on a network of industrial partners throughout the world for manufacture and supply of components systems. The UK has many high-tech instrumentation companies in computing and hardware that we partner with. These include Oxford Instruments, Kromek, Micron Semiconductor, Teledyne-e2v and numerous smaller companies associated with our academic groups and campuses such as Quantum Detectors and Radtest who are both based at the Harwell campus.

UK Industry example: Teledyne e2v

Teledyne e2v, based in Chelmsford UK, is the leading global supplier of silicon image sensors for space science, ground-based astronomy, and Earth observation applications. They have an impressive record of successful deliveries to a wide range of customers over 40 years, equipping many telescopes including the NASA Hubble telescope, space based solar observatories and large ground based focal plane arrays and is a key supplier to the Copernicus missions.

Working under contract in world-wide international projects, Teledyne e2v regularly supply fully or partially customised sensors, focal planes and electronics to deliver the world leading system performance our science applications demand. The team undertakes all the design, manufacture, assembly and test.

With most of their leading-edge sensors back-illuminated for highest sensitivity, the resulting sensors perform with very low noise.

Teledyne e2v built its reputation with charge coupled detectors (CCDs). Today their use is still expanding with wider applications including mosaics for high resolution telescope imaging cameras, spectroscopic imagers, auto-guiding systems, data acquisition, and adaptive optics systems. They are also active in CMOS image sensor technologies for space which bring other advantages such as higher frame rates and incorporate many additional features such as integrated data conversion and customer system integration benefits.

www.teledyne-e2v.com

International collaboration

The UK works with many partners throughout the world. The UK expertise in instrumentation forms a natural way into many collaborations and often represents a highly valued contribution that the UK can make.

Figure 4: Current key STFC international instrumentation partnerships

Leading international science centres that we currently collaborate with include:

CERN

Based on the Swiss-French border, CERN provides the particle accelerators and other infrastructure needed for high-energy physics research. The site hosts numerous experiments that have been constructed through international collaborations. The main site at Meyrin also hosts a large computing facility, which is primarily used to store and analyse data from experiments, as well as simulate events.

In 2020 the European Strategy for Particle Physics was updated[5]. This highlighted the importance of innovative instrumentation:

"To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large".

Researchers from the UK are active in almost all experiments and, working internationally, contribute to the construction of the particle trackers, calorimeters, trigger, data acquisition and computing systems. The UK can be an important player in helping realise the ambitions in the updated stratgey.

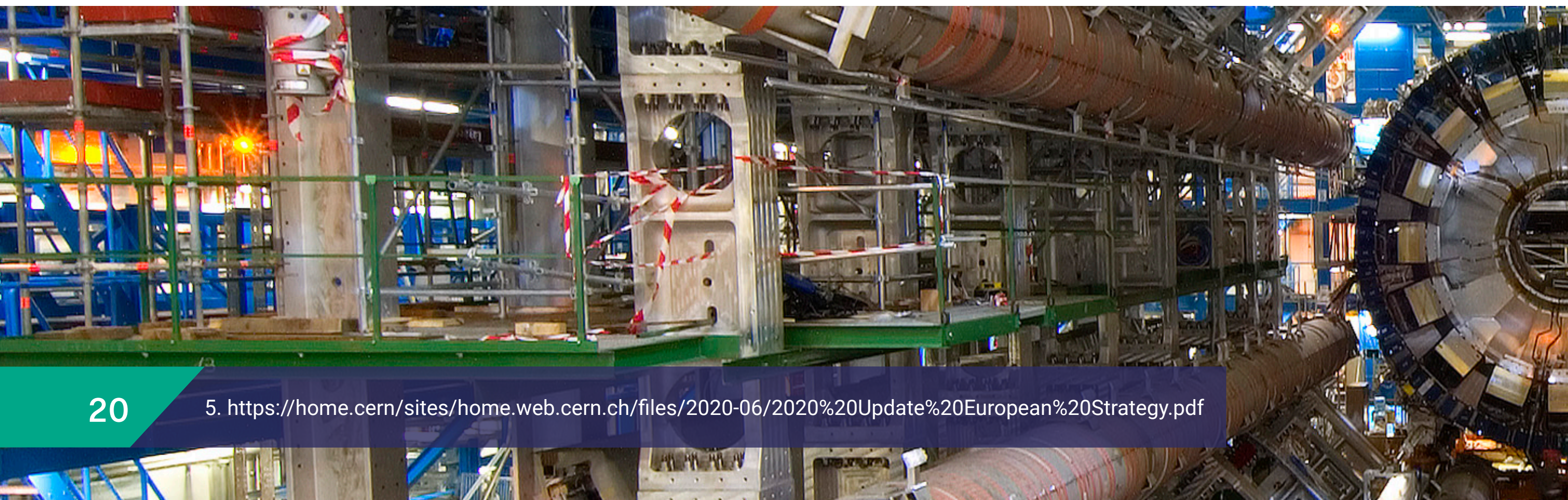
ESS

The European Spallation Source (ESS) is a multi-disciplinary research facility based in Sweden. It is currently under construction in Lund, with the data management and software centre to be located in neighbouring Copenhagen, Denmark. The 13 European member countries act as partners in the construction and operation of ESS. ESS will start the scientific user programme in 2025, and the construction phase will be complete by 2026. ESS aims to be the world's most powerful next-generation neutron source and will enable scientists to see and understand basic atomic structures and forces at length and time scales unachievable at other neutron sources.

Teams of STFC engineers, technicians and physicists have assisted in the design and construction of the facility, providing beamline instruments and data acquisition systems.

European XFEL

The European X-Ray Free-Electron Laser Facility (XFEL) is a high repetition rate X-ray research laser facility commissioned during 2018 with twelve participating countries. The laser generates high-intensity electromagnetic radiation by accelerating electrons to relativistic speeds and directing them through special magnetic structures. The European XFEL is constructed such that the electrons produce X-ray light in synchronisation, resulting in high-intensity X-ray pulses with the properties of laser light and at intensities much brighter than those produced by conventional synchrotron light sources.



5. https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

UK teams of engineers and physicists have assisted in the design and construction of the facility, providing beamline X-ray imaging instruments and data acquisition systems.

SKAO

The Square Kilometre Array Observatory (SKAO) is an intergovernmental radio telescope project being planned for construction in Australia and South Africa. Conceived in the 1990s, when completed it will have a total collecting area of approximately one square kilometre. It will operate over a wide range of frequencies and its size will make it 50 times more sensitive than any other radio instrument. It will operate very high-performance central computing engines and long-haul links with a capacity greater than the global internet traffic as of 2013. It will be capable of surveying the sky more than ten thousand times faster than before.

The UK hosts the project headquarters in Greater Manchester and researchers from the UK are currently active in developing instrumentation and firmware for the telescope.

Creating a national focus for detectors and instrumentation

Detector systems groups are currently operating at all of the STFC facilities (e.g. ASTeC, ISIS Neutron Source, CLF and Diamond Light Source), as well as within initiatives from our sister councils in UKRI (EPSRC, MRC, BBSRC, NERC), international partners (CERN, ESA, ESS) and funded programmes and networks. This creates a distributed capability but also an opportunity to create a hub which can support both intra and cross-sector translation across this enabling discipline to champion the field and deliver the UKRI impact that this sector offers.

Recent UKRI initiatives such as the Rosalind Franklin institute (RFI) and the National Quantum Computing Centre (NQCC), both hosted by STFC, are using a hub and spoke model to bring together capabilities and apply them to multidisciplinary problems that can transform progress in important research and industry sectors such as life sciences. The hubs are supported by the existing scientific infrastructures at our campuses as well as the high-tech business networks and clusters that have been developed to create collaborative ecosystems. The spokes enable close engagement with the expertise in the wider science communities.

Establishing a Detectors Hub modelled on this proven approach will enable the development of the UK's leading scientific instrumentation technology. It will address tomorrow's critical measurement and data handling challenges, as well as be a vehicle to apply this key enabler across the whole of UKRI and create impact in many national priority research areas. The centre will engage academia and industry, nationally and internationally, to catalyse development, training and academic collaboration. It will stimulate and accelerate the development of UK expertise, so we are equipped to address tomorrow's scientific challenges in many important fields and create flagship national capability that can help the UK to secure leadership roles in key international research initiatives and infrastructure.

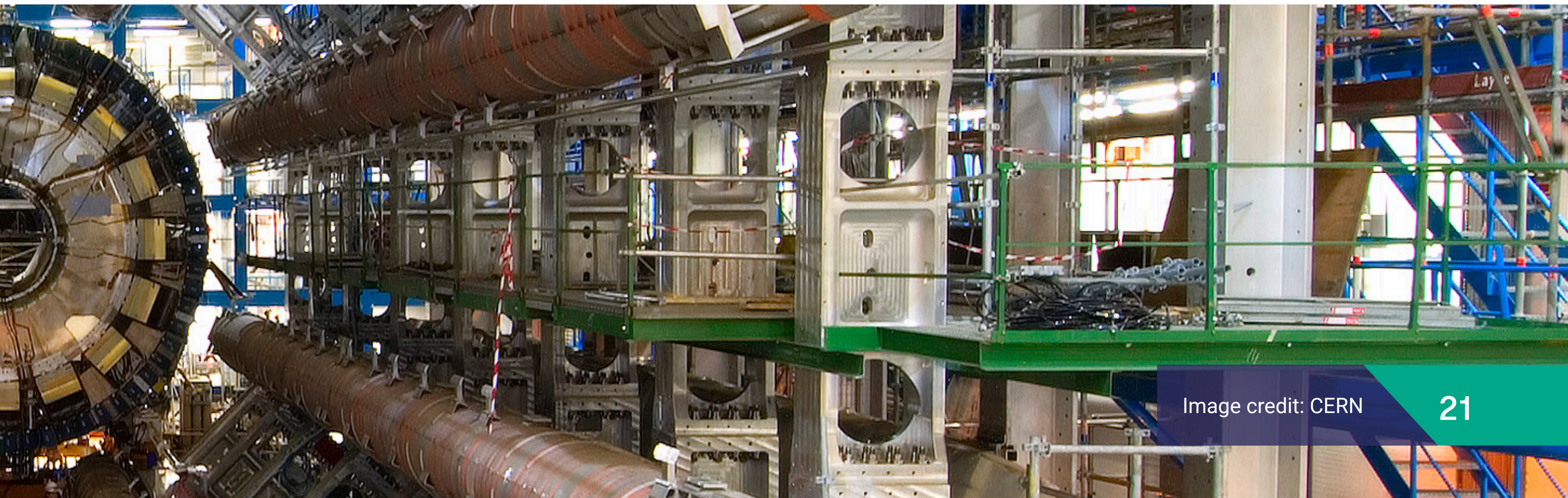


Image credit: CERN

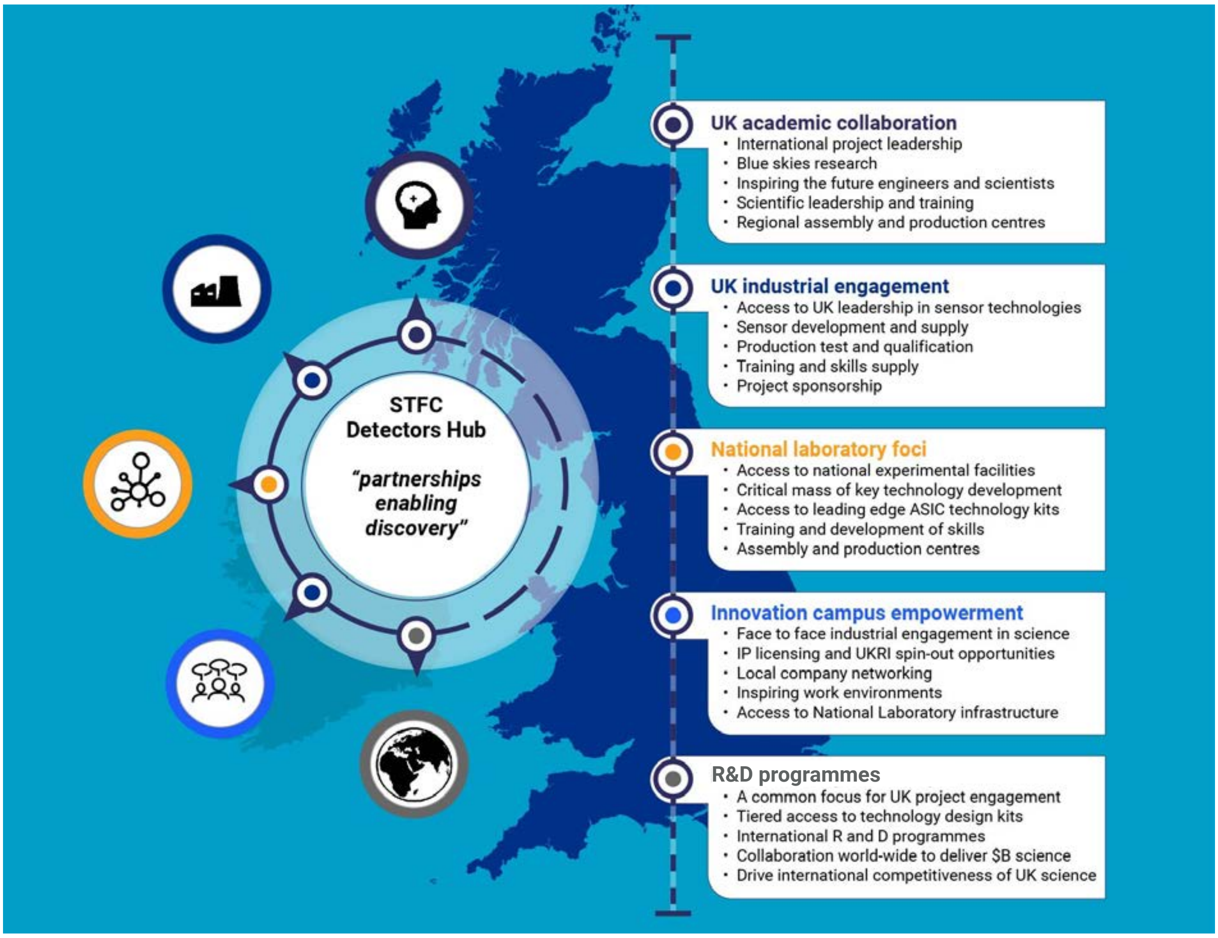


Figure 4: Current key STFC international instrumentation partnerships

The Detectors Hub will showcase our technology, provide a one-stop design and manufacture capability and be an attractor for additional investment. It will combine design and development teams with manufacturing and test facilities, dynamic laboratories and computing infrastructure. It will leverage recent investments in related capabilities (such as STFC's new clean rooms) and enable our UK teams to excel in the delivery of complete systems for the STFC programme and the broader UKRI priorities.

Enhancing industrial collaboration

Building stronger industrial partnerships will be part of the engagement approach that is central to the hub and spoke model. This will help bring benefits to many aspects of detector development such as interconnects where STFC already has established relationships that can be built upon, for example through the International Microelectronics Assembly and Packaging Society (IMAPS-UK).

STFC is well placed to both deliver and coordinate this effort. We currently facilitate commercial exploitation of the skills and the technologies developed across the national laboratories, as well as providing funding in the form of transitional grants to enable the transfer of intellectual property through licenses and spin-out companies, stimulating knowledge and technology exchange. Over 100 companies in sectors such as biomedicine, energy and security having benefitted in the last six years. In addition, we play an important role in promoting opportunities for UK companies to win commercial contracts from international science facilities and organisations, such as ESO, CERN, ESRF and ILL, ensuring a return for UK businesses from government's global investments. Over the past 10 years, UK companies have won over £220 million in contracts from our international facilities and collaborations. Together, these activities combine to create an innovation ecosystem where new and developing high-tech companies can grow and flourish, developing better products and services utilising our advanced technology and facilities spinning-out new ventures.

STFC supports the effective use of facilities wherever possible so that the best returns are achieved for the investments made in establishing them. It is anticipated that the engagement actions in the strategy will assist with this, potentially including facilities within industry for fabrication and testing.

Summary and actions

1. Build the case for instrumentation centres and a UK Detectors Hub.
2. Develop industrial links and deliver and industrial engagement strategy.

5) Advancing key detector technologies

To maximise impact and foster increased collaboration within all of STFC's UK teams engaged in instrumentation development, we recognise that we must promote and support shared common development objectives across the community. We will approach this by identifying champions for each of the challenge areas that arise from our road mapping exercises and work with them to summarise the need and relevance of each challenge. From this, a limited number of key results will be identified for each challenge that will then be promoted throughout the community and used to track and share progress. This shared view of the key parameters will then enable everyone to align development activities.

The role of Theme Champions will not just be restricted to their particular science interest but rather extend to include the whole of STFC's programme and wider UKRI integration. Their role will help build the case for investment in the discipline and will be able to present their ideas and plans to the hub and advisory structures to help shape and drive the STFC funding programme into the future. The goal being that the champion is the key leader in the community to go to for industrial and new project contacts. The role will be timebound for three years and communicate closely with the Instrumentation Hub.

The suggested Theme Champion role includes:

	Aims	Actions
Planning	Promote and champion the theme across STFC's communities.	With the Detectors Hub, help develop, monitor, and update the STFC plans for the technical challenge topic area.
Coordinating	Networking with the relevant research groups.	Help lead engagement throughout the UK community to enhance synergies, including academic and industrial groups.
Outreach	Seeking opportunities to engage with other potential research activities.	Help ensure the hub maximises the impact of the programme across wider challenge area activities and act as an ambassador for the UK capabilities.
Support	Help advise researchers for example on potential funding opportunities.	Provide the 'go-to' contact point for the topic area.
Reporting	Provide updates on progress in the topic area to the Detectors Hub.	Give feedback to the hub and its advisory structure.
Communications	Help the Detectors Hub maintain a public profile of the field in the UK.	Specifically help with maintaining web summaries of the challenge and ongoing activities.

To help communicate the work of the Theme Champions, a simple table will be created with each champion that summarises each identified challenge. In the draft example for radiation hardness on page 26, the table summarises the primary (key) motivation for investment in this challenge. It goes on to illustrate the wider application of this need across the STFC and UKRI landscape. Each of STFC's relevant facilities and international programmes are identified and the key results listed. The term 'key results' is used rather than trying to define specific target objectives as in almost all the challenge areas we know the general ranges of the required performance, and the specific targets evolve over time within each application. In the radiation hardness example, currently we have one limit for the inner LHC pixel systems and another for the outer regions of the tracking detectors at high luminosity running. Over time we know that these will all evolve as machine luminosity increases further.

The first priority areas will be based on the output from the Instrumentation Review that reported in 2019 and then iterated each year with the Advisory Boards.

Innovation example: CERN pixel detectors

The LHC large detector systems are many-layered instruments designed to detect some of the tiniest yet most energetic particles ever created on earth. They consist of systems concentrically wrapped in layers with the innermost made with hybridised pixel detectors.

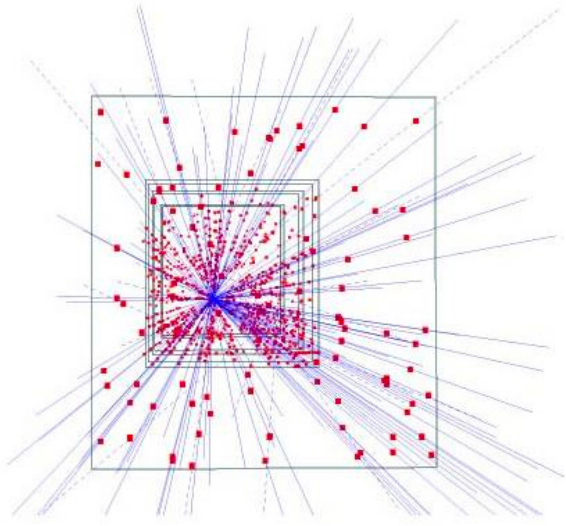
One of the first uses of such detectors is illustrated by the picture below. It shows 153 high energy particle tracks flying through layers of half a million pixels in the pioneering WA97 experiment at CERN in 1995. Every red dot in this image signifies a pixel which has sensed a charged particle.

The Medipix story

This result inspired the very first Medipix chip that was produced in the 1990s when an informal collaboration of four institutes demonstrated the potential of this new technology to provide noise free single-photon counting. Their new chip used the same front-end architecture as WA97 but incorporated a counter in every pixel to create greyscale images. The system worked perfectly and it was quickly recognised that such systems would have many useful applications outside of high-energy physics.

To maximise the impact of this work a new Medipix2 Collaboration was born in 1999, followed by a third in 2005 and most recently the Medipix4 Collaboration in 2016. Through these team efforts, three generations of Medipix chips have been developed, each with innovations and new features. Today Medipix4 is creating chips that for the first time are ready for new three dimensional assembly technologies. This will enable the breakthrough systems to be tiled on all four sides allowing very large areas to be covered seamlessly.

From the UK, Glasgow University was a founding member of Medipix and continues to hold a leading role in the latest developments. Today the UK collaboration partners also include the Diamond Light Source (Medipix3,4), the Laboratory of Molecular Biology, Cambridge (Medipix2) and the University of Oxford (Medipix4). This team, along with the industrial partners and license holders are commercialising the Medipix technology. These range from established enterprises to start-up companies generating new businesses, commercial wealth and a significant number of highly skilled jobs.



1995 - tracks in the WA97 experiment at CERN

https://medipix.web.cern.ch.

<table>
<tr><th>Challenge</th><th colspan="2">Radiation hardness</th></tr>
<tr><td>Primary motivation:</td><td colspan="2">The high luminosity environment at the HL-LHC will lead to significantly higher integrated radiation dose of both ionising and non-ionising radiation. Current designs of LHC sensors, electronics, mechanics and services will not survive.
Addressing this issue now will ensure UK investment in detectors will prepare the UK groups and raise the value of the UK's contribution to CERN.</td></tr>
<tr><td>Other STFC areas:</td><td colspan="2">Ionising radiation dose is also an issue for high frame rate X-ray imaging systems at Diamond2, CLF's high-power lasers, EBIC's transmission electron microscopes, Free Electron Lasers and space missions.
Non-ionising radiation is an issue for space missions as well as instrumentation for neutron spallation sources such as ISIS, ESS and ILL.</td></tr>
<tr><td>Wider UKRI impact:</td><td colspan="2">Medical imaging, microscopy, security applications.</td></tr>
<tr><td>STFC programmes and UK facilities</td><td>Particle Physics
Diamond Light Source
EBIC, CLF, EPAC
UK-FEL</td><td rowspan="8">Notes:
Expected LHC high luminosity accumulated dose:
Outer Tracker Region: ~ 0.1 MGy, 10^{14} n_{eq}/cm^2
Outer Pixels: ~ 1 MGy, 10^{16} n_{eq}/cm^2
Inner Pixels: ~ 10 MGy, 10^{17} n_{eq}/cm^2
Current active initiatives:</td></tr>
<tr><td>Champion/Owner</td><td></td></tr>
<tr><td colspan="2">Key results:</td></tr>
<tr><td>#1</td><td></td></tr>
<tr><td>#2</td><td></td></tr>
<tr><td>#3</td><td></td></tr>
<tr><td>#4</td><td></td></tr>
<tr><td>#5</td><td></td></tr>
</table>

Table 4: The radiation hardness development challenge draft template

Further tables will be created, one for each of the priority challenge areas. By creating a simple common format summary for each objective, this will allow us to communicate progress clearly and manage the list of challenges in a unified manner.

The following table illustrates how each of the example challenge areas in figure 3 relate to the ongoing STFC Programme. The Strategic Review that reported in 2019 identified many challenges and the relevant key themes are identified in the table.

Example challenge themes

	Connecting billion channel systems **	TB/s data transmission	Picosecond timing	Quantum sensors **	Extreme dynamic range	Non-silicon sensors and high-Z materials **	Single photon sensitivity	Multi MHz frame rates	Radio pure sensors	Radiation hardness	ASICs and wafer scale integration **	Low power design
Diamond and Diamond II	✓	✓	✓		✓	✓	✓	✓		✓	✓	
EPAC	✓	✓	✓		✓	✓	✓			✓	✓	✓
VULCAN 2020			✓		✓	✓	✓			✓		
HiLUX	✓		✓		✓		✓					
UK FEL	✓	✓	✓		✓	✓	✓	✓		✓	✓	
ISIS ENDEAVOUR						✓						
ISIS II		✓		✓		✓					✓	
IMAGING (NMR/ MRI/RUEDI)	✓		✓					✓			✓	✓
ESS		✓	✓					✓			✓	
Electron-Ion collider	✓		✓			✓		✓		✓	✓	✓
HL-LHC CERN	✓	✓	✓			✓		✓		✓	✓	✓
FCC CERN	✓	✓	✓			✓		✓		✓	✓	✓
Hyper-Kamiokande							✓		✓			
DUNE/LBNF							✓		✓			
SKA	✓	✓	✓			✓						✓
European Solar Telescope					✓		✓	✓		✓	✓	
Einstein Telescope		✓			✓							
FAIR		✓			✓	✓		✓		✓	✓	
Cherenkov Telescope Array			✓			✓	✓		✓			
EU-XFEL	✓	✓	✓		✓	✓	✓	✓		✓	✓	
Space				✓	✓	✓	✓			✓	✓	
NQCC	✓			✓								
RFI	✓	✓	✓		✓	✓	✓	✓				
AION10, AION100 ...			✓			✓						

Table 5: An illustration of how example themes relate to the ongoing STFC Programme with priorities from the 2019 External Review highlighted**

Summary and actions

1. Create first set of challenge themes and identify theme leads.
2. Invite theme champions to prepare summary tables and agree key results within the community.
3. Combine into a combined challenge overview with the current STFC programme and facility roadmap summaries.
4. Review challenges against funding mechanisms and consider preparing a case for new funding calls or applications.

Periodically, perhaps annually, with Science Board and TAAB and CFI Board, review the current set of challenges, update retiring challenges or adding any new ones.

Image credit: CERN

6) Resourcing the development programme

Whilst much of the detector development supported by STFC is carried out within specific projects, it is recognised that there is a requirement to also invest to develop new capability to meet the needs of the emerging programme for tomorrow's science.

Such investment is essential because the limits of instrumentation performance often defines our experimental boundaries and shapes the science STFC can deliver. We also recognise that leadership in this area is often key to the UK community securing senior roles in our international projects and thereby maximising the impact of our UK contributions.

Current STFC funding mechanisms

Funding for complete systems are prioritised and drawn from the relevant science programme area budgets (Particle Physics, Particle Astrophysics, Astronomy, Nuclear Physics). These, often major investments, are subject to in-depth scrutiny and review by the relevant peer review panels and by STFC's Science Board and Technology and Accelerators Advisory Board. In some infrastructure specific cases, instrumentation costs can be included in the capital cost of facility build programmes.

In addition, our academic partners may receive consolidated grants which are awarded where institutions roles in long duration research programmes are grouped together to streamline the award processes and give the necessary funding stability to support recruitment and training.

Alongside direct project funding in national laboratories, a centralised fund called the Centre for Instrumentation provides some limited resourcing for instrumentation development. The Project Research and Development (PRD) scheme has been a mechanism to provide grant support to university research groups to address urgent technical problems including those related to detectors and instrumentation. STFC's Programmes Directorate reviewed the success of the PRD scheme in 2020 to inform the future direction of this scheme.

Within our Innovations Directorate, for exploring commercial exploitation opportunities of STFC owned intellectual property, there are funds for proof of concept or follow-on development of existing instrumentation to help bridge the gap between simple demonstrators of new technologies and building larger scale prototype systems. These investments are needed to de-risk the commitment necessary to enable the deployment of larger instrumentation systems in our facilities and science programme.

Case study: Space technology for sepsis

A technology developed to measure gases on Mars is part of a pilot clinical study testing its effectiveness as a medical diagnostic tool for sepsis.

Sepsis is one of the most significant causes of premature death in the world. In the UK there are 120,000 critical care unit admissions and 44,000 deaths per annum attributed to sepsis. 14,000 of these deaths are thought to be preventable through improved diagnosis and reduced treatment delays.

The Laser Spectroscopy Group at RAL Space has developed an instrument, the Laser Isotope Ratiometer (LIR), that builds on RAL Space's expertise in innovative space technologies to provide a more efficient diagnosis tool for sepsis in hospital patients using a simple breath test.

The LIR was developed to study gases in the Martian atmosphere. The compact, lightweight and robust design that makes it ideal for use on a spacecraft also means that it could be adapted into a portable medical device. Because it can be used at the bedside, it is easier to use and administer compared to existing laboratory-scale equipment currently used to diagnose sepsis.

The device will be able to provide results instantly, helping doctors start treatment earlier which could reduce the number of sepsis linked deaths. The breath test is non-invasive, making it safer for frequent use by patients than blood tests which require an extended waiting period due to laboratory analysis.

Other funding sources

The UK government's Industrial Strategy[6] has led to the establishment of several collective fund mechanisms, including the Industrial Strategy Challenge Fund, the Strategic Priorities Fund and Strength in Places. This is an evolving set. In addition, there is the recently launched Research Infrastructures Fund that enables substantial capital investment which could include instrumenting major facilities and centralised test and measurement facilities.

Other common funding sources include ESA, Horizon 2020, and other government funding agencies. In addition to the above funding routes, commercial contracts may also be secured in some disciplines (e.g. space instrumentation), where a commercial organisation has been appointed as the lead for a specific programme.

Summary and actions

1. Review and identify potential funding sources for the UK community.
2. Consider opportunities for future PRD grant funding.
3. Seek to grow and enhance current funding mechanisms.
4. Ensure that relevant consolidated grants are appropriately aligned to the challenge needs.

6. https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges

7) Recognising the importance of detectors and instrumentation skills

Critical to the development of tomorrow's system solutions is the development and support of a career path that enables doctoral students through to leadership positions in academia and the national laboratories.

People working in the science areas, national and international facilities and national laboratories that STFC funds and supports can be working at the forefront of detector and instrumentation technologies. These detector specialists are often working in large, multidisciplinary teams of scientists, technologists and engineers. The performance of the detection function is critical first step that defines the capability of a multi-million-pound measurement system, yet the contribution of the detector specialist can go unrecognised within the usual metrics.

This can often be seen in the multi-author science exploitation publications that arise from major instrumentation developments. Although the detector elements may be strongly acknowledged, the contributing detector specialists are generally not the lead authors and therefore can be missed in measures such as citation analysis. STFC welcomes the use of a wide range of measures that can be used to raise the profile of key specialists. Examples can include highlighting the role of detector specialists in case studies and organisation's staff profiles, and in professional bodies award schemes.

Case study: Institute of Physics Technician Award

With the aim of raising the professional status of technicians, the IOP Technician Award highlights the diverse role of technicians in education, research and industry The Award enables the community to recognise and celebrate the skills and experience of technicians and their contribution to physics.

The IOP Technician Award in 2020 included two winners who were recognised for their role in detector and instrumentation projects.

IOP Institute of Physics

Anthony Clarkson – University of Glasgow

For his pioneering contribution towards the industrial deployment of cosmic-ray muography technology and his outstanding, ongoing contributions to high-energy, fundamental nuclear physics experiments across the globe.

Warda Heetun – National Physical Laboratory

For her outstanding contributions to measurement science and establishing the world's first standard for quantitative nuclear medicine imaging.

More information on the IOP Technician Award can be found at: www.iop.org/about/awards/technical-skills-awards/technician-award

Creating career development opportunities

Solving challenging detection problems needs skill sets that can take many years to acquire. Attracting and retaining people whilst they build and practice these skills needs a career path that provides a combination of opportunities and rewards.

STFC has a unique role in the UK as both a direct employer and as a funder of other organisations who recruit and employ detector and instrumentation specialists. We therefore have an interest in and a responsibility for ensuring that there are mechanisms in place to provide attractive and stimulating career paths for these roles that are critical to achieving our research and innovation goals.

We are already taking steps across a range of job and career types as described below. We are also developing plans for a Skills Academy to help tackle the technical skills gap.

Apprentices

STFC has a strong and successful apprenticeship programme in the national laboratories and national facilities. We will ensure that skills relevant to detectors and instrumentation continue to feature strongly in the training opportunities provided. For example, STFC is a partner with the UK Atomic Energy Authority, in the Oxfordshire Advanced Skills (OAS) project.

Technicians

Technicians play a key part in maintaining STFC's leading edge in research excellence and driving solutions to technological challenges. In 2019, STFC joined with 84 other universities and research institutions to become a signatory of the Technician Commitment initiative, supported by the Science Council and the Gatsby Charitable Foundation's Technicians Make It Happen campaign. The commitment has four pillars: to ensure visibility, recognition, career development and sustainability for technicians across all disciplines working in higher education and research. The Technician Commitment has recently been embraced by UKRI and an action plan has been published[7].

Case study: Oxfordshire Advanced Skills

Located at Culham Science Centre near Abingdon, OAS is a partnership between STFC and the UK Atomic Energy Authority.

The two organisations have a history of apprentice training in science and engineering stretching back more than 70 years. Our new centre, opened in September 2019, is managed by our apprentice training partner MTC Apprenticeships. MTC's advanced engineering apprenticeship helps learners develop the skills needed for delivering the technologies of the future in the high value manufacturing sector.

Image credit: OAS

7. https://www.ukri.org/wp-content/uploads/2021/02/UKRI-040221-TechnicianCommitmentActionPlan.pdf

Doctoral training

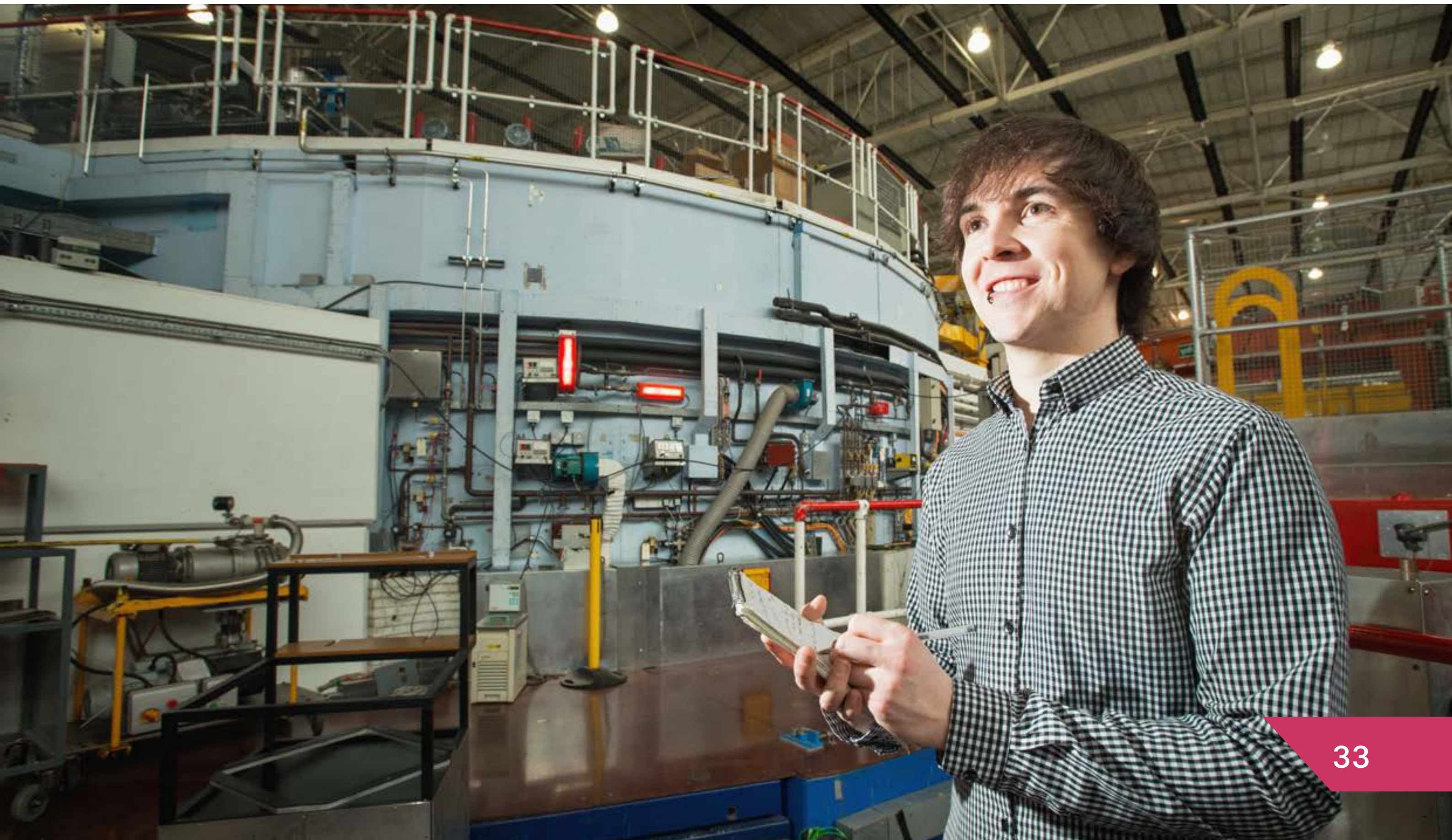
As a constituent part of UK Research and Innovation, STFC uses mechanisms such as Doctoral Training Partnerships (DTPs) and Centres for Doctoral Training (CDTs) to provide doctoral students with training targeted at the relevant research specialisms.

Fellowships

STFC funds several fellowship schemes to support talented early career researchers. Fellowships can help overcome the problem of gaps between grant funded projects that can hinder researchers from maintaining their development of specialist skills. For example, the Ernest Rutherford Fellowships enable early career researchers with clear leadership potential to establish a strong, independent research programme.

Summary and actions

1. We will ensure that instrumentation skills requirements for graduates and apprentices are included in future initiatives such as the proposed STFC/UKRI Skills Academy.
2. We will work with our partners to continue to build technical training opportunities for young people across the science and innovation areas that we support.
3. We will develop and implement actions within the framework of the Technician Commitment as part of the UKRI plan.
4. In future rounds of DTP and CDT funding, we will consider the merits and feasibility of supporting initiatives specifically aligned to the needs of advanced detector and instrumentation technologies.
5. In future fellowship funding opportunities, we will consider the options for targeting detectors and instrumentation specialists with the specific aim of improving the visibility and influence of detectors specialists within institutions and disciplinary communities. The need for a small capital budget to be associated with a fellowship grant can also be considered.



8) Summary of opportunities and actions

Strategy actions

The table below summarises all the opportunities, measures and actions that have been proposed across the elements of the strategy and indicates for each one the key players who will be involved in taking them forward. Throughout, the proposed Detector Hub will be engaged and represented by staff from the national laboratories in the first instance. The Advisory Boards include the Technology and Accelerators Advisory Board (TAAB), Science Board (SB) and the Centre for Instrumentation Board (CfI).

Action	Players
3.1 Engage with roadmap exercise to identify lead STFC projects and programmes.	STFC Programmes, Instrumentation Hub
3.2 Identify priority instrumentation challenge priorities and share with Advisory Boards.	Instrumentation Hub, Advisory Boards
3.3 Annually present SB, TAAB and CfI boards the current set of challenges, update retiring challenges or adding any new ones.	Instrumentation Hub, Advisory Boards
4.1 Build the case for instrumentation centres and a UK Detector Hub.	STFC Programmes and national laboratories
4.2 Develop industrial links and deliver and industrial engagement strategy.	Instrumentation Hub and STFC Business and Innovations
5.1 Create first set of challenge themes and identify theme 'owners'.	Instrumentation Hub
5.2 Invite Theme Champions to prepare summary tables and agree key results within the community.	Theme Champions
5.3 Combine into a combined challenge overview with the current STFC programme and facility roadmap summaries.	Instrumentation Hub
5.4 Review challenges against funding mechanisms and consider preparing a case for new funding calls or applications.	Instrumentation Hub, STFC Programmes and Executive
6.1 Review and identify potential funding sources for the UK community.	Instrumentation Hub, STFC Programmes
6.2 Consider and seek to implement the recommendations of the PRD Review.	STFC Programmes
6.3 Seek to grow and enhance current funding mechanisms.	Theme Champions, Instrumentation Hub and STFC Executive

6.4 Ensure that relevant consolidated grants are appropriately aligned to the challenge needs.	STFC Programmes and Instrumentation Hub
7.1 Ensure that instrumentation skills requirements for graduates and apprentices are included in future initiatives such as the proposed STFC/UKRI Skills Academy.	STFC Programmes and Instrumentation Hub
7.2 STFC will work with our partners to continue to build technical training opportunities for young people across the science and innovation areas that we support.	STFC Programmes and Instrumentation Hub
7.3 We will develop and implement action plans within the framework of the Technician Commitment.	STFC Programmes and Instrumentation Hub
7.4 In any future rounds of CDT funding, we will consider the merits and feasibility of supporting CDTs specifically aligned to the needs of advanced detector and instrumentation technologies.	STFC Programmes and Instrumentation Hub
7.5 In future fellowship funding opportunities, consider the options for targeting detectors and instrumentation specialists with the specific aim of improving the visibility and influence of detectors specialists within institutions and disciplinary communities.	STFC Programmes and Instrumentation Hub

Strategy implementation timeline

The table below shows an approximate timeline for building the portfolio of theme champions and establishing the central hub. In addition, external reviews of the activity are expected every five years.

We assume there will be of the order of 12 Theme Champions with four appointed in the first year, then more added each year as the discipline evolves. Over time, themes will be retired as the portfolio is refreshed.

Activity	Yr1	Yr2	Yr5	Yr10	Yr15	Yr20
Establish hub structure	✓					
Establish priority themes	✓					
Appoint theme Champions	4	8	12	12	12	12
Review with Advisory Boards	✓	✓	✓	✓	✓	✓
Finalise case for hub infrastructure	✓					
Establish site and finalise case		✓				
Establish physical hub			✓			
Externally review and revise			✓	✓	✓	✓

Annexe 1: Risk management

Description	Likelihood	Impact	Mitigation strategy
Failing to realise potential of forming UKRI Prior to the formation of UKRI, STFC was already working with other research councils delivering instrumentation and other benefits in an ad-hoc one off basis. This situation has continued within UKRI but to make a difference and deliver the full potential of merging the councils the investment in a national focus committed to delivering the benefits of UKRI is required.	High	Critical	Targeted investment and coordination with other research councils. Without such investment this key impact pathway will just continue to evolve sporadically and in a disjointed way as other initiatives start and stop. This will lead to temporary work that prevents UKRI growing established teams. The absence of a one-stop solution on this field will also continue to prevent industry from seeing a strong core to the instrumentation UKRI develops and prevent many innovations from being delivered. The recent investment in STFC's cleanrooms will also remain with limited access for externals.
Loss of international presence The UK groups need to prepare for the demands of tomorrow's facility projects. With horizon scanning activities in each field, key technology challenges need to be identified and investments made in preparatory work to ensure that leading science is delivered and the UK plays a leading role.	High	Critical	The delivery of tomorrow's detector systems in every STFC field is becoming increasingly complicated. The advances of modern accelerators, if not matched with advancing instrumentation we will not deliver their full potential and we will remain in a regime where beams are 'stopped down' to limit flux to the capability of their ageing instrumentation. Readout speed and high dynamic range are becoming common themes in many new photon science beamlines and unless the UK really invests in expertise in these fields we will forever be 'following' other countries who will lead in instrumentation and we will become relegated to 'followers'. This in turn will limit the scientific success of the UK and limit our potential to occupy leadership positions in international projects in the future.
Loss of areas of excellence The requirement for next generation instrumentation systems is clear in every field that uses sensing technology and imaging systems. Currently we possess leadership in fields such as High-Z sensor materials, high speed data acquisition and silicon sensor technology. With our work published and many institutes investing abroad our leadership in these fields will not be sustained.	Medium	Critical	Establish and support the future of this field for the UK. Current highlights of the work ongoing in STFC include world-leading developments in cryo-electron microscopy sensor developments, image sensors for particle tracking and spectroscopy detectors for photon science along with world-leading gamma detection for nuclear physics. Without investment these will not happen.
Isolated pockets of skills in individual institutions To enable long term success investment in sufficient critical mass is necessary in key areas.	High	Critical	Invest in training and fellowships to secure posts in our partner institutions, that we support from the national laboratories, with placements and central test facilities.

Annexe 2: A summary of UK funding sources relevant to STFC detectors and instrumentation

Funding Scheme	Comments
UKRI* research grants • Open or regular grant funding calls that can include detector and instrumentation elements	STFC provides research grant funding to UK Higher Education Institutions and other eligible research organisations for research in the fields of astronomy, particle physics and nuclear physics, and for associated technology development, research infrastructure and knowledge exchange. EPSRC programme grants provide flexible funding to world-leading UK research groups addressing significant research challenges. EPSRC funds research into chemistry, engineering, information and communications technologies, materials, mathematical sciences and physics. EPSRC funds strategic equipment grants for cutting-edge equipment that improves the ability to carry out research in any area funded by EPSRC.
Other UKRI* funding routes relevant to detectors and instrumentation • Regular or occasional calls for specific funding schemes	Knowledge Transfer Partnerships help businesses to partner with an academic organisation, research organisation or a Catapult, to employ a graduate with the skills and knowledge that can help the business to innovate and grow. Commercialising quantum technologies: UK registered businesses can apply for a share of up to £46.8 million for collaborative research and development or technology projects in quantum.
Strategic Priorities Fund • Occasional calls for proposals • Strategic Priorities Fund opportunities may also be offered by non-UKRI partners or by the research centres and institutes set up with the funding	The Strategic Priorities Fund is an £830 million investment in multidisciplinary and interdisciplinary research across 34 themes. It is funded through the government's National Productivity Investment Fund and managed by UKRI
Industrial Strategy Challenge Fund • Occasional calls for proposals	The Industrial Strategy Challenge Fund (ISCF) addresses the big societal challenges being faced by UK businesses today. It's made up of 23 challenges, covering the four themes of the government's industrial strategy.
Strength in Places Fund • Occasional calls for proposals	The Strength in Places Fund invests in research and innovation projects that aim to drive economic growth in specific areas of the UK. Strength in Places projects build on existing research excellence and supply chains and must demonstrate that they will drive significant economic impact.

* Up to date information on all UKRI funding opportunities can be found at: https://www.ukri.org/opportunity/

UKRI Infrastructure Fund • The Infrastructure Fund is not an open funding opportunity for proposals.	The 2020 Government Research and Development Roadmap highlighted how UKRI will provide a long-term, flexible pipeline of research and innovation infrastructure investment priorities for the next 10 to 20 years. The Infrastructure Fund will support step-changes in infrastructure capability and/or capacity, including: new infrastructure, major upgrades, repurposing, transformative developments and decommissioning. UKRI councils and teams identify potential projects which are assessed by the infrastructure advisory committee, set up to make recommendations to UKRI's decision-making boards on the pipeline and prioritisation of infrastructure investments through the fund.
STFC Innovations Partnership scheme • Occasional calls for proposals	Funding to work with industry or other non-academic partners to turn STFC-funded research into commercial products and services. Support of up to £360,000 is available for 80% of the full economic costs of projects with a total value of up to £450,000 and lasting up to 36 months.
STFC follow-on funding • Occasional calls for proposals	Funding for proof-of-concept work that follows up STFC-funded research and shows how it could be turned into a potential commercial application. Support is available for 80% of the full economic costs of projects with a total value of £110,000 and lasting up to 12 months.
STFC large and/or complex projects funding • Open grant funding	Funding for major new projects in fields supported by STFC. This includes participation in new experiments or missions, the development of new instruments, upgrades to existing detectors and ongoing operation of existing facilities.
STFC Centre for Instrumentation funding • Annual call for STFC national laboratories.	Academic partners can be included in proposals.

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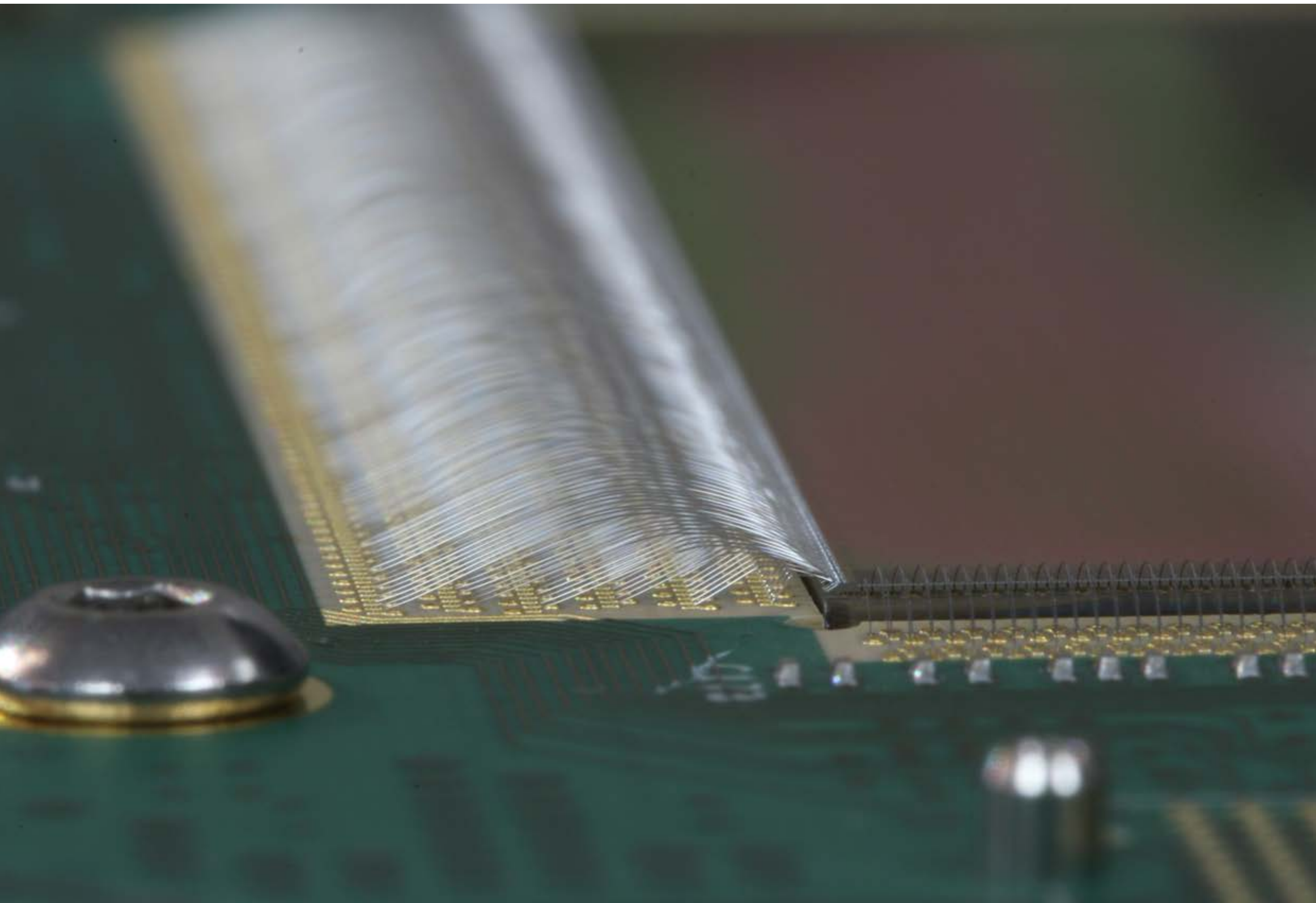

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