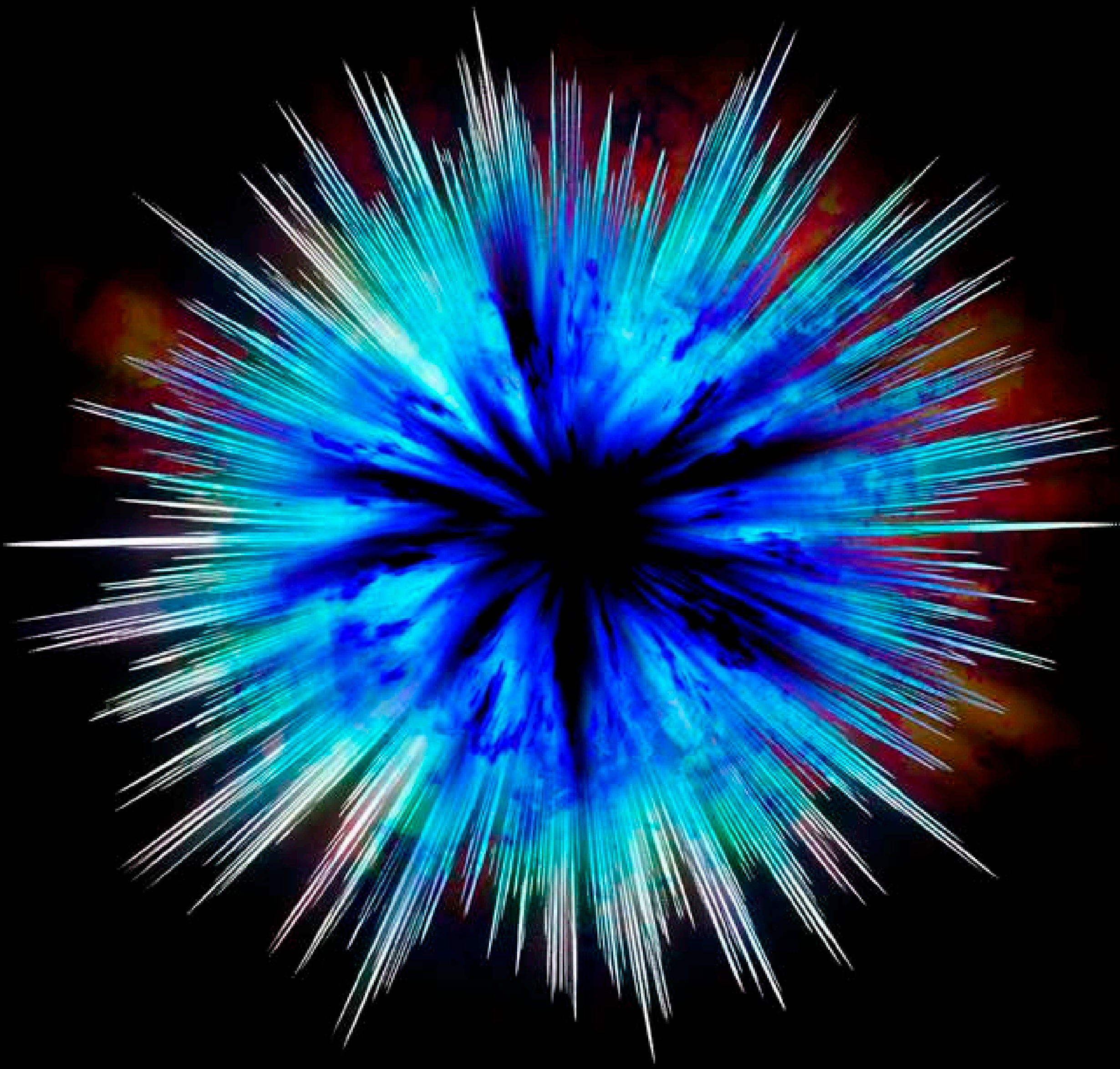
2017 Accelerator Strategic Review Report



Science & Technology Facilities Council

Contents

Executive Summary

Accelerators are a key underpinning capability enabling large parts of the STFC core science programme. They also serve a range of other physical and life science programmes that are funded by other Research Councils, Wellcome Trust, and industry. Accelerators have played a central role in many of the major discoveries made in particle and nuclear physics over the past century. The development of accelerators as tools for the diffraction, scattering and spectroscopy of beams of neutrons and photons has enabled significant discoveries to be made in the physical and biological sciences. Additionally, the application of accelerator technology to industry, medicine, security and defence has led to benefits for the economy and society more widely.

The UK's capability in accelerator research and development is recognised as being world-class. The UK's contributions to many of the breakthroughs in accelerator research and development, and the range of influential international leadership positions held by UK researchers provides evidence of the excellence of the work currently being conducted. A range of national and international science strategy documents indicate that accelerators will continue to play a key role in future discoveries and applications. Maintaining the UK's capability in accelerator research and development is therefore of strategic importance for the UK, in terms of the capability it provides to the science base and industry.

UK Research and Innovation (UKRI) are currently developing the UK Infrastructure Road Map which will direct the development of research infrastructure, including accelerator facilities. In anticipation of this, the recommended strategy for STFC's Accelerator Programme is the strengthening of basic underlying research and development capability across the programme. This will enable the programme to respond flexibly to opportunities if and when they arise.

Activities and technologies that support basic underlying accelerator research and development capability across the programme have been identified. Expeditious and sustained support for these activities and technologies is recommended over the next 5-10 years to enhance the underlying skills and capabilities of the programme, and enable a flexible response to opportunities arising over the next 10–20 years.

Introduction

The STFC accelerator science programme comprises research towards light sources, neutron sources, and high energy particle and nuclear physics machines. STFC also provides facilities to support access to electron beam test facilities. Together with Diamond Light Source (DLS) Ltd., STFC manages, develops and maintains the UK's large particle accelerator facilities (ISIS Neutron and Muon Source and DLS) and the Central Laser Facility (CLF). STFC also funds UK access to international frontier research facilities including CERN.

In a constrained funding environment, a considered approach is required to ensure that the UK maintains capabilities and its international position in accelerator science. An accelerator strategy will also allow the UK to position itself to take timely decisions and influence investment both in the UK and internationally.

2018 will see the formation of UK Research and Innovation (UKRI), a single body that will incorporate the functions of the 7 Research Councils (including STFC), Innovate UK and the research functions of the Higher Education Funding Council for England (HEFCE). Each Research Council will retain current responsibilities for disciplines, so STFC's science and facilities remit will remain unchanged. The formation of UKRI is intended to strengthen strategic thinking on overarching and cross-cutting priorities and enable a more agile and responsive research and innovation funding system.

It is therefore timely that STFC considers an overarching strategy for its cross-cutting Accelerator Programme. The expectation that UKRI will deliver a greater focus on industrial applications, and the introduction of the Industrial Strategy Challenge Fund, indicates a growing pull from government for industrial applications. STFC's functions naturally lend itself to the development of industrial applications; however, a strategic approach is required to take full advantage of this funding opportunity.

In recognition of the fact that a considered approach is required to ensure the UK maintains its world-class capabilities in accelerator research and development, STFC Executive Board commissioned a panel of international accelerator physicists and representatives from the user communities to consider the highest priorities for accelerator science in each of the following themes as well as overall priorities:

- Neutron Sources
- Light Sources
- Particle Physics and Nuclear Physics Machines
- Novel Accelerators
- Industrial, Medical, Defence and Security Applications

As part of the strategic review process, members of the accelerator community coordinated the development of thematic roadmaps under the themes outlined above. The roadmaps propose activities within thematic areas and provide justification for proposed research portfolios. The roadmaps include timelines, milestones and indicative costs for accelerator science and technology activities. The thematic roadmaps contain outline plans for constructing facilities, which can be developed if and when funding is granted. The Review Panel considered the thematic roadmaps when synthesising recommendations for the STFC Accelerator Programme.

The 2017 Accelerator Strategic Review identifies issues, activities and technology areas where investment and resources should be targeted, taking into consideration strategic direction from government and the current funding landscape. Enabling technologies and synergies, and also the broader context of government strategies for technology applications to health, industry and international development were taken into account.

Background and Context

The 2013 STFC Programmatic Review recommended that a focused review of the STFC accelerator science programme be conducted, which could assist in the development of a high-level strategic plan to guide future investment.

The 2014 Accelerator Strategic Review Report which followed provided a narrative overview of the breadth and scope of the accelerator programme. The report focused on accelerator research and development support for the wider STFC programme, including light sources, neutron sources and high energy particle and nuclear physics machines, as well as the development of novel accelerator techniques. A panel of accelerator experts and facility users synthesised input from standardised pro-forma questionnaires and resource tables from a wide variety of stakeholders.

The panel assessed the accelerator programme, considered its optimum balance and the development required to meet the needs of the STFC science community and users of STFC's large facilities. The balance of the programme, its strengths and weaknesses, and how it might best respond to opportunities and threats were considered by the panel.

The report made a number of observations and provided recommendations to STFC. A key observation was that the breadth of the accelerator programme allows different research groups, in particular the CI and JAI, ASTeC and the UK large facilities, to develop differing portfolios of skills and technical strengths. The report recognised that this diversity allows the UK to make a broader range of important contributions to many areas of accelerator science and technology, but that it also means that the skills required to design and build future accelerator facilities are distributed across a variety of groups. The report therefore recommended that the UK's centres of excellence should be encouraged to collaborate closely to deliver the skills and technologies required by future accelerator projects in a coherent way. An over-arching strategy for STFC's accelerator research, development and facilities would facilitate closer collaboration and coherence as recommended. The purpose of the 2017 Accelerator Strategic Review is to develop such a strategy.

The 2017 Accelerator Strategic Review is not a review of STFC's programmes or institutions, although the results from recent reviews, where available, will inform the strategy. Its purpose is not to identify activities or technologies that should no longer be engaged with. Rather, the purpose of this strategic review is to identify activities and technologies which will enhance the STFC Accelerator Programme over the next 15-20 years. The 2014 Review concluded that a prioritised list of major investment opportunities for future facilities and projects would enable a strategically planned accelerator programme. The Review Panel for the 2017 Accelerator Strategic Review are tasked with generating options for possible strategies moving forward.

Recommendations for STFC's Accelerator Programme

In developing recommendations for STFC's Accelerator Programme, it is essential that the current landscape and future horizon for the programme be considered.

This includes: upcoming changes to Research Council structure and organisation; the funding environment; current accelerator research, development and delivery activities. In discussions, the panel was mindful of the available strategies for each of the thematic areas.

A critical analysis of the current programme was conducted, and the accelerator community's aspirations were taken into consideration. Issues, activities and technologies relevant to supporting basic research and development capability within thematic areas were identified. These form the basis of the thematic recommendations. Synergies across themes were also identified. These are the issues, activities and technologies which support basic research and development across a number of thematic areas and form the basis of the overarching recommendations. There is therefore some overlap between the thematic recommendations and the overarching recommendations.

Given the lack of strategic direction in regards to facility development and the constrained funding environment, it was concluded that the overarching recommendations should be prioritised above the thematic recommendations.

In this way, funding will be directed towards issues, activities and technologies which support basic skills and capabilities for the overall Accelerator Programme.

The current programme was found to be broad and vibrant. In particular, the Novel Acceleration theme was identified as important for supporting basic underlying research and development for facilities and applications in the future. The Novel Acceleration theme is important for developing concepts for machines of the future, and therefore is a priority for the future of the accelerator programme.
Novel acceleration research in the UK is centred on CLF and the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA). Work conducted within the Novel Accelerators thematic area was found to cover most important aspects of novel accelerator techniques.

Laser wakefield acceleration (LWFA), a technique for accelerating charged particles, is an area of strength in the UK. UK researchers have contributed to many breakthroughs in LWFA including plasma targetry and laser guiding, injection and high brightness beam production, and high efficiency laser drivers.

Particle beam driven plasma wakefield (PWFA), related to LWFA, has not been experimentally performed within the UK.

The Compact Linear Accelerator for Research and Applications (CLARA) could potentially change this, by allowing the investigation of innovative approaches to PWFA. PWFAs are known to be able to multiply the energy, and improve the emittance or brightness available in existing electron accelerators by several orders of magnitude.

The use of dielectric structures as hosts for particle acceleration is a more recent advance in the UK Novel Acceleration field. These structures can be driven either by particle beams or electromagnetically. Recent results with such low-energy laser-driven structures have demonstrated impressive acceleration gradients; with low energy, the laser drivers would allow novel accelerators operating at multi-kHz rates, enabling the use of technologies such as fibre or thin disk lasers. The UK involvement in dielectric accelerators is clustered around the use of CLARA.

CLARA is being developed as a Free Electron Laser (FEL) test-bed, designed to demonstrate novel concepts and extend the capabilities of FELs. CLARA therefore enables the UK to maintain capability in the latest generation of light sources. There is international interest in in exploiting CLARA from SwissFEL, SLAC, CERN FERMI@Elettra and INFN Frascati. There is a possibility that CLARA could be used as a European FEL test facility; the League of European Accelerator-based Photon Sources (LEAPS) is considering the institution of a European FEL test facility. This formalisation of international user access would provide additional resources for enhancing and upgrading the facility to maintain a positon at the cutting edge.

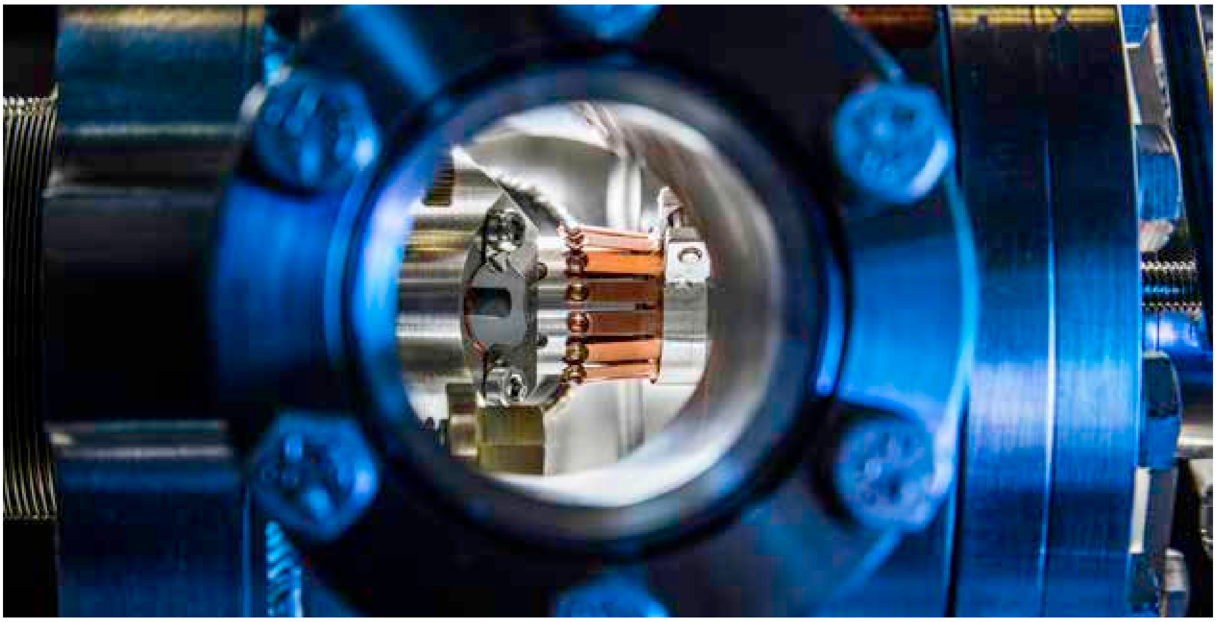
Daresbury Laboratory has a history of industry interaction. Using the CLARA concept, the laboratory has recently designed a FEL facility for a company specialising in X-ray semiconductor lithography. Constructing a facility with the rigorous stability, reliability and tolerances required for an industrial context demonstrates the potential of CLARA to be used as a test-bed facility for industrial applications.

Overarching Recommendations for the STFC Accelerator Programme

Synergistic issues, activities and technologies, those which support basic research and development across a number of thematic areas, are detailed in Recommendations 1-7. Recommendations 1-7 are not in priority order.

There is necessarily some overlap between these recommendations and the thematic specific recommendations 8 -15 below. Given the lack of strategic direction in regards to facility development and the constrained funding environment, the overarching recommendations should be prioritised above the thematic recommendations to support basic research and development across the programme more broadly.

The UK Government is increasingly concerned with developing applications from research and development funding. This is evident from newly introduced funding schemes such as the Newton Fund, Global Challenges Research Fund (GCRF) and the Industrial Strategy Challenge Fund (ISCF). The accelerator applications theme has the potential to play a significant role in realising the full scientific, societal and economic benefits of STFC-funded programmes. STFC currently funds novel acceleration research to a limited extent, via Accelerator Institute core grants and the AWAKE project.



Research into novel acceleration techniques has the potential to lead to the development of future industrial and commercial applications. For example, LWFA sources of spatially coherent hard x-rays have been used to demonstrate phase contrast micro-tomography, applicable to medical imaging.

The creation of high energy positrons through electron beam conversion is an area of interest for future laser-based particle colliders. Experimental campaigns are being conducted to generate pulsed neutron sources through conversion of ions in a catcher target; such a source of fast neutrons could be applied to industrial imaging challenges. Recent results with low-energy laser-driven structures have demonstrated impressive acceleration gradients; with low energy, the laser drivers would allow novel accelerators operating at multi-kHz rates, enabling the use of different technologies such as fibre or thin disk lasers. The Newton Fund, GCRF and ISCF offer opportunities for investment in accelerator applications.

Recommendation 1 – Expeditious investment in novel acceleration over a 5-10 year timescale is recommended to support accelerator applications development in collaboration with industry.

The role of industry is critical to realising the full scientific, societal and economic benefits of accelerator development. UK industry recognises the impact accelerators can make to industrial processes but are often unsure about whom to engage with to access them. A test-bed for industrial applications could facilitate academic/industrial collaboration for developing industrial applications.

Technologies and skills relevant to light sources research and development using CLARA, include radio frequency (RF) systems, laser systems, and high performance electronics for diagnostics and feedback systems have cross-thematic applications for accelerator research and development, and for industrial applications. Continued investment in CLARA, both to complete its development and to exploit it for cross-thematic research and development, is recommended.

This will serve to maintain and develop the skills base irrespective of whether funding for a UK FEL is granted.

Recommendation 2 – Investment to complete development of CLARA and support its exploitation is recommended to enable:

- Research and development for FELs as a European test-bed facility;
- Novel acceleration development;
- A test-bed for industrial applications.

The expertise that Daresbury Laboratory has developed with Super Conducting Radio Frequency (SCRF) technology has enabled the laboratory to provide SCRF systems for the new European Spallation Source (ESS) under construction in Lund, Sweden. This activity forms part of the UK's in-kind contributions to the ESS accelerators. The Daresbury Laboratory's SCRF expertise contributes to the development of the UK accelerator skills base. This capability is applicable to the Neutron Sources, the Particle Physics machines High Energy accelerator research and development programme and potentially the Light Sources theme. Continued investment in SCRF to develop UK fabrication capability for multi-cell SCRF structures is recommended to support cross-thematic research and accelerator development.

Recommendation 3 – Investment in Super Conducting Radio Frequency (SCRF) is recommended to support:

- The Particle Physics and Nuclear Physics Machines theme;
- Neutron facilities research and development;
- Research and development for FELs for photon science.

High power proton beams and targets were also identified as a strong UK capability with cross-thematic relevance. UK activity in the area includes the Fixed Field Alternating Gradient (FFAG), the Front End Test Stand (FETS) and the Intense Beam EXperiment (IBEX). FFAG is concerned with high power proton beams and has applications for neutron spallation sources. FETS is a generic proton accelerator research and development programme and IBEX studies the intense beam dynamics of non-neutral plasma. Continued investment for these activities is essential for supporting basic research and development capabilities across thematic areas.

Recommendation 4 - Investment in high power proton beams and targets is recommended to support:

- The Particle Physics and Nuclear Physics Machines theme;
- Neutron facilities research and development.

Recruitment, retention and professional development of key scientific and technical staff is fundamental to maintaining capability for the STFC Accelerator Programme. Steps should be taken to ensure this is achieved. Healthy and vibrant research, development and delivery programmes play a role in the retention and recruitment of talented staff. A number of vacancies for staff in critical roles have existed for some time at UK national laboratories. Exit surveys of staff members in these roles indicate that competitive salaries are also important for maintaining the skills base.

Recommendation 5 – Maintain the skills base through effective recruitment, retention and professional development of scientific and technical staff at all levels, and across all relevant disciplines.

Collaborations with international accelerator projects, such as the UK contributions to ESS, often prove beneficial to UK user communities in terms of influence and access arrangements, as well as contributing to the development of the UK accelerator skills base. There is international interest in exploiting CLARA as a FEL test-bed from SwissFEL, SLAC, CERN, FERMI@Elettra and INFN Frascati. The advantages that would result from a formalisation of international user access include additional resource streams and development of the UK skills base.

Recommendation 6 - Collaboration with international partners on facility development and accelerator research activities is recommended, where appropriate.

UK Accelerator research and development is performed by national laboratories, the Daresbury and Rutherford laboratories, Accelerator Science and Technology Centre (ASTeC), and twoaccelerator institutes, the Cockroft (CI) and John Adams institutes (JAI). Daresbury and Rutherford laboratories are funded from STFC. The accelerator institutes are funded by STFC core and project grants as well as contributions from universities and Higher Education Funding Council for England (HEFCE) or Scottish Funding Council (SFC). The accelerator institutes operate as a collaboration between regional universities staffed by academic accelerator scientists. STFC advises the accelerator community via the Accelerator Strategy Board (ASB).

The 2016 Accelerator Institute Review concluded that the institutes serve as regional conglomerations of universities, which prove to be an efficient system for accessing different streams of resource. Research and development for novel acceleration is focused in the institutes whereas the national laboratories focus on established accelerator technology.

The Accelerator Strategy Board is concerned with blue-skies research and development across the Institutes, ASTeC, and the national laboratories.

There is a tendency for STFC accelerator science communities to self-organise. Work towards a UK FEL is a successful example of this model. Outside of the UK, R&D for new facilities is typically managed by national laboratories, and universities are brought in to collaborate. The national laboratories should do more to co-ordinate research and development activities across stakeholders in development of new facilities; this would ensure alignment with STFC's mission.

Recommendation 7 – The UK national laboratories should be charged with the co-ordination of research and development activities across stakeholders in development of future neutron and x-ray sources.

Thematic Recommendations for the STFC Accelerator Programme

Issues, activities and technologies relevant to supporting basic research and development capability within specific thematic areas are detailed below in Recommendations 8 – 15. Given the lack of strategic direction in regards to facility development and the constrained funding environment, these recommendations are of lower priority than overarching recommendations 1-7 above which support basic research and development across the programme more broadly.

Neutron Sources

The current UK landscape for accelerator activities associated with neutron production is dominated by operation of the ISIS spallation neutron source, and management and delivery of the UK's in-kind contributions to ESS.

ISIS has a unique position as Europe's only short-pulse neutron source. ISIS has made continuous developments and improvements in accelerator science, target technology, remote handling and instrument construction, and has contributed to the development of neutron spallation sources internationally.

The ISIS accelerator research and development community have proposed an upgrade to the facility, ISIS II, detailed in the thematic roadmap. A range of upgrade options at variable costs are possible. It is recommended that ISIS keep technology options open to enable the pursuit of a range of upgrade options; user preferences should also be solicited.

The UK's in-kind contributions towards ESS accelerators comprise linac components and the SCRF distribution system, developed at Daresbury Laboratory and Huddersfield University. Such research and development activities serve to maintain the UK skills base. Other research and development activities underway at ISIS include the Fixed Field Alternating Gradient (FFAG), the Front End Test Stand (FETS) and the Intense Beam EXperiment (IBEX).

FFAG is concerned with high power proton beams and has applications for neutron spallation sources. FETS is being developed as a generic test stand to demonstrate the beam properties required for a variety of projects that require a high power proton driver. IBEX is an international collaboration which includes ASTeC, ISIS, JAI and Hiroshima University. It has been recently built and commissioned at ISIS and studies the intense beam dynamics of a non-neutral plasma confined in an electrodynamic trap, equivalent to that in an accelerator focusing channel.

Recommendation 8 – Enable implementation of a range of ISIS II upgrade options. A programme of continued investment in developing advanced technology for high-intensity accelerators should be pursued. In particular, focus on cost effective accelerator technology options for MW-scale beams applicable to other fields such as:

- Super Conducting Radio Frequency Accelerating Structures;
- High intensity H- beam front end test stand;
- High power target development;
- High intensity H- ion sources.

International Collaboration on Accelerators for Neutron Production

The ISIS Neutron and Muon source is an internationally recognized facility, attracting researchers from across the globe. ISIS has also enabled more than 100 companies to develop a wide range of products from catalysts and lubricants to airplane components and consumer goods. An econometric study published in 2016 revealed that ISIS has delivered a return on investment of more than 200% over its lifetime.[1]

The first major facility of its kind in the world, ISIS has played a critical role in demonstrating the feasibility and benefits of spallation sources. This has helped to secure ISIS's highly regarded international reputation; its work has also changed the global landscape and opened up fresh opportunities internationally, with a number of neutron sources that are based on ISIS developments.[2]

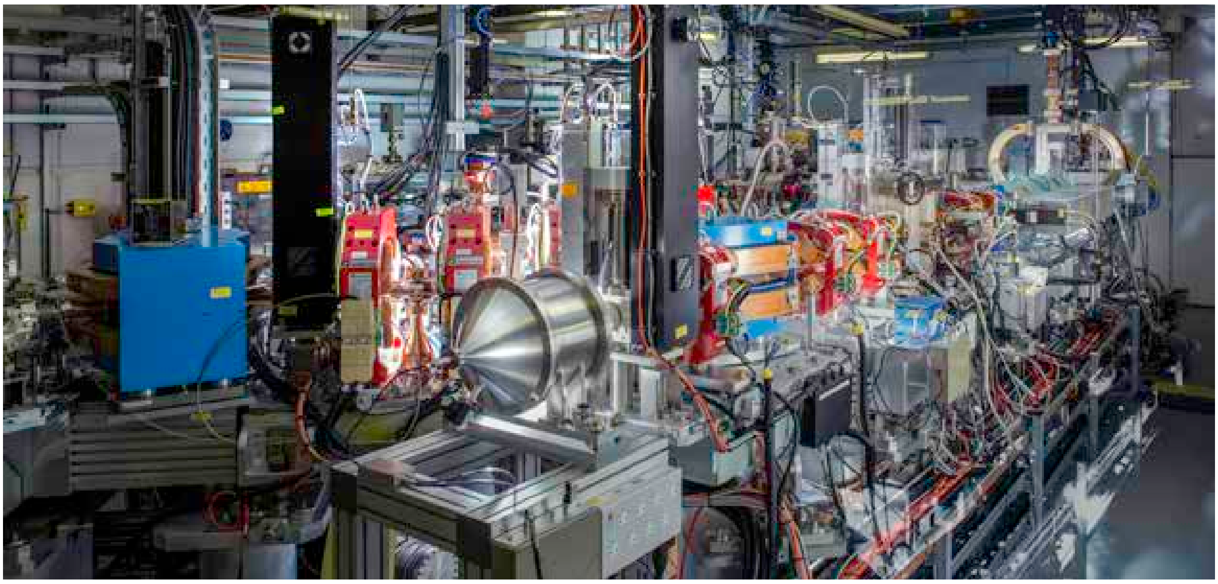
Many accelerator components developed specifically for ISIS, and which have contributed directly to ISIS's impact, have been employed at other spallation sources. The China Spallation Neutron Source (CSNS), part of the Chinese Academy of Sciences, has had a series of collaborations with the ISIS Accelerator Division covering ion sources, injection foils, synchrotron radio frequency acceleration systems and resonant magnet power supplies. This has allowed CSNS to replicate some ISIS equipment, test components with beam at the ISIS facility and advance rapidly with equipment development, subsequently promoting the manufacture of accelerator components within China and thus diversifying the supply chain and driving innovation in the field. First neutron production was achieved at CSNS in August 2017.

The UK is also contributing significantly to the European Spallation Source (ESS) currently under construction in Lund, Sweden, which will complement ISIS in the European neutron production landscape and is expected to have similar impact to ISIS in the future. The STFC's Accelerator Science and Technology Centre along with Technology Department is coordinating the UK delivery of accelerator components, particularly for the superconducting RF (SRF) linear accelerator, ultra-high vacuum preparation facilities and complete integration of SRF linac warm modules, comprising magnets, beam diagnostics and vacuum pumping systems for the entire SRF linac. Such activities have enabled considerably enhanced UK capability in complex sub-system engineering integration, testing and qualification of high performance, large-scale accelerator technologies, which will be further exploited in the UK participation in the international DUNE collaboration. ISIS and ESS illustrate how the UK exploits its expertise in accelerator science and technology to enable research into some of our biggest global challenges, such as energy storage materials.

[1] https://www.isis.stfc.ac.uk/Pages/home.aspx

[2] https://www.isis.stfc.ac.uk/Pages/ISIS%20Lifetime%20Impact%20Study.pdf#search=impact%20study

Light Sources



The UK has expertise in delivering state-of the-art storage ring facilities; SRS (in operation from 1981-2008) and DLS (in operation since 2007). Although the UK has not invested in a national FEL facility, the latest generation of light source, CLARA is currently being developed as a FEL test-bed. The UK has a strong tradition of expertise in the areas of accelerator science and technology (e.g. RF systems, laser systems, high-performance electronics for diagnostics and feedback systems) needed to provide state-of-the-art facilities for the well-established light source user community.

An advanced storage-ring based light source (in line with the prosed DLS upgrade, DLS II) would be complementary to the proposed UK FEL. The two facilities would provide radiation with different characteristics in terms of temporal structure.

A FEL test-bed facility i.e. CLARA is an essential step towards the development of a state-of-the-art user facility.

The research programme for CLARA includes the development of technologies in the generation, manipulation and diagnosis of high-brightness, high-stability electron beams, as well as the investigation and demonstration of techniques for the production of short-wave photon beams with novel properties. CLARA has the potential for development into a FEL user facility in its own right. Stable funding for CLARA over the duration of its development, 3 years, is recommended as expressed in Recommendation 2.

There is a strong case for DLS II as a user facility, notwithstanding the accelerator research and development opportunities it offers. A number of 3rd generation synchrotron facilities have been upgraded to date and much of the fundamental research and development has already been performed. A detailed technical design for DLS II is required; technological and engineering research and development is also required.

FEL Research at the University of Strathclyde
A research group at the University of Strathclyde has developed new methods that will greatly improve the output from large scale X-ray FEL facilities to allow for a far more detailed investigation of the natural world. The improvements in facility designs of X-ray FELs will enable greatly enhanced imaging of biological, chemical and physical processes in the temporal domain, allowing the creation of 'movies' of processes at the molecular scale.

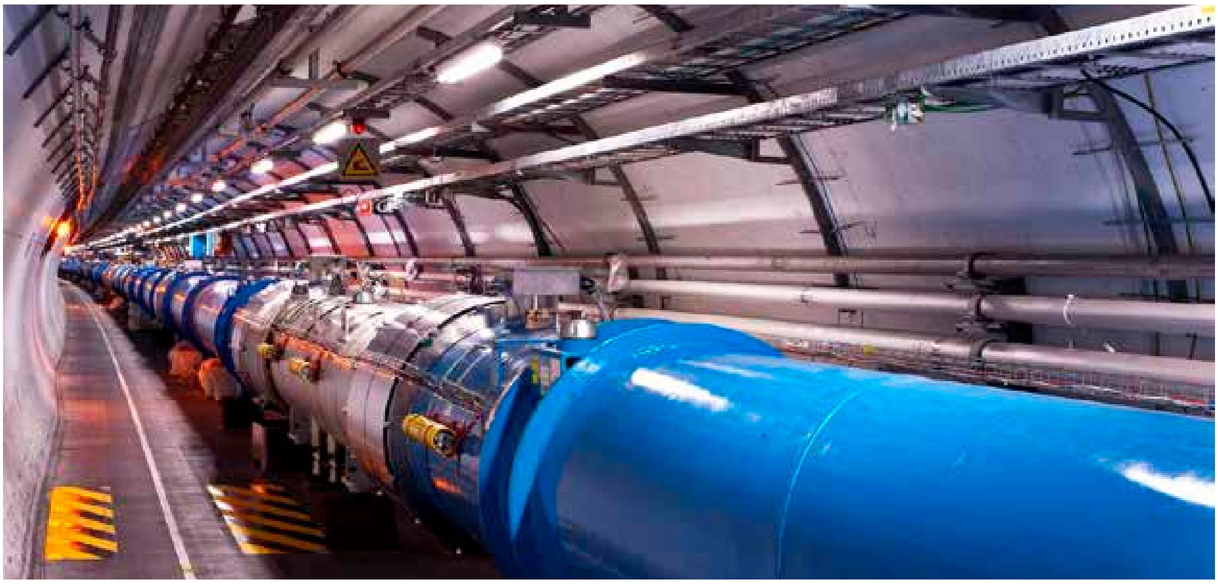
These improvements will be tested and developed at the CLARA FEL facility currently under construction at the Daresbury Laboratory; the group at Strathclyde are co-authors of the CLARA Conceptual Design report[1]. The underpinning research software[2-8] developed by the group is enabling researchers to explore new methods to greatly improve FEL output quality, in particular minimising pulse durations[2-4], maximising temporal coherence5, and increasing operating wavelengths[6,7]. This will benefit all light-source facility providers and their users.

A specific example of the impact of this research is in the redesign of the SwissFEL facility to incorporate UK design details and methods into the facility. This late change is currently being implemented and will have direct impact for users of SwissFEL within the next few years.

The groups research has also resulted in collaboration with Stanford University[9,10] in the US via a joint PhD programme which started in October 2017. This collaboration supports joint research and may well lead to further impact by influencing the design of X-ray FEL facilities being built globally, such as Stanford's LCLS-II facility.

[1]JA Clarke et al., JINST, 9, T05001, 2014
[2]NR Thompson & BWJ McNeil, Phys. Rev. Lett. 100, 203901, 2008
[3]E Kur, DJ Dunning, BWJ McNeil, J Wurtele & AA Zholents, New J. Phys. 13, 063012, 2011
[4]DJ Dunning, BWJ McNeil & NR Thompson, Phys. Rev. Lett., 110, 104801, 2013
[5]BWJ McNeil, NR Thompson & DJ Dunning, Phys. Rev. Lett., 110, 134802, 2013
[6]BWJ McNeil, GRM Robb, MW Poole & NR Thompson, Phys. Rev. Lett. 96, 084801, 2006
[7]LT Campbell, BWJ McNeil & S Reiche, New J. Phys., 16, 103019, 2014
[8]LT Campbell & BWJ McNeil, Phys. Plasmas 19, 093119, 2012
[9]JR Henderson, LT Campbell & BWJ McNeil, New J. Phys., 17, 083017, 2015
[10]B Garcia, E Hemsing, T Raubenheimer, LT Campbell & BWJ McNeil, Phys. Rev. Accel. Beams 19, 090701, 2016dy

Particle Physics and Nuclear Physics Machines



CERN is the focus of the UK's accelerator research and development activities for particle physics machines. Due to commence operations in 2025, the Large Hadron Collider (LHC) high luminosity project (HL-LHC) is a high priority for both UK and CERN. Current UK contributions to the upgrade research and development include advanced collimators, crab cavities, beam instrumentation and cold-powering systems. Involvement in this project enables the UK to make high profile and important contributions to the LHC machine upgrade. This is in support of the European Strategy for Particle Physics. The UK is fully aligned with the European Strategy for Particle Physics.

The future direction of the energy-frontier programme beyond HL-LHC will be an important consideration for the European Strategy for particle physics update in 2020. Options being considered include: an energy upgrade for the LHC (HE-LHC); linear electron-positron colliders: International Linear Collider (ILC) and Compact Linear Collider (CLIC); the Future Circular Collider (FCC).

The UK has recently invested over £65m in the Long Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). Activities for LBNF are synergistic with activities relevant to other thematic areas, particularly with Neutron Sources in relation to SCRF.

The UK has a high level of commitment to and investment in HL-LHC and LBNF/DUNE. Synergies with other thematic areas and industry collaboration should continue to be exploited for the benefit of the UK skills base and the economy and society more widely.

Recommendation 9 - Maximise the scientific and industrial return on the significant, long-term UK investment in CERN by exploiting synergies across thematic areas, and industry involvement.

Recommendation 10 – Maximise the return on the UK investment in LBNF/DUNE by exploiting synergies across thematic areas, and industry involvement.

CERN is carrying out research and development for high field magnets, and aspirations exist within the UK, at RAL and Daresbury Laboratory, to develop capability in this area. Engagement with research and development for high field magnets would create opportunities for UK industry to bid for commercial contracts. In addition, high field magnets have cross-thematic relevance.

The Electron-ion collider (EIC), currently being developed as an international collaboration, is set to be the next major hadron physics facility for nuclear physics. Its focus will be precision studies of the strong interaction. UK scientists have taken a role in defining the physics case and detector systems and could have a prominent role in the collaboration aiming to finalise the design of the new facility. Although there is currently no UK accelerator research and development effort towards EIC, there are potential synergies with the current Accelerator Programme. To enhance the UK's influence and access to the EIC, opportunities for UK engagement in the EIC accelerator project should be explored. Potential contributions that will maintain and enhance UK capability include energy-recovery systems, SCRF technology and accelerator design and diagnostics.

Recommendation 11 – Explore opportunities for participation in accelerator research and development for the Electron Ion Collider to support the UK nuclear physics community.

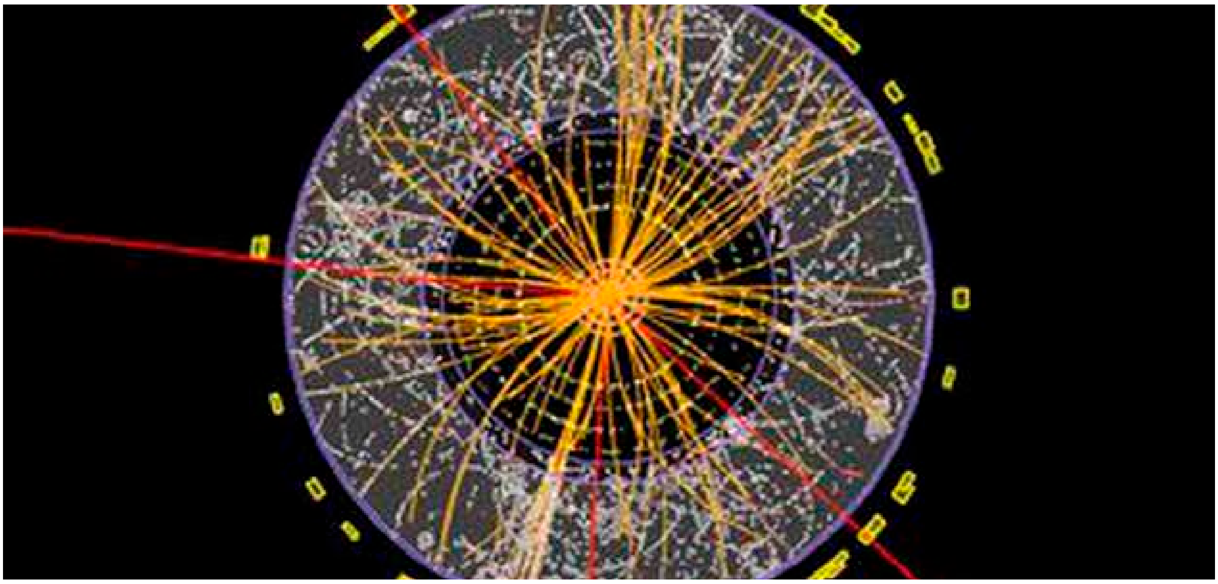
Discovery of the Higgs Boson

Developed in the 1970's the Standard Model of elementary particle physics provides the best understanding of the fundamental particles which constitute our universe. Through numerous experiments, the Standard Model has become established as a well-tested physics theory. In 2012, the discovery of the Higgs boson, an essential ingredient of the Standard Model, further contributed to our understanding of the universe.

The Higgs boson was discovered at the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. The LHC is an international collaboration, and the UK has played an instrumental role in the accelerator research and development which enabled the discovery of the Higgs boson.

Work is currently underway to upgrade the LHC, the High Luminosity project, in order to better understand the Higgs Boson. Research and development work associated with the High Luminosity project will enable researchers to build on the discovery of the particle, and explore its properties and branching fractions in some detail. This will allow a deeper understanding of the universe. The UK is involved in research and development of superconducting radio frequency (SCRF) and crab cavities for the High Luminosity LHC.

There is significant scope to develop industrial applications from the accelerator technologies being developed for the LHC. This includes SCRF, magnets, cryo-modules and laser treatment of vacuum chambers. UK involvement in the High Luminosity LHC is in alignment with the European Strategy for particle physics, and provides support for an essential component of the world programme at the energy frontier.



Novel Accelerators

Funded mainly through EPRSC, the UK novel acceleration community have developed expertise in novel accelerator techniques. These techniques will form the basis of development for future accelerators and applications, serving user communities across disciplines and society more widely. Although limited funding for this thematic area comes from STFC, the provision of accelerator development, delivery and access is part of STFC's mission and therefore novel acceleration is an area where STFC funding should be directed.

Laser wakefield acceleration (LWFA), a technique for accelerating charged particles is an area of strength for the UK novel acceleration community. UK researchers have contributed to many breakthroughs in LWFA including plasma targetry and laser guiding, injection and high brightness beam production, and high efficiency laser drivers. LWFAs also serve as sources of spatially coherent hard x-rays that have been used to demonstrate phase contrast micro-tomography, applicable to medical imaging. The creation of high energy positrons through electron beam conversion is an area of interest for future laser-based particle colliders.

In an effort to develop a more coordinated approach for the UK, the UK-wide Plasma Wakefield Accelerator Steering Committee (PWASC) was established in 2016. Their stated goal is the development of a coherent roadmap, the development of steps suitable to support progress on the roadmap, and exploration and initiation of additional funding mechanisms.

The UK groups working on ion acceleration collaborate through a current EPSRC-funded programme (2013 – 2019) which follows on from a previous EPSRC-funded programme. Research is conducted by university groups both in their own labs and through access to CLF and Laserlab-Europe user facilities. The main focus of this effort is the application of laser ion acceleration to healthcare. Experimental campaigns are also conducted to generate pulsed neutron sources through conversion of the ions in a catcher target. Such a source of fast neutrons could be applied to industrial imaging challenges.

The UK has two high power laser systems that are available for novel accelerator R&D: the PW-class Gemini dual-beam user facility at CLF and a commercial 300 TW system recently commissioned by SCAPA at the University of Strathclyde. New technology is being developed by the Centre for Advanced Laser Technology and Applications (CALTA) at the CLF, to further increase repetition rates. CALTA have installed the DiPOLE100 laser at the Czech HiLASE facility and are constructing a second system for the European XFEL.

The novel acceleration theme is important for maintaining basic research and development skills and capability for the UK accelerator programme in general.

Thus the lack of adequate funding, and the lack of funding from STFC in particular, poses a risk to the overall programme. Therefore, funding for a dedicated beam line on CLF for laser wakefield acceleration is recommended.

Recommendation 12 – Funding for the creation of a dedicated beam line at the CLF for laser wakefield acceleration research and development is recommended.

Particle beam driven plasma wakefield (PWFA), related to LWFA, has been identified as a potentially promising area for the UK to explore. PWFAs are known to be able to multiply the energy, and improve the emittance or brightness available in existing electron accelerators by several orders of magnitude. Development of CLARA as a test-bed facility to further develop beam driven wakefield, in addition to FEL research, is recommended.

Recommendation 13 – Funding to support beam driven wakefield and FEL research on CLARA is recommended.

The use of dielectric structures as hosts for particle acceleration is a more recent advance in the UK Novel Acceleration field. These structures can be driven either by particle beams or electromagnetically. Recent results with such low-energy laser-driven structures have demonstrated impressive acceleration gradients; with low energy, the laser drivers would allow novel accelerators operating at multi-kHz rates, enabling the use of different technologies such as fibre or thin disk lasers.

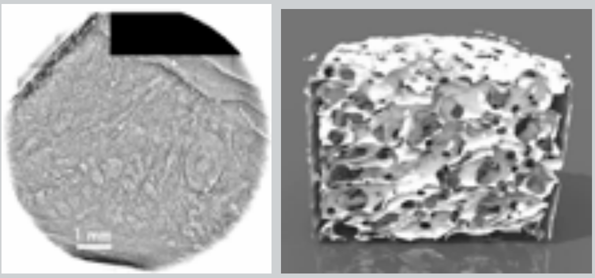
The UK also leads collaborations for many areas of the Advanced Wakefield Experiment (AWAKE) at CERN. This project aims to demonstrate proton driven plasma wakefield acceleration with a view to a future high energy collider. Other notable UK collaborations include the Europe-wide initiatives EuroNNAc, EuPRAXIA and Extreme Light Infrastructure (ELI) to develop plasma based acceleration. A Centre for Doctoral Training has been established specifically for Next Generation Accelerators.

Medical Imaging

Recent results suggest that the x-ray sources driven by novel accelerators such as laser-driven plasma accelerators have the potential to revolutionise medical imaging. The semi-coherent x-ray beams they produce allow a new type of imaging that can highlight even small changes in tissue composition, with micron-resolution – a capability available only with advanced x-ray sources such as synchrotrons.

The high-quality x-ray beams are produced by laser driven plasma wakefield acceleration (LWFA). Groups from Imperial College and University of Strathclyde have shown that these laser-driven x-rays (Betatron x-rays) can be used for imaging biological samples such as bones, breast and prostate tissues and mouse embryos. These teams use high power lasers such as Gemini at the Central Laser Facility or the Terawatt laser at SCAPA for these experiments.

In a laser wakefield accelerator, a high-power laser is fired into a gas cell to create a hot soup of electrons and ions, forming a plasma. The intense pressure of the high power laser then generates a cavity in the plasma that can accelerate some of these electrons almost to the speed of light in distances of a centimetre or less. A focused beam of energetic electrons exits the plasma, forming a compact accelerator.



Phase contrast image of prostate tissue and tomographic image of a human trabecular bone using laser-driven accelerator, showing rich structures. In comparison, a conventional absorption radiograph would appear almost homogeneous

As the electrons naturally oscillate in the cavity in which they are accelerated, they emit a beam of high-energy x-ray particles. Since the cavity from which the x-rays are emitted is micron-sized, the size of the x-ray source is point-like, enabling high-resolution imaging simply by propagation through a sample. The point-like source size also ensures a degree of spatial coherence, making the imaging sensitive to the refractive index – or density – of the sample, instead of absorption as in the case of common x-ray sources. It is this property – phase contrast – that makes this unique x-ray source capable of far superior image contrast, particularly for distinction between soft tissues and tumours.

Micron-resolution imaging will revolutionise medical diagnosis. For example, present imaging technology is not yet sufficiently refined to detect microfractures in bone, which can be an early indication of osteoporosis. High resolution, tissue-specific imaging can detect the onset of cancer at cellular level, in principle. Currently, this level of advanced x-ray imaging requires expensive facilities such as synchrotrons, which are not ubiquitous. Novel accelerators have the potential to change this scenario.

At present, the main limitation of these laser-driven sources is their repetition rate, defined by that of the laser. But, laser technology is developing at a fast rate. With next-generation high-power laser technology, it is possible to produce LWFA-driven beams enabling full tomographic scanning with micron-resolution within a few minutes rather than the hours needed by commercial sources.

Industrial, Medical, Defence and Security Applications

Activities within the accelerator applications theme have the potential to play a significant role in realising the full scientific, societal and economic benefits of STFC-funded programmes. A robust strategy and stable funding line is needed in order to take full advantage of the newly introduced applications focused funding schemes: Newton Fund, Global Challenges Research Fund and the Industrial Strategy Challenge Fund. UK industry recognises the potential benefits accelerators offer to industrial processes, but is unsure about whom to approach to engage with them. The test-bed centre for industrial applications, included in Recommendation 2, could remedy this issue.

Industrial collaboration in the development of accelerator applications is pivotal to success. The gaps in technology readiness levels between existing technologies and commercial applications are a barrier to industrial collaboration on applications development. There is a lack of necessary resource to support ideas beyond the initial conception, through the early development stages and onto technology/skills transfer into academia or industry. It is therefore recommended that the appropriate STFC staff identify potential accelerator application technologies and take steps to increase their technology readiness levels. These activities should include an independent and fair analysis of the commercial opportunity, which is currently lacking.

Recommendations 14 – In development of a coherent plan, with a stable and increased funding line for accelerator applications development, STFC should conduct or commission market research to identify 2-3 potential accelerator technology applications. Steps should be taken to increase their technology readiness levels.

Radiotherapy

The most widespread application of particle accelerators today is for radiotherapy, mainly small linacs. The UK's fleet of over 300 such linacs delivers over 2.5 million treatments a year, over half of which are for breast and prostate cancer patients. A radiotherapy linac delivers electrons at a modest energy of 10 MeV to a target which generates X-rays by bremsstrahlung that are then directed through computer-controlled multileaf collimators to create a desired dose in a patient. Elekta produces many of these linac treatment systems and has its main manufacturing site in the UK, supporting skilled jobs and high-tech manufacturing locally.

Many of the technologies used in modern-day intensity-modulated radiotherapy are based on research and development carried out in the UK. Whilst X-ray therapy is an excellent choice for many patients, benefits can be made in obtaining treatments that are better at sparing organs and tissues adjacent to the treated tumour site. One rapidly advancing technique is that of proton therapy, which whilst incurring a higher capital cost offers reduced side-effects for some treatments. The NHS and private providers are investing heavily in a number of treatment centres in the UK. These treatment centres will provide improved quality of care whilst lowering per-patient costs; at the moment patients must be referred abroad for proton therapy.

All the new proton treatment centres planned for the UK use commercially provided equipment that was developed using research done at universities and national laboratories around the world. There is a vibrant research programme in the UK funded nationally and through European projects that aims at both improving proton therapy and cutting its costs. These programmes naturally benefit from a close connection between clinical scientists, particle accelerator researchers, and industry. Research is being conducted into reducing the size of the proton accelerator source through the use of improved superconducting magnet technology using conventional cyclotrons or more modern methods that include laser-based techniques.

The development of modern radiotherapy has gone hand in hand with the development of modern particle accelerator science. Maintaining a vibrant research programme in this area is therefore vital to both continually improve the quality of treatments and to support the high-tech industry that delivers it to patients.

Appendix

A.1 Terms of Reference

To develop a strategy for STFC accelerator science that:

1.1 Provides a vision for the development of accelerator science over the next 15 - 20 years taking into account financial scenarios;

1.2 Identifies the highest priorities for accelerator science in each of the following themes as well as the overall priorities:
- Neutron sources
- Light sources
- Frontier Machines
- Novel Accelerators
- Cross-cutting themes;

1.3 Outlines the high-level actions needed to deliver these priorities, taking into account financial scenarios;

1.4 The strategy development should consider:
- The current STFC accelerator science programme, including strengths and weaknesses
- The future opportunities for accelerator science, both in the UK and internationally
- STFC, national and international priorities relevant to accelerator science and the relative priorities of the five themes including a steer on the financial investment needed
- Where STFC should take an international leadership role, or conversely areas where minimal or no involvement would be appropriate
- What underpinning technologies are required to deliver the high priority facilities, where there are any gaps and how these should be addressed
- How commercial opportunities arising from accelerator R&D can be maximised
- How STFC's relationships with other organisations impact on the accelerator science programme and where there are opportunities to develop or create new partnerships to benefit the programme.

1.5 Input for the strategy will include the 2014 Accelerator Review Report, the strategic guidance from Executive Board, the STFC Corporate Strategy, the 2016 Accelerator Institute Reviews, the 2016 FEL strategic review, and national and international strategy documents.

A.2 Review Panel Membership:

Stewart Boogert (ASB, JAI, Royal Holloway, University of London) *Chair*

Ralph Assmann (DESY)

Mei Bai (GSI)

Hans Braun (SwissFEL)

Håkan Danared (ESS)

Rory Duncan (SB, Herriot Watt University)

Terry Garvey (SwissFEL)

Norbert Holtkamp (SLAC)

Victor Malka (LOA, France)

Victoria Martin (PPRP, University of Edinburgh)

Hugh Montgomery (Thomas Jefferson National Accelerator Facility)

Andy Wolski (ASB, University of Liverpool)

Nigel Boulding (FMB Oxford)

Phil Kaziewicz (IAB, GI Partners)

A.3 Roadmap Coordinators:

Neutron Sources
Robert McGreevy (ISIS)
Peter McIntosh (ASTeC)
John Thomason (ISIS)

Light Sources
Riccardo Bartolini (ASB, JAI, Diamond)
Brian McNeil (Strathclyde)
Susan Smith (ASTeC)

Particle Physics and Nuclear Physics Machines
Rob Appleby (CI, Manchester)
Andrew Boston (Liverpool)
Philip Burrows (JAI, Oxford)
Ken Long (Imperial College)
Dan Watts (Edinburgh)

Novel Accelerators
Bernhard Hidding (CI, ASB, Strathclyde)
Zulfikar Najmudin (JAI, Imperial College)
Rajeev Pattathil (CLF)

Industrial, Medical, Defence and Security Applications
John Allen (Elekta)
Anthony Gleeson (ASTeC)
Hywel Owen (ASB, CI, Manchester)
Frank den Van Heuvel (Oxford)

A.4 Thematic Roadmaps

Frontier Science

Executive Summary

An Executive Summary of the current landscape and future horizon, of up to 2 pages (12pt font), is requested for each thematic roadmap. This is in addition to the 25 page (12pt font) limit for answering the roadmap questions.

Accelerator facilities serving particle- and nuclear-physics experiments have an impressive track record of discovery. The incremental development of accelerator technology and the innovation of novel techniques underpins future discoveries. The UK's scientific priorities are defined through the STFC's Particle Physics and Nuclear Physics Advisory Panels and its Science Board. These priorities are defined with reference to the European Strategy for Particle Physics, the Nuclear Physics European Collaboration Committee's long-range plan and other regional or international prioritisation exercises. The present accelerator R&D programme is aligned with these priorities. The UK's track record of world-leading contribution to the development of new accelerator techniques is internationally recognised and UK personnel occupy positions of international leadership.

The purview of the Frontier (particle) and Nuclear Physics theme is broad. The R&D programme required to deliver STFC's scientific objectives in this theme has been considered with reference to three categories of facility: "energy frontier" facilities, "flavour frontier" facilities, and nuclear-physics facilities. The energy-frontier programme includes the LHC and its upgrades, future proton-proton and electron-positron colliders, and a possible future electron-proton collider. The flavour-frontier programme includes accelerators for studies of quark flavour, neutrino sources and muon sources. The authors are not aware of accelerator R&D in the UK in support of quark-flavour physics. The nuclear-physics programme includes the new electron-ion collider facility as well as stable- and radioactive-ion beam facilities. Recently the potential for novel neutrino sources to benefit nuclear physics has begun to be considered. These classes are not "hermetic" and accelerator R&D programmes often have impact across the categories.

Continued, strategically-targeted, investment is required to deliver facilities capable of serving the UK's particle- and nuclear-physics priorities and to maintain and enhance UK leadership and influence.

Future facilities in each category of the Frontier (particle) and Nuclear Physics them relies on the development of super-conducting magnet and RF technology. Therefore, an overarching conclusion of this review is that the STFC should enhance the development of high-field super-conducting magnet technology and superconducting RF (SCRF) capability by promoting collaboration between UK Universities and Laboratories with appropriate industry with a view to increasing the performance of the technologies and reducing the capital and operating costs.

The key considerations, priorities and principal opportunities identified in this roadmap are:

Energy-frontier facilities

LHC luminosity upgrade (HL-LHC): An upgrade to increase substantially the luminosity of the LHC will be executed in the 2024/25 long shut-down. Current UK contributions to the upgrade R&D include advanced collimators, crab- cavities, diagnostics and cold-powering systems.

Energy-frontier beyond 2035: The future direction of the energy-frontier programme beyond HL-LHC will be an important consideration for the European Strategy for Particle Physics update in 2020. The options being considered are: an energy upgrade for the LHC (HE-LHC), linear electron-positron colliders (ILC and CLIC), the Future Circular Collider (FCC), which includes a proton-proton and an electron-positron option, and an electron- proton collider. A circular electron-positron collider similar to that considered in the context of the FCC is also being considered in China.

The UK has a strong track record in linear electron-positron collider R&D for both ILC and CLIC and has gained PI leadership in CLIC. UK personnel are making leading contributions to the development of the FCC and the study of the LHeC. In preparation for the European Strategy Update, CERN has established a panel to review the muon- collider option; through the MICE experiment the UK has influence and leadership in this area.

Strategic priorities: The precise study of the Higgs boson and the top quark, as well as direct and indirect searches for new phenomena at the energy frontier, are identified consistently in national and international prioritisation exercises as the top priority for particle physics. Therefore, the strategic priorities of the UK programme are:

LHC luminosity upgrade:
- Complete the present HL-LHC-UK programme to deliver the prototypes of UK HL-LHC deliverables: beam collimators; crab cavities; diagnostics and cold-powering systems;
- Through appropriate calls, position consortia of UK industry, universities and laboratories to bid successfully for delivery contracts for HL-LHC upgrade hardware in the early 2020s in the areas developed in HL-LHC-UK. This will allow the UK to benefit from its innovations in HL-LHC-UK and to deliver components for the luminosity upgrade; and
- Support for the installation and commissioning of the UK contributions to HL-LHC in the period 2024-2026.

LHC energy upgrade and Future Circular Collider: Complete (by end 2019) the UK deliverables to the EuroCirCol H2020 Design Study programme, including the development of the interaction region and the machine detector interface and the investigation of coatings to mitigate beam-induced vacuum effects;

- Through EuroCirCol deliver UK responsibilities to the FCC-hh design report as input to the European Strategy update in 2020; and
- Following the update of the European Strategy for Particle Physics in 2020, build on the key UK areas of expertise-collimation, crab cavities, diagnostics and cold powering, super-conducting-magnet design and SCRF, to position the UK to contribute to HE-LHC and/or the FCC.

Linear electron-positron Collider:
- Complete (by early 2020) the UK deliverables to the CLIC-UK programme, in particular the CLIC Project Plan for submission to the European Strategy update. Continue to monitor the ILC status and be prepared to position the UK for a leading role should Japan proceed with international negotiations to realise the ILC;
- Continue to invest in the detailed design of the Beam Delivery System (BDS). The programme should include investment in beam dynamics, feedback and control systems, beam instrumentation systems, magnets, vacuum systems, and crab cavities. Together with earlier investment in targets and beam dumps, energy spectrometry, collimators, and wakefields, this will position the UK to take a leadership role in the BDS of any future e+e- collider;
- Continue to be prepared to capitalise on UK expertise in: advanced electron-storage rings (notably Diamond); undulators and targets; and RF technology, both normal-conducting and superconducting. This will provide a platform for possible delivery of UK contributions to the damping rings, the positron source, and the main linacs, respectively;
- Continue to develop and exploit the strong synergies between linear collider R&D and the capabilities required to deliver a future UK XFEL facility based on either normal-conducting or superconducting linac technology. The BDS capabilities in particular are required for providing the high-quality beams for a FEL; and
- Continue to monitor international developments on a large circular e+e- collider. Should such a facility proceed in China (CEPC) or at CERN (FCCee) the UK's linear collider BDS capability would allow us to play a significant role.

Opportunities for development of alternative future capability: The UK should exploit its position of leadership in alternative approaches such as the LHeC and muon acceleration and:

- Continue to invest in design studies of the LHeC and engage with the work of the muon-accelerator review panel in preparation for the European Strategy update.

Flavour-frontier facilities:

High-power and novel neutrino sources: The flagships of the next generation of long-baseline neutrino-oscillation experiments, DUNE and Hyper-K, each require a proton-beam power of 1.2MW-1.3MW. The UK government recently announced an investment of £65M in the DUNE programme to support UK contributions to the accelerator-facility (LBNF) upgrade as well as the DUNE experiment. The UK now has the opportunity to maintain and enhance the expertise in SCRF that will have been established through the HL-LHC and ESS cavity-test programmes. The UK (RAL, TD) delivered the target for the J-PARC neutrino beam and the FNAL management now look to the UK to take a lead in providing the neutrino target for LBNF. Incremental upgrade of the J-PARC accelerator complex is underway such that a beam-power of 1.3MW is available by 2025. Investment in the J-PARC Main Ring and neutrino-beam-line programme will allow UK groups to maintain and enhance UK expertise in beam dynamics and diagnostics and provide a valuable training ground in neutrino-beam-line commissioning. A small muon storage ring (nuSTORM) to serve a definitive programme of neutrino-nucleus cross section measurements is being considered by the CERN Physics Beyond Colliders Study Group. UK personnel have leadership roles in this study and UK groups have responsibility for the design and simulation of the accelerator facility.

Charged-lepton flavour violation: The experiments g-2 and mu2e at FNAL and COMET at J-PARC each require excellent understanding of the muon beam. In addition, mu2e and COMET each require a novel particle- production/capture system and exploit “bent-solenoid” lattices to transport the muons to the muon-absorption target. UK personnel are playing key roles in the accelerator-science aspects of these experiments.

Technology demonstration: The UK has established a position of leadership in the demonstration of ionization cooling for a future Neutrino Factory or Muon Collider through the MICE experiment. The Radiation Damage in Accelerator Target Environments (RaDIATE) collaboration, in which the UK has both leadership and key technical roles, seeks to generate new data on material properties for application within the accelerator communities.

Strategic priorities: The search for CP-invariance violation in neutrino oscillations violation will remain a priority for the UK, and the international, particle physics community while the study of charged-lepton flavour violation requires key accelerator-expertise. Therefore, the strategic priorities of the UK programme are:

High-power and novel neutrino sources:

- The development and execution of a programme to deliver the UK contributions to the FNAL Proton Improvement Plan and the LBNF pion-production target. The programme should exploit and enhance UK skills in super-conducting RF technology, targetry, diagnostics and simulation and provide training opportunities in installation, commissioning and operation; and
- By contributing to the understanding of beam dynamics in the J-PARC Main Ring and the neutrino beam line, the development and enhancement of UK expertise and capability in neutrino-beam optimisation;

Charged-lepton flavour violation:

- Completion of the present accelerator deliverables to the g-2, mu2e and (through the consolidated grants) the COMET experiment;

Technology demonstration:

- Completion of the MICE experiment and continued investment in the RaDIATE programme;

Opportunities for development of future capability: The Neutrinos from Stored Muons (nuSTORM) facility will allow electron- and muon-neutrino cross sections to be measured with %-level precision to the benefit of next generation of long-baseline neutrino-oscillation experiments and the understanding of the physics of nuclei. The feasibility of implementing the facility is being considered within the CERN Physics Beyond Colliders Study Group. UK groups have responsibility for the optimisation of the accelerator facility downstream of the pion-production target. To influence and then to benefit from the outcome of the European Strategy update, the STFC should:

- Support UK contributions to the nuSTORM accelerator feasibility study within the Physics Beyond Colliders study group.

Nuclear-physics facilities:
The UK nuclear-physics community exploits a variety of international facilities in Europe, Asia and the USA. There are currently three funded STFC projects: ALICE and ISOL-SRS at CERN; and various experiments at the Thomas Jefferson Laboratory (JLAB) in the USA. The UK has also recently completed construction of instrumentation for the NUSTAR experiment at the future FAIR(GSI) facility.

Opportunities for development of future

capability: A key long-term opportunity identified in the nuclear physics roadmap is the electron-ion collider, which has the energies and beam intensities to enable the study of the gluonic components of nucleons and nuclei with high resolution for the first time. This will be built at either JLAB or BNL. Accelerator R&D work is underway for this facility at the two proposed sites and the science programme brings together UK nuclear physicists from the electromagnetic and relativistic heavy ion collider communities. JLAB is also hosting work relevant to the development of energy-recovery-linac technologies at GeV electron energies. To enhance the UK's influence and access to the EIC, following the Critical Decision Zero (CD0) review of the EIC in the US, the STFC should:

- Review the opportunities for UK engagement in the EIC accelerator project with a view to identifying a contribution that will maintain and enhance UK capability in energy-recovery systems, SCRF technology, accelerator design and diagnostics.

1a. Map current, planned and proposed accelerator science and technology activities within this theme against the science priorities (supported by STFC) they will enable over the next:

i. 1-5 years

ii. 5-10 years

iii. 10-20 years

1 The European Strategy for Particle Physics; Update 2013
2 Update to the UK Particle Physics Roadmap, 2015
3 Balance of Programme Exercise – PPAN, 2017
4 Appendix A produced by Executive Board for this review
5 STFC Corporate Strategy 2010-2020
6 STFC Delivery Plan 2016-2020
7 NuPECC Long Range Plan 2016/2017, http://www.nupecc.org/index.php?display=lrp2016/mai
8 UK nuclear physics roadmap document

		Science priorities								Strategic objectives										Timescale		
		Frontier (particle)						Nuclear														
Accelerator science and technology activity		Full exploitation of LHC including HL-LHC[1,2,3,4,5,6]	FCC as a future energy frontier pp, e+e- and ep facility[1,2,3,4,5,6]	Linear e+e- colliders (ILC and CLIC)[1,2,3,4,5,6]	Long-baseline neutrino oscillation experiments[1,2,3,4,5,6]	Novel techniques for the study of quark and lepton flavour physics[1,2,3,4,5,6]	Novel acceleration techniques (e.g. laser-driven systems such as AWAKE)[2,4,5,6]	Hadronic physics[7,8]	Nuclear structure and astrophysics[7,8]	Focus on investment for UK facilities[4]	Support areas of STFC scientific leadership[5]	High impact in Global Challenges and Industrial Strategy[5]	Reflect needs of other Research Councils[5]	Collaboration with universities[5]	Economic and campus impact[5]	Inspire training, STEM development and public awareness[5,6]	Fully exploit synergies with different branches of science and technology[5]	Integrate STFC's international activities[5]	Technology capability development with industry[4,5,6]	i. 1 - 5 years	ii. 5 - 10 years	iii. 10 - 20 years
Energy frontier	HL-LHC-UK	X	X							X	X	X		X	?	X	X	X	X	X	X	X
	EuroCirCol and FCC	X	X							X	X	X		X	?	X	X	X	X	X	X	X
	CLIC-UK	X	X	X						X	X	X	X	X	X	X	X	X	X	X	X	X
	LHeC		X							X	X	X		X	?	X	X	X	X	X	X	X
	AWAKE			X			X		X	X	X			X		X		X	X	X		
Flavour frontier	LBNF, PIP II/III at FNAL		?		X	?					X			X	X	X		X	X		X	X
	J-PARC Main Ring and neutrino-beam upgrade				X	X		?	?		X			X		X		X		X	X	X
	g-2, mu2e					X					X			X		X		X		X	X	
	COMET and PRISM					X					X			X		X		X		X	X	
	nuSTORM				X	X				X	X			X	X	X	X	X	X	X	X	
	FETS				X			?	?	X	X	X		X	X	X		X	X	X		
	MICE				X		X		X	X	X			X	X	X		X	X	X		
	RaDIATE	?	?		X			?	?	X	X			X		X		X	X	X	X	
Nuclear physics	Electron-ion collider (EIC)					X		X	X		X	X		X		X	X	X	X	X	X	
	NuSTAR upgrade							X	X	X	X	X		X		X	X	X	X		X	
	EURISOL								X		X	X		X		X	X	X	X		X	
	GANIL, GSI, GANIL, RIKEN, NSCL, ISOLDE, ISAC								X		X	X		X		X	X	X	X		X	X
	CBAF 12 GeV upgrade							X	X	X	X	X		X		X	X	X	X	X	X	X
	Secondary Kaon beam at JLAB: (KLong project)					X	X	X	X		X			X		X	X	X	X		X	X
	Upgrade to NPL van de Graaf												X	X	X		X		X		X	X
Opportunity	PERLE injector																	X	X	X		
	CBETA(ERL/ns FFAG)																	X	X	X		
	LESS (e- cloud)																	X	X	X		
	IOTA																	X	X	X		

Energy-frontier facilities:

HL-LHC-UK: The 2013 update to the European Strategy for Particle Physics, placed the full exploitation of the LHC "including the high-luminosity upgrade to the machine" as the top priority. This prioritisation has been reflected in each STFC prioritisation exercise since the European Strategy Update was published. Recently, the PPAP Update to the UK Particle Physics Road Map[1] endorsed this view and the Balance of Programmes Exercise[2] recognised the priority given to the LHC luminosity programme by the UK particle- physics community. The HL-LHC-UK programme will deliver hardware prototypes to the HL-LHC project in the key areas of beam collimation, crab cavities, diagnostics and cold-powering systems. The programme capitalises on the major investments made by STFC (and CERN) in the UK capability in the design and construction of small-scale hardware for proton-proton colliders. The HL-LHC-UK project will position the UK to bid for substantial contributions in the HL-LHC construction phase.

EuroCirCol and FCC: HL-LHC is scheduled to run until ~2035. An energy upgrade to double the beam energy (HE-LHC) is being considered. This would require the replacement of all dipoles. In parallel, CERN has initiated the study of a Future Circular Collider, in a new 80km—100km tunnel, to deliver proton-proton collisions at 100TeV. The UK leads the study of the interaction region, the machine-detector interface and is developing vacuum coatings to mitigate beam-induced vacuum effects. This study is funded in part through the H2020 EuroCirCol Design Study. The UK contributions to EuroCirCol and FCC will position the UK to make substantial contributions to the next phase proton-proton accelerator R&D following the European Strategy update.

CLIC-UK: Between 2003 and 2011 PPARC, CCLRC and STFC invested £25M in linear collider R&D which set strong foundations for the UK to play a major role. The 2013 update to the European Strategy for Particle Physics recommended that 'CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high- gradient accelerating structures'. It recognised the 'strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded'. For ILC it stated 'Europe looks forward to a proposal from Japan to discuss a possible participation'. Since 2011 CLIC-UK, a £13M programme co-funded by STFC and CERN has specifically addressed the European Strategy priorities. It has strengthened UK capability in key systems, notably Beam Delivery System technologies, magnets and RF systems, such that we are well placed to take responsibility for a major system should ILC or CLIC proceed. CLIC-UK is committed to providing key deliverables for the CLIC Project Plan which will be submitted to the European Strategy Update in 2019. The CLIC accelerator collaboration is led by a UK scientist.

LHeC: The study of an electron-proton collider as an option for the future development of the LHC is led by a UK scientist. A recirculating linear accelerator, that includes an energy recovery linac, brings the electron (positron) beam up to 60 GeV. The beam is brought into collision with the LHC and returns to the energy-recovery linac. A prototype for the Energy Recovery Linac (ERL) is included in CERN's Medium Term Plan. Work on the LHeC enhances the UK's expertise in energy-recovery systems and positions the UK to strengthen its position of leadership following the European Strategy update.

AWAKE: The AWAKE[3] collaboration seeks to demonstrate proton-driven plasma wakefield acceleration for the first time. Electrons will be accelerated by wakefields of about 1 GV/m generated by protons from the CERN SPS in a plasma column. The first phase of the AWAKE programme is underway. Further comment on the AWAKE programme is contained in the Novel Accelerators roadmap.

Flavour-frontier facilities:

LBNF, PIP-II/III at FNAL: The Long-Baseline Neutrino Facility[4] at FNAL will serve the DUNE[5] experiment. The PIP-II[6] upgrade will replace the existing 400 MeV FNAL linac with an 800 MeV superconducting linac to deliver a beam power of 1.2 MW. The upgraded linac is designed to be capable of CW operation so that it can serve a diverse experimental programme alongside the long-baseline neutrino-oscillation programme. PIP-III[7] is conceived as a further upgrade to the proton-accelerator complex to deliver a further factor of 2 increase in beam-power. Contributions to the beam line are accepted as contributions that allow collaborators to gain access to the data from DUNE. Benefits to the UK of involvement in the programme include extension of UK skills in super-conducting RF technology, diagnostics, simulation and training in commissioning and operation.

J-PARC Main Ring and neutrino-beam upgrade: An incremental upgrade programme for the J-PARC Main Ring and neutrino beam has been initiated[8]. The upgrade programme will deliver a beam power of 1.3 MW to serve the Hyper-K neutrino oscillation experiment. The upgrade programme includes the implementation of second-harmonic RF in the Main Ring, improvements in the Main Ring optics to reduce beam loss and improved instrumentation, feedback and control in the Main Ring and the neutrino beam line. Contributions to the beam line are accepted by the T2K, T2K-II and Hyper-K collaborations as contributions to the experiment. Benefits to the UK of involvement in the programme include enhancement of expertise in optics, beam-simulation and diagnostics.

g-2 and mu2e: The g–2[9] experiment at FNAL aims to measure the anomalous magnetic moment of the muon with high precision using polarised muon decays. The mu2e[10] (FNAL) experiment will search for muon-to-electron conversion. Both experiments are funded by STFC and require a precise understanding of the muon-beam dynamics. UK groups have established leadership roles in these experiments. Support for these experiments enhances the beam-dynamics expertise in the UK.

COMET and PRISM: The COMET[11] (J-PARC) experiment will search for muon-to-electron conversion; UK contributions are funded through consolidated grants. PRISM[12] is conceived as the successor to the COMET experiment. By using a scaling FFAG to rotate the beam in longitudinal phase space, a very short bunch can be delivered to the muon-absorption target allowing a substantial increase in sensitivity to be achieved. Both COMET and mu2e experiments exploit novel “bent solenoid” beam-transport systems to bring the muon beam onto a target placed within a high-field solenoid. UK personnel have established positions of leadership in COMET and PRISM and contributions to these experiments enhance UK capability in beam design and simulation.

Neutrinos from stored muons (nuSTORM): The nuSTORM[13] facility will provide electron- and muon-neutrino beams from the decay of low energy muons confined within a storage ring. The facility is based on a horn- focused pion beam and can be built with state-of-the art components. Excellent instrumentation for the ring is essential to determine the neutrino flux at the %-level or better. The precision cross-section measurements that nuSTORM can provide will serve the next generation of long-baseline neutrino-oscillation experiments and, by delivering precise measurements with a pure weak probe, contribute to the understanding of the physics of nuclei. The feasibility of implementing the facility is being studied within the CERN Physics Beyond Colliders study group.

Front-end Test Stand (FETS): The Front-end Test Stand[14] when completed (second quarter of 2018) will comprise an H-ion source, low-energy beam transport, RFQ (325MHz), medium-energy beam transport and chopper along with associated instrumentation. It is designed to demonstrate the technologies required of an injector for a future, high-power, pulsed circular accelerator (such as neutron or neutrino-production facilities). A feature of the test stand is the chopper which is designed to introduce micro-second-long voids in the bunch train to allow kickers to be energised.

Muon Ionization Cooling Experiment (MICE): The international Muon Ionization Cooling Experiment[15] is taking data at the Rutherford Appleton Laboratory. The MICE collaboration seeks to prove, for the first time, the principle of the ionization-cooling technique. Intense muon beams of low emittance have the potential to deliver neutrino beams of precisely known flux and flavour and provide a route to multi-TeV lepton-antilepton collisions. Ionization cooling is the technique by which it is proposed to cool the muon beam prior to acceleration. The international collaboration is composed of 32 institutes from Asia, Europe and the USA.

Radiation Damage in Accelerator Target Environments (RaDIATE): The Radiation Damage in Accelerator Target Environments[16] collaboration draws on existing expertise in fission and fusion research to carry out a research programme to generate new data on material properties for application within the accelerator and fission/fusion communities and to coordinate the application of this data both to proton-accelerator and to clean energy technologies.

Nuclear-physics facilities:

The nuclear-physics community in the UK exploits a number of accelerator-facilities across the world. These facilities include:

- **EURISOL:** the ultimate ISOL facility in Europe will be EURISOL for which an extensive R&D program and a design study have been carried out in the last decade. It consists of a superconducting linear accelerator providing 1 GeV protons with a power of 5 MW, but also capable of accelerating deuterons, 3He and ions up to mass 40;
- **NuSTAR at FAIR:** FAIR will be a European flagship facility in nuclear physics for the coming decades. It will produce intense, high brilliance beams of all chemical elements up to uranium with energies in the range E~1-30 GeV per nucleon and also have a dedicated antiproton beam facility. Such beams and FAIR's unique infrastructure (e.g. storage rings) will provide capabilities unmatched worldwide, especially regarding the study of heavy elements. Based on these, and future developments in detector technology and electronics, an NUSTAR upgrade project is envisaged in the future. This is likely to include support for the dedicated decay spectroscopy gamma-ray array at DESPEC;
- **GANIL, GSI, GANIL, RIKEN, NSCL, ISOLDE, ISAC:** experimental studies in the nuclear-structure and astrophysics theme take place at particle accelerators capable of delivering stable or unstable (radioactive) nuclei with a wide range of energies and intensities. Both the Nuclear Structure and Nuclear Astrophysics communities study nuclei at the extremes. This requires the exploitation of the best currently available stable beam facilities, such as Jyvaskyla and Argonne National laboratory (ANL); Fragmentation facilities, such as those at GSI, GANIL, RIKEN in Japan, NSCL at Michigan State University; and ISOL facilities, such as ISOLDE at CERN and ISAC at TRIUMF;
- **CEBAF 12 GeV (JLAB) upgrade:** The JLAB facility recently completed an upgrade in the energy (6 to 12 GeV) and intensity of its electron beam. The equipment in the experimental halls has been upgraded for this new regime and a new experimental hall (Hall-D) has been added. The STFC project grant for the JLab Upgrade cements the UK's position in this field. A proposal for intense electromagnetic beams are used to create secondary beams of short-lived hadrons, with the main physics focus on creating an intense beam of of neutral kaons (the KLONG facility (KLF) at JLAB) is being brought forward; and
- **National Physical Laboratory (NPL) Van de Graaf:** There is an upgrade under discussion for the Van de Graaff at NPL to create a tunable mono-energetic neutron source (0.1-18 MeV) for ion beam analysis (PIXE, PIGE, RBS), industrial dose calibrations, nuclear data for generation IV reactor designs and astrophysics measurements. There are opportunities for STFC-supported accelerator-scientists to contribute to the design and development.

The principal accelerator R&D opportunity by which the UK can develop its accelerator-science capability and enhance the capability of its nuclear-physics community is the Electron-ion Collider being considered in the US for implementation at either JLAB or BNL.

Electron-ion collider (EIC): The next major hadron physics facility for nuclear physics looks likely to be a high-energy Electron-Ion Collider (EIC). Its focus will be precision studies of the strong interaction. UK scientists have taken a leading role in defining the physics case and detector systems, starting with phenomenological and simulation studies in 2016, leading to an extensive R&D programme in tracking and particle identification detectors and trigger systems from 2019 onwards.

The EIC specifications are that it will provide highly polarized (~70%) electron and nucleon beams; Ion beams from deuteron to the heaviest nuclei (uranium or lead); variable centre of mass energies from 20 – 100 GeV, upgradable to 150 GeV; High collision luminosity 10^{33-34} cm^{-2}s^{-1}; and multiple interaction regions. The machine would not be built from scratch and two different designs have been investigated. One option is to add an electron-beam facility to RHIC – a plan that would depend on some as-yet-unproven technologies. Another option is to add an ion accelerator and new collider rings to the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLAB) in Newport News, Virginia. The EIC project was given the highest priority for the next US nuclear physics facility in the most recent Nuclear Science Advisory Committee (NSAC) report.

Opportunities:

There are some future opportunities for which the UK is well positioned:

- PERLE: The Powerful Energy Recovery Linac Experiment (PERLE) facility is a proposed high-energy (1 GeV) energy-recovery linac. The proposal (arXiv: 1705.08783) is generic and notes that CERN, LAL Orsay and GSI Darmstadt are possible host laboratories. The aim is to establish a technology test bed and an associated physics programme. UK interest is through ASTEC and Liverpool university. Personnel at these institutes have expertise in ERLs (e.g. ALICE) as well as in possible applications of the technology (such as LHeC).
- CBETA: The Cornell-BNL ERL Test Accelerator (CBETA) is an energy-recovery test facility that is being built at Cornell and will deliver a 150 MeV beam. It uses FFAG optics using permanent magnets and is seen as a test bed for the techniques required at future accelerators such as the EIC.
- LESS (e-cloud): "Laser Engineered Surface Structures" (LESS) (see Appl. Phys. Lett. 105, 231605, 2014) is an STFC-funded project to produce in situ laser treatment of beam screens to reduce electron cloud and multipacting effects in future frontier machines. The technique is understudy at ASTeC and Dundee with a view to improving the beam lifetime at LHC.
- IOTA: The Integrable Optics Test Accelerator (IOTA) facility at FNAL (see e.g. JINST 12 T03002 2017) is a storage ring for advanced beam physics research currently being built and commissioned at Fermilab. It will operate with protons and electrons using injectors with momenta of 70 and 150 MeV/c, respectively. The research program includes the study of nonlinear focusing integrable optical beam lattices based on special magnets and electron lenses, beam dynamics of space-charge effects and their compensation, optical stochastic cooling, and several other experiments. UK expertise in beam dynamics, simulation and analysis are well matched to the needs of this programme.

1b. Please comment on the current UK position of each accelerator science and technology activity in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and capacity be exploited**

Energy-frontier facilities:

HL-LHC-UK: The full exploitation of the UK's investment in the LHC is underpinned by the work carried out on the luminosity upgrade by the UK institutes in the project HL-LHC-UK. This runs until the end of 2020, and involves ASTeC, the CI, JAI, University of Southampton and the University of Huddersfield. This group has established a core team with proton-collider expertise that has strong synergies with the ISIS and the UK neutron-source. The scope of the work includes studies of beam collimation, advanced diagnostics and high-bandwidth beam-position monitors, the design and implementation of crab cavities, beam dynamics, cold powering and advanced simulation. The LHC provides a testbed for some of the advanced diagnostics. The crab-cavity work has enhanced the UK's SCRF expertise. In addition, LHC is one of only a few machines at which young researchers can gain experience. For example, UK personnel (Imperial) have been participating in the CERN UA9 experiment that has demonstrated the use of silicon crystals for channelling. As a result of this work, crystal collimation will become the baseline for the LHC. In the future, crystals can be used for beam extraction. Contributions that enhance beam quality, reduce beam loss etc. materially enhance exploitation of UK investment in the LHC.

There is clear opportunity to build on the successful innovations to date to build consortia of UK industry, Universities and Laboratories to bid to deliver significant components for the HL-LHC build phase. The expertise that will be gained with the construction of components followed by their installation and commissioning on the LHC will be of great value to the UK in future projects.

EuroCirCol and FCC: The current UK effort on FCC is directed through EuroCirCol, with involvement in machine detector interface, vacuum and communications. The UK will complete its commitments in this project and watch with interest the European Strategy Update with regard to future high-energy machines. The UK should look to maintain its current position and exploit leadership positions in this and related areas to lead areas in the FCC-hh TDR phase.

CLIC-UK: The CLIC-UK project capitalises on the £25M investment made between 2003 and 2011 by PPARC, CCLRC and STFC in linear collider technology capability via the Linear Collider Accelerator and Beam Delivery (LC-ABD) project. This included participation from 80 accelerator scientists and engineers from 11 UK institutes; more than 40 PhD and postdoctoral early-stage researchers were trained. This investment allowed the UK to take a number of leadership roles in the International Linear Collider (ILC) Global Design Effort, which culminated in the delivery of the ILC Technical Design Report in 2013 with UK lead authorship. The investment was strategically focussed on Beam Delivery System technologies (beam dynamics, feedback and control systems, beam instrumentation, energy spectrometry, targets and beam dumps, magnets, collimation systems, and RF systems including crab cavities) with additional leading contributions to the positron source and damping ring designs. Since delivery of the ILC TDR, UK capability has been further strengthened via the CLIC-UK programme, amounting to £14M investment between 2011 and 2020, jointly funded by CERN and STFC, with a focus on advanced beam instrumentation, feedback, feed-forward and beam control systems, permanent magnet design and high-power RF systems including crab cavities and klystron design. The UK is recognised to have world-leading strengths in these areas which position us to take leadership of one or more major linear collider technical systems, as well as plan our own advanced facilities: it would not be possible today to consider the design of a UK XFEL without this prior investment in linear collider R&D. A UK scientist leads the CLIC accelerator Collaboration.

The LC-ABD and CLIC-UK projects have allowed us to build strategic partnerships with overseas laboratories and we have directly contributed to a number of international test facilities, including: the Accelerator Test facility (ATF) at KEK; End Station A (ESA) at SLAC; the CLIC Test Facility (CTF3) at CERN; FLASH and PETRA3 (DESY); and FACET (SLAC). These overseas facilities are vital for underpinning the UK R&D programme on advanced beam handling for future electron-based accelerators, and we should continue to exploit them for as long as they remain cutting edge and relevant to support of our science goals and programme.

LHeC: The LHeC project receives modest funding from CERN and a low level of UK funding through academic time on consolidated grants. The UK provides the LHeC project spokesman. The LHeC-UK collaboration is composed of Birmingham, Cockcroft, Liverpool, Oxford, QMUL. Interest in eA programme has also been expressed by several nuclear physics groups and collaboration. ASTeC and several University groups collaborate on the development of the ERL test facility and other accelerator topics.

The present focus of the design work is to prepare a submission as input to the update of the European Strategy for Particle Physics. The UK is well placed to provide leadership and to benefit from the future development of an ep collider once the outcome of the European Strategy update is known.

AWAKE: AWAKE provides the possibility of very high gradient acceleration of an electron beam to high energy. The technique has application in the delivery of electron-proton as well as electron-positron collisions. Through its leadership roles, its position and strong contributions to the international collaboration and its close connection to CERN, the UK collaboration is well place to continue its leading position in the development of this novel technique.

Flavour-frontier facilities:

LBNF, PIP II/III at FNAL: The investment of £65M in UK contributions to LBNf and DUNE gives the UK the opportunity to make substantial contributions both to the experiment and the accelerator facility. By contributing to the PIP II programme, the UK has the opportunity to maintain and enhance the expertise in SCRF that will have been established through the HL-LHC-UK and ESS cavity-test programmes. The UK programme would be centred on the ASTeC group with opportunities for University groups to contribute through instrumentation, diagnostics etc. The PIP

III programme is presently at the conceptual-design stage offering significant scope for University and lab-based groups to contribute thereby maintaining and enhancing the UK's capability in the areas of beam dynamics, the analysis of collective effects such as space charge, and advanced simulation techniques.

The UK has unique expertise in the High Power Targets group at RAL. The group contributed the target for the J-PARC neutrino beam and designed the beam dump. The group was instrumental in creating the RaDIATE collaboration and is well respected in the international community. By contributing to the LBNF target, the expertise of this group would be maintained and enhanced to the benefit of the ISIS upgrade programme and future UK contributions to high-power machines elsewhere.

The STFC should seek to negotiate substantial contributions to the FNAL proton improvement plan that maintain and enhance UK capability in the areas outlined above.

J-PARC Main Ring and neutrino-beam upgrade: The UK has strong links to KEK and J-PARC and has existing collaborations on the 3 GeV ring. The target for the J-PARC neutrino beam was provided by the UK. The J- PARC accelerator and neutrino-beam upgrades are required for the T2K, T2K-II and Hyper-K programmes to reach their specified sensitivity. Indeed, for T2K-II, since the far-detector mass will not be increased, the beam-power upgrade is critical. Initial discussions of contributions in the areas of studies of beam dynamics in the Main Ring with a view to reducing beam loss, advanced instrumentation and feedback and control of the extracted proton beam as well as beam commissioning are underway. The benefits to the UK include maintaining and enhancing the beam-dynamics expertise, enhancing capability in beam-line instrumentation in areas that have synergy with application in other proton accelerators including future particle therapy facilities and the provision of a hands-on training ground for beam-line commissioning and optimisation.

The STFC should seek to negotiate a modest contribution to the J-PARC accelerator upgrade to complement its existing accelerator and experimental collaborations with KEK and J-PARC.

g-2 and mu2e: For g-2 the UK is responsible for the design and construction of the straw trackers, including the data acquisition system and will provide an independent technique to measure the magnetic field calibration. Work on simulating the beam dynamics of the ring has also been supported by Liverpool/Cockcroft. For mu2e, the UK is contributing the stopping-target monitor and collimators (UCL, Manchester, Liverpool).

COMET and PRISM: For COMET the UK led the establishment of the Online/Offline Software, contributed to early muon beam line design studies, designed and produced detector triggering/DAQ electronics, provided conceptual designs for beam targetry and handling etc. In addition, the UK is coordinating subdetector raw data interfaces across the experiment and leading the use of machine learning techniques in triggering, tracking and reconstruction and performing large-scale data processing. Work on simulating the beam dynamics of the ring has also been supported by Liverpool/Cockcroft.

Cockcroft, Imperial, Oxford, and the ISIS High Power Beams groups are involved in the "PRISM Task Force" which is designing an FFAG-based next-generation muon-to- electron conversion experiment. The UK provides the international PRISM Task Force leader. PRISM will provide two orders of magnitude improvement in the sensitivity of COMET Phase-II and mu2e. The programme offers opportunities t0 maintain and enhance expertise in beam dynamics, instrumentation and simulation. Should the FFAG technique form the basis of ISIS II, valuable experience will be gained by continued and enhanced contributions to PRISM.

nuSTORM: UK scientists have consistently taken the lead in making the case for nuSTORM as a means of studying neutrino-nucleus scattering as a service to the long- and short-baseline programmes and as a possible means to study nuclear physics using a pure weak probe. A UK scientist made the case to CERN that nuSTORM be included in the PBC study and now co-leads the nuSTORM work package. While the baseline for the facility calls for quadrupole focusing in the decay ring, the alternative FFAG-focussing ring proposed by UK groups (Imperial, Manchester and RAL) has a significantly larger dynamic aperture which would translate into a greater neutrino-beam intensity.

nuSTORM at CERN gives the UK the opportunity to spearhead the international collaboration required to design the accelerator facility and to work closely with CERN in its implementation.

The activity should be supported to the end of the feasibility-study phase as part of the CERN Physics Beyond Colliders activity. Investment in the medium and longer term should be considered once the European Strategy for Particle Physics has been updated.

FETS: The FETS RFQ has been manufactured using a novel, modular approach that is of interest to other facilities. FETS will include a high duty-factor beam chopper that is designed to remove (chop) particles from the beam with the near 100% efficiency required for the injector of a high-power circular proton accelerator. The FETS collaboration has strong links to the CERN accelerator development programme (particularly LINAC4) and continued collaboration with the ESS through ESS Bilbao, the FETS programme receives considerable international attention and its results are likely to be influential in the international community. The test stand can be exploited to serve accelerator-development projects such as a demonstration of components or systems for future pulsed-proton systems.

MICE: By hosting MICE at RAL, the UK placed itself at the heart of the programme gaining significant influence in the field of accelerators for the production of muon and neutrino beams. Since its inception, the UK has significant leadership roles within the collaboration and presently provides the international spokesman, the Collaboration Board Chair and Physics Coordinator, the Project Manager and a number of other key leadership roles.

The present configuration of MICE will be used to deliver a systematic study of the factors that determine the performance of an ionization cooling channel. STFC was unable to support a modest upgrade by which acceleration would be added to the lattice to allow a proof of principal experiment to be carried out. International interest in the project is such that the Institute of High Energy Physics in Protvino is considering hosting the proof-of-principal experiment. In view of its leading position, the UK continues to have influence over the future development of the programme through, for example, the study of nuSTORM within the CERN Physics Beyond Colliders study group and the discussion of possible six-dimensional-cooling experiments to follow MICE.

RaDIATE: A collaboration including the High Power Target Group and the Materials Science Department of Oxford University was established early in the RaDIATE programme. This collaboration yielded important results that were well received by the international community. Continuation of UK involvement in this programme will yield benefits in the understanding required to develop a future target for ISIS and enhance the UK's capability to contribute to, and benefit from, high-power accelerator projects such as LBNF/DUNE.

Nuclear-physics facilities:

Electron ion collider (EIC): UK scientists have a prominent role in the collaboration aiming to finalise the design of the new facility. The facility will be an upgrade to the JLAB (or Brookhaven) facilities, where the UK already has focussed efforts in hadron and relativistic heavy ion physics. The UK university effort for the EIC is currently focussed on realising the next generation particle detector systems needed to deliver the science. However, the accelerator R&D may offer opportunities for the UK. There appear to be synergies in the ongoing accelerator science developments for the EIC with existing programmes e.g. xFEL.

2a. What enabling accelerator technologies/ capabilities (including computing, vacuum, RF, lasers etc.) are necessary to pursue each accelerator activity?

Frontier (particle) and nuclear facilities require a large range of capabilities (see matrix), many in common with other types of accelerator facility. The UK must maintain a breadth of expertise within the various disciplines to allow it to maintain and enhance its domestic facilities (including CERN, the 'UK's laboratory for particle physics'). For future machines, the UK does not necessarily require to be world leading in each discipline, but, the STFC should recognise and support skills development in order to be ready to contribute to and to benefit from the construction of future machines.

Key skills areas identified in the matrix above include:

- **Beam dynamics:** is universal and required to design,

	Accelerator science and technology activity																					
	Energy frontier					Flavour frontier								Nuclear physics						Opportunity		
Key technologies	HL-LHC-UK	EuroCirCol and FCC	CLIC-UK	LHeC	AWAKE	LBNF, PIP II/III FNAL (inc cavities)	J-PARC Main Ring and neutrino-beam upgrade	g-2 and mu2e	COMET and PRISM	nuSTORM	FETS	MICE	RaDIATE	Electron-ion collider (EIC)	EURISOL	GANIL, GSI, GANIL, RIKEN, NSCL, ISOLDE, ISAC	CBAF 12 GeV upgrade	Secondary Kaon beam at JLAB: (KLF project)	Upgrade to NPL van de Graaf	PERLE injector	CBETA(ERL/ns FFAG)	LESS (e- cloud)
Beam Dynamics	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	
Diagnostics			x		x	x	x	x	x	x	x	x		x	x	x	x	x			x	
Normal conducting RF											x	x								x		
Superconducting RF	x		x	x		x								x	x	x	x	x		x	x	
Lasers		x	x		x									x	x	x	x			x		x
Permanent Magnets			x								x			x	x	x	x	x				
Superconductive magnets						x				x		x		x	x	x	x	x				
Resistive Magnets			x			x				x	x	x								x		
Undulators			x	x																		
Energy Efficiency			x	x		x								x	x	x	x					
Linacs			x	x		x					x	x		x	x	x	x			x	x	
ERLs				x										x	x	x	x			x	x	
FFAGs										x											x	
System integration				x	x	x		x	x	x	x	x										
Targets						x				x		x	x	x	x	x	x	x				
Vacuum	x	x	x			x				x	x	x	x	x	x	x	x	x		x		x
Surface Science	x	x	x			x								x	x	x	x			x		x
Computing	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x		x	x	x
Controls						x	x	x	x	x	x	x		x	x	x	x					
Front End				x	x	x					x	x									x	
Wakefields		x	x	x																	x	x
Skills/retention/training/development	x	x	x		x	x	x	x		x	x		x	x	x	x	x	x	x	x	x	x

commission and operate all machines. This is an underpinning capability for the design of all future facilities and the maintenance and enhancement of UK expertise in this area is essential;

- **Diagnostics:** are essential for the commissioning and operation of all accelerators; to measure beam parameters, to diagnose faults and to optimise the beam;
- **RF systems, including SCRF:** both design and engineering aspects are crucial both for acceleration and for beam control in, for example, crab cavities; and
- **Particle production targets:** is a key requirement, and again a UK strength. Expertise in this area can also be applied to collimators which are mandatory in all high power and high energy machines;

In nuclear science, a similarly large range of capabilities is necessary to enable world-leading international facilities (see table). In recent decades, the direct involvement of the UK accelerator science community in nuclear projects has been limited (the one major exception being the ELI-NP programme where STFC was contracted to build the electron linac). The nuclear community gains access to international facilities mainly through leading developments of particle detectors, data acquisition systems and data analysis infrastructure for these facilities. UK leadership in beam developments (e.g. the polarised gamma beams at MAMI and JLAB) have been carried out by University based nuclear scientists. However, the next generation nuclear physics facilities, particularly the EIC, have synergies with existing accelerator R&D directions in the UK.

2b. Please comment on the current UK position of each enabling technology/capability in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and/or capacity be exploited?**

The requirements matrix shows what is needed, and the UK is strong in many of these areas.

- Particle-beam dynamics: The UK is blessed with a strong beam-dynamics community, world-leading in places, which should be exploited to the full in current and future projects. This is located in both the national labs and the universities. There is strong support for HL-LHC and CLIC within this UK community through CLIC-UK and HL-LHC-UK. This broad base of skills and experience should position the UK well for future frontier machines and should be exploited. As stated in Q2a, diagnostics are crucial to machine operation. The UK is strong, particularly in the institutes and this should be exploited in future projects.
- RF resonators and power engineering: Expertise in RF cavities and RF power is strong in the UK, with particular UK expertise in cavity design and cryo-module design. There is strong support for HL-LHC and CLIC with the UK community. The UK has an excellent track record in lasers and active international project participation and leadership.
- Magnets: The UK has a strong track record in the exploitation of permanent-magnet technology located in the national labs, with large contributions to past and proposed future projects. This is a national resource that is broad and should be supported. Super-conducting magnets are important for high-field projects such as the FCC. There is some UK knowledge but the development of super- conducting-magnet expertise beyond its current level would bring benefits in terms of increased opportunities to benefit from accelerator-facility projects in the future. The UK has world-leading expertise in undulators in the national labs, with experience of design and construction for several international projects. For example, the UK has led the undulator for various linear-collider incarnations.
- Linac design: The UK has strong expertise in linac design, in universities and in industry, which is exploited at the current time. Expansion in this area would be beneficial, in part to the cross-over to and associated benefits to application areas. Linked to linacs are energy recovery linacs (ERLs). The UK is a key player in ERLs, after the success of ALICE and is a recognised international expert in the field. ERL technology underpins a number of future particle physics (LHeC) and nuclear physics facilities (e.g. JLAB, EIC, MESA) currently being developed or planned.
- FFAGs: The UK is prominent in the development of fixed field alternating gradient accelerators (FFAGs) having successfully delivered EMMA and with several groups across the UK active in FFAG development. This should be supported and exploited, with the proven application of FFAGs to the intensity frontier (e.g. PRISM), to accelerator applications (e.g. medical) and proposed for ISIS II.
- Collimators: The UK is world leading in targets and collimators, with crucial leadership of many international projects. This is particularly strong in the national labs, where the High Power Targets Group (RAL/TD) is exceptional. There is strong support for HL-LHC and CLIC with this UK community. Daresbury laboratory has leading expertise in providing thin, isotopically pure targets for nuclear science.
- Short lived hadron beams: UK university groups have a lead in international projects aiming to develop a new generation of secondary unstable hadron beams, generated from intense electron beams (e.g. JLAB).
- Computing: The UK has a strong computing heritage, from the experimental particle physics Grid support to the Hartree Centre. This is currently exploited by the frontier machine community and should be supported.

3. Map the necessary enabling technologies/ capabilities required for activities within this theme against accelerator activities within the other accelerator themes.

There are clear and direct synergies of the CLIC-UK technology capabilities with the light sources theme, for both storage rings (Diamond) and linac-based sources (CLARA, UK-XFEL):

- Beam dynamics
- Beam instrumentation systems
- Beam feedback, feed-forward and control systems
- Undulators and advanced magnet design
- High-gradient normal conducting accelerating cavities (for CLARA and a UK XFEL).

There are also synergies with the novel accelerators theme:

- Beam dynamics, instrumentation, and control for improving beam quality in plasma-wakefield accelerators;

and with the applications theme:

- High-gradient CLIC-style RF cavities for compact accelerators for medical (eg. high-energy electron therapy), security (eg. X-ray cargo scanning) and industrial (eg. X-ray sterilisation) applications.
- Novel beam collimation and targets.

There are also synergies with the light source theme, through:

- Electron lattice beam dynamics and optics e.g. FCC-ee;
- High performance diagnostics.

4a. What skills, experience and leadership is necessary to achieve each accelerator science and technology activity?

The accelerator activities listed in matrix 1a require the technology capabilities listed in matrix 2a along with the commensurate skills base.

4b.Please comment on the current UK position regarding the necessary skills, experience, leadership and capacity in the international context.

In broad terms the UK possesses a skills base, via ASTeC, the John Adams and Cockcroft Institutes, the STFC accelerator facilities (Diamond, ISIS, CLF etc.) and the other university-based accelerator R&D groups, in all of these technology areas. However, it is generally difficult to attract and retain experienced staff in most of the technology areas, and this is true of the STFC laboratories, the universities and companies.

Through its current and former domestic facilities the UK has significant experience of building and operating both large-scale electron (SRS, Diamond) and proton (NIMROD, ISIS) accelerators as well as R&D facilities (eg. EMMA, VELA, CLARA, MICE, FETS) and this gives us the capacity to play significant roles in developing frontier electron- and proton-based accelerators in collaboration with international partners. The UK exercises overall PI leadership in linear collider (CLIC, ILC) and electron-hadron collider design, and MICE, as well as system PI leadership in aspects of the HiLumiLHC project and the FCC design. Via the John Adams and Cockcroft Institutes the UK's capacity for formally training accelerator physicists has increased from almost zero 15 years ago to a situation whereby the UK is now an international leader. However, greater investment in underpinning skills training for accelerator technicians and engineers would balance the accelerator physicist skills capability and almost certainly enhance the supply of relevant skilled personnel for UK industry.

It is generally agreed that, despite pockets of excellence in eg. magnet and RF device manufacturing, the UK does not possess a significant, coherent accelerator supply industrial capability. In tandem with the skills training just mentioned, this is an area that would benefit from a more strategic government approach to investment towards building industrial capability.

5. What are the milestones, timescales and indicative costs for pursuing each accelerator science and technology activity?

Energy-frontier facilities:
It is not possible to give exact dates or milestones for the next frontier facility. Below we give best estimates based on current knowledge.

HL-LHC:
- HiLumi-UK design project ends 2020
- HL-LHC construction ends 2025
- HL-LHC runs 2026 – 2037

ILC:
Japan statement on ILC (ahead of European Strategy update) ~2018
- ILC pre-preparatory phase: until 2020
- ILC preparatory phase ~ 2020 - 2025

- If approved, ILC construction 2026-35

CLIC:
- CLIC-UK design project ends April 2020
- Ongoing CLIC preparatory phase, pending a project decision, 2020-2025
- If approved, CLIC first-stage construction 2026-35

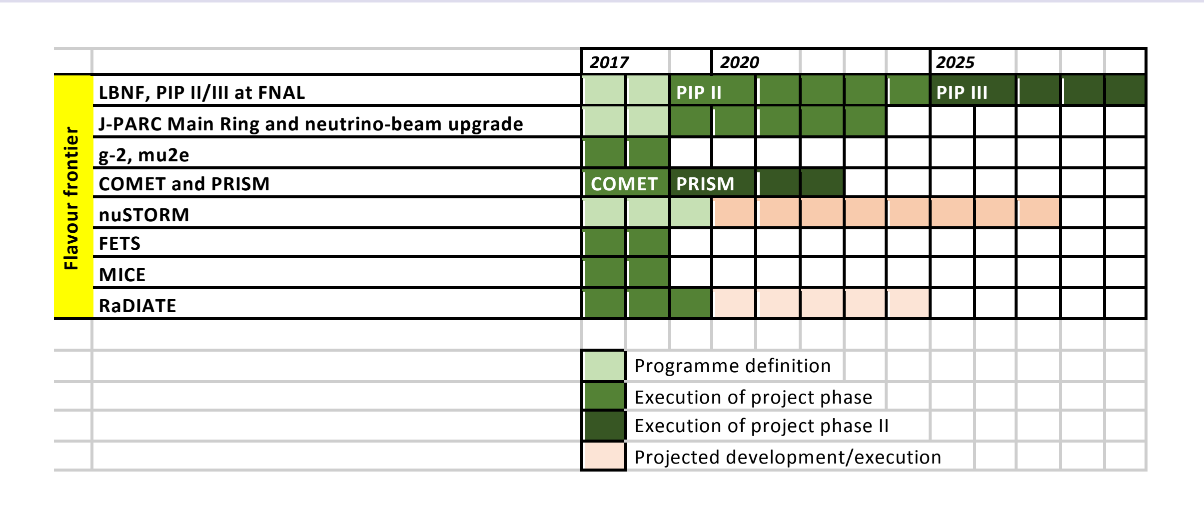
FCC/HiE-LHC:
EuroCirCol ends in time for the European strategy update.
- Enter a TDR phase until 2026.
- FCC-hh civil would start in the late 2020s.

A HE-LHC option would start in mid 2030s

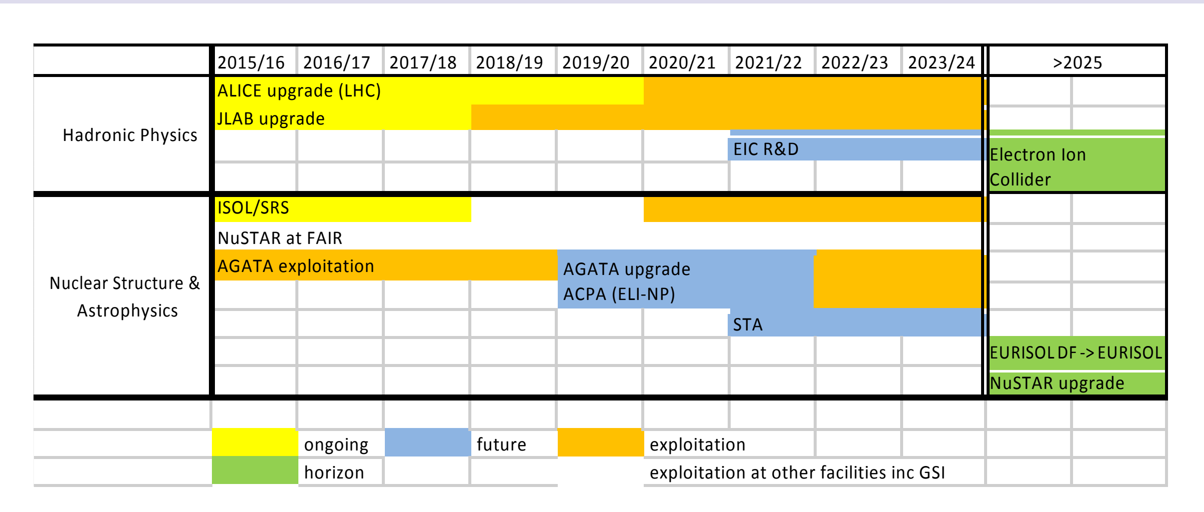
There is a strong degree of correlation between the possible outcomes above. For example, if Japan decides to proceed with ILC, and Europe participates, it seems unlikely that CLIC would proceed in Europe. Were ILC not to proceed, it is possible that Europe could proceed with CLIC. Were CEPC to proceed as a large circular accelerator facility in China it is possible that FCC would not proceed in Europe. Were there a good physics case, HiE-LHC could proceed in Europe, in which case FCC would presumably not proceed on the same timescale.

Whatever the scenario, the UK should position itself to make a major contribution to the facility that is realised. An in-kind contribution, based on UK expertise and capabilities, and subject to agreement

Flavour-frontier facilities:



Nuclear-physics facilities:



with international partners, would, for example, sensibly be at the level required to build a major system. To take one example, for the ILC/CLIC beam delivery system the cost magnitude is £100-£200M spread over a ten- year construction period. This scale is comparable with the UK contribution to ESS.

6a. Map each accelerator science and technology activity and enabling technology/ capability against potential impacts to:

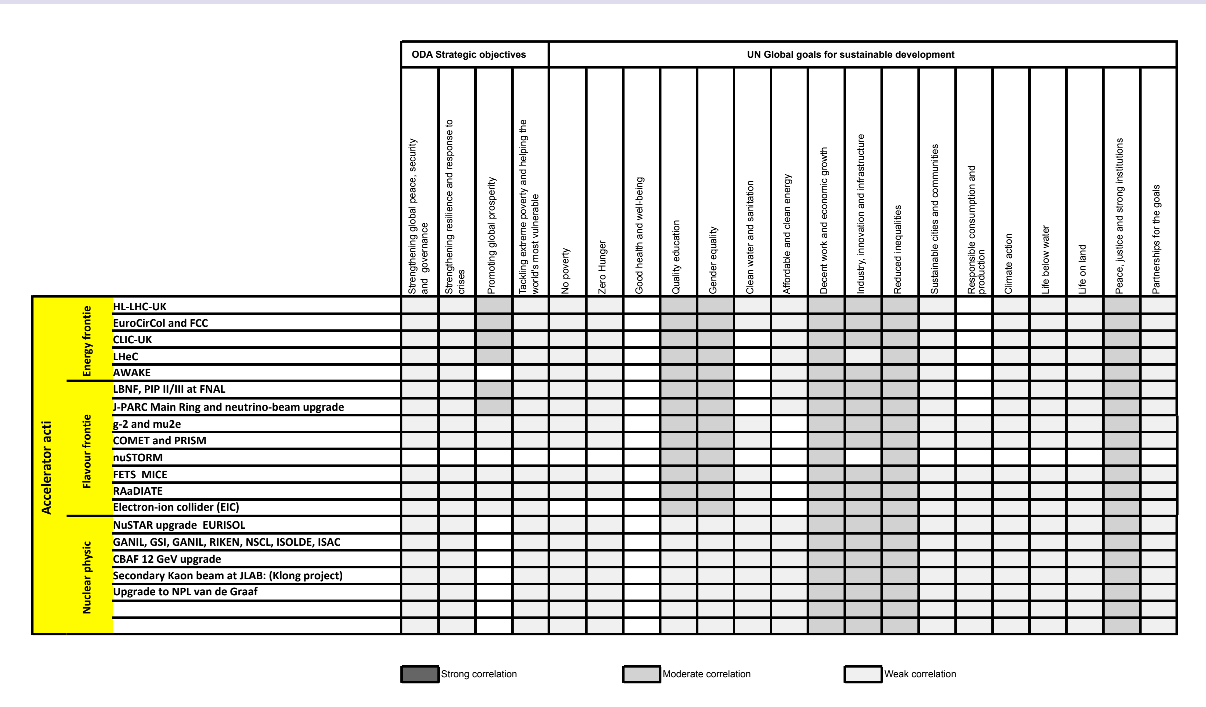
i. ODA Strategic Objectives[1,2]

1 ODA Strategic Objectives: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/478834/ODA_strategy_final_web_0905.pdf
2 UN Global Goals: http://www.globalgoals.org/

The matrix above shows the mapping of Frontier activities to the ODA strategic objectives. The nature of Frontier activities is such that the applicability of the activities to the objectives is often indirect, through spin-offs and other innovation activities.

The broad base of the UK programme does mean it can meet objectives in several areas. The following areas may be the highest rated candidates for funding:

- **Good health and well-being:** This objective is stimulated by developments in novel accelerators and magnets with direct application to the delivery of therapeutic/diagnostic beams and the production of radioisotopes. For example PRISM developments have a direct application in the use of FFAGs for proton therapy and high field magnets for medical devices.
- **Clean water:** This advances in high-gradient linacs at the energy frontier can be used for water purification.
- **Industry, innovation and infrastructure:** STFC is very active in promoting industry and innovation through IPSs and spin-outs. For example, novel diagnostics in an industrial setting.
- Generic capacity building is done through the general infrastructure development in this sector.



ii. Industrial Strategy Pillars[3]

3 Industrial Strategy Pillars: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/611705/building-our-industrial-strategy-green-paper.pdf

Accelerator activ			Industrial Strategy Pillars									
			Investing in science, research and innovation	Developing Skills	Upgrading infrastructure	Supporting businesses to start and grow	Improving procurement	Encouraging trade and inward investment	Delivering affordable energy and clean growth	Cultivating world-leading sectors	Driving growth across the whole country	Creating the right institutions to bring together sectors and places
Accelerator activ	Energy frontier	HL-LHC-UK	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		EuroCirCol and FCC	Strong	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		CLIC-UK	Strong	Strong	Moderate	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		LHeC	Strong	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		AWAKE	Strong	Strong	Weak	Weak	Weak	Weak	Weak	Moderate	Weak	Weak
	Flavour frontier	LBNF, PIP II/III at FNAL	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		J-PARC Main Ring and neutrino-beam upgrade	Strong	Strong	Strong	Weak	Weak	Weak	Weak	Strong	Weak	Moderate
		g-2 and mu2e	Strong	Moderate	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		COMET and PRISM	Strong	Moderate	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		nuSTORM	Strong	Strong								
		FETS	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		MICE	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		RaDIATE	Strong	Strong	Weak	Weak	Weak	Weak	Weak	Strong	Weak	Weak
	Nuclear physics	Electron-ion collider (EIC)	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		NuSTAR upgrade EURISOL	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		GANIL, GSI, GANIL, RIKEN, NSCL, ISOLDE, ISAC	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		CBAF 12 GeV upgrade	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak	Weak
		Secondary Kaon beam at JLAB: (Klong project)	Strong	Strong	Strong	Moderate	Weak	Weak	Weak	Strong	Weak	Strong
		Upgrade to NPL van de Graaf	Strong	Strong	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak
			Strong	Moderate	Strong	Weak	Weak	Weak	Weak	Weak	Weak	Weak

Strong correlation | Moderate correlation | Weak correlation

iii. Other industrial applications and spin-out opportunities

The Industrial Challenge Fund gives the STFC an opportunity to enhance investment in the schemes it has promoted to enhance industrial engagement, produce spin-out companies and to license IP. These schemes such include the Industrial Partnership Scheme (IPS), Challenge-led Applied Systems Programme and Proof of Concept fund (PoC).

We recommend the STFC considers enhanced investment in these areas funded by attracting additional resources from the Industrial Challenge Fund.

6b. How could STFC support the development of the potential impacts identified?

The support given by STFC is going a long way to developing these activities through the main programme.

7a. In a reduced funding environment, which accelerator activities would you prioritise within this theme?

- **What is the minimum activity level required to keep skills alive within this theme over the next 15-20 years?**
- **What are the wider impacts of maintaining skills within this theme?**

Energy-frontier facilities:
The frontier roadmap has four key elements:

- Delivery of UK contributions to HL-LHC over the next 5-8 years;
- Preparation for a major contribution to a possible linear e+e- collider: ILC (Japan) or CLIC (CERN) with an R&D phase progressing until 2020, a preparatory phase ~ 2020 – 2025 and a construction start beyond 2025;
- Preparation for a future large circular collider: FCC / HiE-LHC to be realised as a post-LHC project at CERN, with an R&D phase progressing until 2020, a preparatory phase ~ 2020 – 2025 and a construction start beyond 2025; and
- Monitoring and preparing to capitalise on opportunities for UK contributions to construction of other overseas facilities such as accelerator-based neutrino sources at FNAL and/or JPARC, CEPC (China), as well as potential opportunities for the UK to contribute to an electron-ion collider in the USA.

Maintaining UK capability, and indeed credibility, to contribute to frontier accelerators over the next 15-20 years requires support at a critical-mass level for HL-LHC, and for both ILC/CLIC and FCC/HiE-LHC until the direction for the next energy-frontier facility becomes clear, which is possibly no sooner than ~2025.

There is a strong and direct synergy between the UK's work on e+e- linear colliders and a future UK XFEL, which will be based on very similar RF accelerating technology as ILC (superconducting) or CLIC (normal conducting, high gradient) and which requires state-of-the-art magnets, beam monitoring, and beam control, all of which are key strengths underpinned by the UK linear collider R&D programme (CLIC-UK).

Flavour-frontier facilities:
Accelerator-science priorities for the flavour-frontier facilities are:

- In the light of the Governments investment of £65M in the LBNF/DUNE programme:
  - o Execution of an accelerator R&D programme that will culminate in the delivering of substantial components of PIP II and the pion production target; and
  - o Involvement in the conceptual and detailed design of PIP III, thereby enhancing the UK's expertise and capabilities in the design of novel high-power accelerators.
- To enhance the UK's influence on the T2K-II and Hyper-K programmes, to maintain and enhance the UK's beam-optics and beam-diagnostics capabilities and to provide a training ground in neutrino beam-line commissioning and optimisation:
  - o Contribute to the mitigation of beam-loss in the J-PARC Main Ring through simulation and contribute to the development of enhanced instrumentation for the Main Ring and/or the extracted proton beam line.
- Successfully complete the FETS and MICE programmes.
- Build on the UK's investment in MICE by engaging effectively with the study of nuSTORM in the Physics Beyond Colliders Study Group with a view to establishing the case for nuSTORM as a future option for CERN. Investment beyond the present feasibility-study phase is contingent on the outcome of the European Strategy Update.

Nuclear-physics facilities:
At present accelerator R&D in support of the nuclear-physics programme is restricted to small activities in support of specific programmes. The opportunity for investment identified during the consultation period of the present review is the possible investment in the Electron Ion Collider following the CD0 review in the US.

7b. In an environment of increased funding, what additional activities, enabling technologies/ capabilities - or enhancements to activities, enabling technologies/capabilities already specified - would it be desirable to pursue?

- **What aspirations exist for investment into nascent areas of research?**
- **How could current, planned or proposed activities be enhanced?**

In a scenario of increased funding, in addition to the above activities, which could be bolstered to enhance UK visibility, impact, and industrial supply opportunity, one or more of the additional opportunities could also be pursued with a critical-mass effort. For example, a contribution to an electron-ion collider could establish UK credibility in an aspect of nuclear physics accelerators, as well as allow strengthened collaboration with JLAB or BNL.

References

1 The PPAP, "Update to the UK Particle Physics Roadmap", https://www.stfc.ac.uk/stfc/includes/themes/MuraSTFC/assets/legacy/2415_res_2.pdf
2 STFC Science Board, "Balance of Programme Exercise—PPAN", http://www.stfc.ac.uk/about-us/our-purpose-and-priorities/planning- and-strategy/programme-evaluation/balance-of-programme-exercise-ppan/
3 http://awake.web.cern.ch/awake/
4 http://lbnf.fnal.gov
5 http://www.dunescience.org
6 http://pip2.fnal.gov/index.html
7 http://pip3.fnal.gov
8 J-PARC u/g
9 http://muon-g-2.fnal.gov
10 https://mu2e.fnal.gov
11 http://comet.kek.jp/Introduction.html
12 PRISM/PRIME, "A Letter of Intent on Nuclear and Particle Physics Experiments at the J-PARC 50 GeV Proton Synchrotron", http://j- parc.jp/researcher/Hadron/en/pac_0606/pdf/p20-Kuno.pdf
13 nuSTORM, "nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC", https://arxiv.org/abs/1308.6822
14 FETS
15 http://mice.iit.edu
16 https://radiate.fnal.gov

Industrial, Medical, Defence and Security Applications

Executive Summary

It is a welcome development to see an accelerator applications theme roadmap forming part of the input into the STFC Accelerator Strategic Review process. This is an indication of the growing importance of accelerator applications in realising the full scientific, societal and economic impact of STFC-funded programmes, and reflects the now-numerous applied schemes that STFC supports. To understand how the accelerator applications theme can contribute in taking the STFC Accelerator Strategy forward, it needs to be clear what motivates STFC's funding of application-driven science and technology research, and what outcomes it seeks to achieve. These drivers may include:

- Societal impact (e.g. improved healthcare outcomes in oncology)
- Economic impact (e.g. increased market share for UK companies)
- Revenue generation (e.g. through IP licensing, to support STFC core facilities)
- Broadening of the UK science funding base (e.g. Global Challenge Research Fund)
- Reputation enhancement through scientific discovery and innovation
- Development of technology solutions of direct benefit to STFC national laboratory programmes
- Improved Government funding outcomes through impact demonstration

This roadmap aims to provide an overview of the current and future landscape which, combined with an executive-level determination of the relative priorities, can then be used to inform the Accelerator Strategy. For clarity, this roadmap specifically does not consider the prolific applications, technologies and innovations enabled by experiments conducted within the user stations of the large-scale accelerator facilities such as ISIS and Diamond Light Source; it considers only applications which can be influenced by the STFC accelerator R&D spend.

The development of STFC's strategy for applications in accelerator science and technology has historically been driven mostly at departmental level, and often in reaction to opportunities brought in from external sources. The influence of active sector development or horizon scanning has been limited. Moving forward, the strategy for applications should be driven principally by societal requirements and industrial needs, and the organisation needs to be adaptable, flexible and well-resourced in order to best match these external drivers.

The role of industry is critical to realising the full scientific, societal and economic impact of accelerator developments. Industry's key drivers may differ substantially (e.g. prompt return on investment, reliability and maintenance requirements, suitability for cost-effective production) to those typical for national research organisations, and STFC needs to be considerate of these issues in order to partner effectively. However, STFC is already well placed to act as neutral territory for academia, multiple industries and national laboratories to act together for the benefit of the UK. Accelerator applications are, by their nature, multi-disciplinary and together industry, academia and the national laboratories are able to provide research and technology outcomes that cannot be achieved elsewhere.

STFC provides funding for application and industrially focussed activities through proof-of-concept and innovation funding (mainly for the purposes of transferring STFC knowledge and technology into industry). It also provides business development manpower resource through the Business and Innovations Directorate. STFC has seen growth in the application of its particle accelerator technologies and expertise, and wishes to further expand its impact in this theme.

STFC should aim to be recognised as the first place of call for industry wishing to access accelerator knowledge, technology, facilities and collaboration in the UK, in much the same way as for example the Fraunhofer model works closely with industry in Germany. This goal could be assisted through high-visibility promotion of case studies and current activities, and through the rebranding or reconfiguring of existing facilities, infrastructure and expertise as a centre-of-excellence for accelerator applications. This could be focused on the basis of thematic area (e.g. health) or industrial need (e.g. high reliability, low cost) to clearly communicate the role and benefits to industry and encourage inward investment.

In some cases, STFC's facilities and expertise will be of pivotal help to industrial and academic users if supported. Increased activity to further streamline access and clearly illustrate the benefits of accelerator science and technology to academic researchers and industry representatives will be strongly beneficial, but STFC will need to be able to fully provide appropriate staff resources and support in order to successfully conduct trials on industry-relevant timescales.

Whilst priority areas for activities, technology and skills development should be driven by societal needs and industry requirements, STFC should consider enhanced seed funding in topical, high impact areas where industrial funding can be leveraged. STFC should also consider forming formal links with organisations and bodies with significant interest in accelerator applications (e.g. BNMS, NHS, AWE, NNL) to help guide future strategic planning.

a. Map current, planned and proposed accelerator science and technology activities within this theme against the science priorities (supported by STFC) they will enable over the next:

i. 1-5 years

Table 1. Key application areas for particle accelerators mapped against STFC strategic priorities.

Science and Technology Application			STFC Science Priorities										Timescales		
			Support areas of UK scientific leadership	Develop the STFC campuses as national focal points for collaboration, innovation and skills	Reflect the needs of the Research Councils, Universities and Innovate UK	Deliver high impact in the Global Challenge areas	Develop ideas with commercial potential	Fully exploit the synergies between the different branches of our science and technology programmes	Inspire training, STEM development and public awareness	Maintain core national skills and capabilities to support future STFC science	Complementing rather than duplicating what others provide	Provide access to world class facilities	i. 1-5 years	ii. 5-10 years	iii. 10-20 years
	Industrial	keV electron beams		X	X	X		X	X			X	X	X	X
		MeV electron beams	X	X	X	X	X	X	X	X	X	X	X	X	X
		Ion beams		X	X			X	X				X	X	X
	Health	X-ray radiotherapy	X	X	X	X		X	X	X		X	X	X	X
		Proton therapy	X	X	X	X	X	X	X	X	X	X	X	X	X
		Particle therapy	X	X	X	X	X	X	X	X	X	X	?	X	X
		Radioisotope production		X	X	X		X	X	?			?	X	X
	Security	X-ray imaging	X	X	X	X	X	X	X	X	X	X	X	X	X
		Nuclear security		X	X	X	X	X	X		X	X	?	X	X
	Energy and Environmental	ADSR		X	X			X	X	X	X	X			X
		Transmutation		X	X	X		X	X	X	X				X
		Nuclear fusion - material testing		X	X	X		X	X	X			?	X	X
		Water treatment	X	X	X	X	X	X	X	X	X	X	X	X	X
		Flue gas	X	X	X	X	X	X	X	X	X	X	X	X	X
		Sludge treatment	X	X	X	X	X	X	X	X	X	X	X	X	X
		Agri-tech		X	X	X	X	X	X	X	X	X		X	X

The list of suitable applications is principally derived from the EuCARD-2 'Applications of Particle Accelerators in Europe' (APAE) report[i] and the 'Accelerators for America's Future' report (U.S. DoE)[ii], since these provide comprehensive overviews of the current state-of-the-art and future perspectives.

Industrial

The use of accelerators in industrial and manufacturing environments is becoming increasingly widespread, the technology often superseding thermal and UV light-based technologies. Systems with electron beam energies below 350 keV are typically used in mass manufacture applications such as the surface sterilisation of medical devices, ink curing for food packaging, the bonding of surface finishes to laminated wood products and the sterilisation of dry foodstuffs and spices. Beams of this energy range are also used in high precision manufacturing techniques such as e-beam welding, structuring, hardening and drilling.

Higher-energy electron beam systems, typically between 350 keV and a few MeV, can be used to shrink cable insulation, sterilise bulk medical materials, pre-vulcanise tyre components and alter the coloration of gemstones. The accelerator systems required for these industrial-scale processes often require large beam sizes (which can be greater than 1 m^2 in some applications), high duty cycles and minimal scheduled maintenance; qualities that can be in marked contrast to the requirements for national laboratory-scale scientific research instruments. Conventional and novel accelerator systems may also be applied to radiation hardness assurance, particularly for the space sector.

A number of industrial applications have been proposed for very high-energy (hundreds of MeV) accelerator-driven free-electron lasers (FELs), most notably as a source of extreme ultraviolet light for the lithographic production of semiconductor devices.

Another significant area of accelerator exploitation is the in use of ion beams, specifically for ion-beam analysis (IBA), which allows the comprehensive chemical and structural characterisation of surfaces. IBA techniques such as Rutherford Backscattering (RBS) are used extensively in heritage science to help characterise and date significant historical artefacts, whilst Particle-Induced X-ray Emission (PIXE) is commonly used to monitor air pollution.

In most application areas of electron or similar beams, commercial options already exist. However, many of the basic technology requirements and testing platforms are shared with research-type systems (e.g. vacuum surface treatment, magnetic field measurement), suggesting that more opportunities for technology co-development exist in this area than are currently exploited.

Opportunities for 1-5 years:

- Two-way technology transfer between R&D electron accelerators and OEM commercial system suppliers.

Health

Particle accelerators have been used in the treatment of cancer tumours (oncology) and other diseases for many decades. The use of c.10-20 MeV electron linacs in X-ray radiotherapy systems is well established and an extensive commercial marketplace exists to support their application to oncology, which in the UK amounts to over 300 linacs in operation today. Whilst there is innovation in the sector, this is principally concentrated on the development of simultaneous enhanced imaging capabilities (including dynamic measurements using magnetic resonance imaging) and accurate dose detection. Whilst the healthcare market will readily make use of advances in linac technologies regarding manufacturing techniques or efficiency enhancement, the accelerator itself constitutes a relatively small element of the overall cost and complexity of a typical treatment suite. In addition, stringent medical testing protocols strongly favour existing solutions unless a significant patient outcome improvement can be demonstrated. The X-ray radiotherapy market is therefore likely to see incremental system developments, with the market well catered for by commercial suppliers.

A major growth area in health applications of accelerators is in proton therapy. Due to the depth profile of their dose delivery in tissue, proton beams can achieve better patient outcomes in many types of treatment. The use of proton beams for oncology is not yet seen as a widespread replacement for X-ray radiotherapy, but is likely to become the method of choice for certain more complex cancers including brain, spinal and some paediatric treatments. The

i EuCARD-2, Applications of Particle Accelerators in Europe (APAE)
ii US DoE, Accelerators for America's Future

accelerators required are significantly more complex and costly than for X-ray treatment (translating presently to a per-patient cost for proton therapy that is at least twice the c.£10k cost for X-ray therapy) and employ technologies and skills different to those needed for X-ray machine manufacture. The opportunity therefore exists for significant STFC contributions in this area, including developments in functional imaging.

Further opportunities in oncology lie in the use of either ions or Very High Energy Electrons (VHEE) for treatment, the latter employing high accelerating gradient technologies developed for large-scale research accelerators to deliver proton-like patient benefits using a machine with cost and complexity lying somewhere between that of existing X-ray and proton machines. Whilst VHEE has never really been used for patient treatments, ion therapy has been utilised for decades but as yet not really commercialised due to the present much greater capital and operating cost of a suitable facility. Ion therapy is available in several European countries but not presently offered in the UK; helium therapy may be a suitable next step. In both ion and VHEE modalities there are numerous areas to which STFC-funded expertise could be put.

Another significant area of accelerator application is in the production of radioactive isotopes for use in patient imaging. Commercial isotope production principally of ^{18}F is today achieved with high-current (hundreds of μA), low-energy (<20 MeV) proton cyclotrons of mature design obtained from a number of suppliers; alternative routes include electrostatic and plasma-based methods. STFC-funded research could contribute not only to ^{18}F (for example, use of compact novel accelerators to allow local per-dose production) but also to production of other isotopes, but there has not yet been commercial exploitation. In contrast, over 80 percent of nuclear medicine relies on reactor-derived ^{99m}Tc where there is an ongoing risk to supply. Research in the US and Canada has made cyclotron production feasible, and in the UK policy has so far been to rely on the market to maintain supply. STFC may contribute in developing accelerator and target solutions for these and alternative isotopes.

Opportunities for 1-5 years:

- X-ray radiotherapy linacs – enhanced manufacturing techniques and efficiency
- Proton therapy – Design, test and validation services for OEM suppliers
- VHEE – Development of technology towards clinical validation
- Radio-isotopes - Design of compact particle sources for radio-isotope production.

Security and Defence

Accelerator-based systems are already used extensively for threat detection and duty compliance at coastal docks, airports and border crossings. STFC has significant experience in the development of technologies and validation facilities relevant to security applications, and border-security applications in particular.

There is a pressing industry need to make the next-generation of security systems – based on electron linacs – smaller and lighter whilst retaining beam performance. The resultant reduction in shielding requirements due to the smaller footprint may have a significant impact on the overall system cost. The second area of development is in enhancing image quality. Developments in higher repetition rates, image stability, fast energy switching and 3D data reconstruction will help to significantly improve scanning and detection rates.

A potential area for accelerator-based systems to make a significant impact is in nuclear materials detection, particularly the use of nuclear resonance fluorescence (NRF) and muon tomography to identify nuclear material for border control, anti-terrorism or nuclear material storage applications. NRF is more commonly used to detect nitrogen isotopes in explosives, an application that requires the high energies and dose rates currently provided by rhodotrons. Muon tomography presently utilises cosmic rays, but could in principle utilise more intense accelerator-based sources.

High pulsed power particle accelerators are also used in flash radiography, a technique used to verify the potency of nuclear deterrents whilst avoiding the need for full-scale warhead tests.

Opportunities for 1-5 years:

- Compact X-ray systems for overall system cost reduction

- Time-of-flight Compton Scatter Imaging for 3-D image reconstruction
- Design of compact narrowband systems for stand-off nuclear resonance fluorescence and other imaging applications

Energy and Environmental

Particle accelerators have a number of potential application areas within the energy sector. Accelerator-driven subcritical reactors (ADSRs) have been proposed both for the transmutation of nuclear waste and to allow more flexible fuel composition in future advanced reactors; some proposed designs include breeding of ^{233}U from ^{232}Th to extend the usefulness of fission fuels into the far future. Most ADSR designs required the use of a high-current (c. 10mA) 1 GeV proton driver (probably quasi-CW) to generate excess neutrons in a reactor core, and STFC-funded research toward both FFAGs (the EMMA, PAMELA and NORMA projects) and linacs (ESS and ISIS-II linac designs) could be applied to future ADS systems, where high current and operational reliability are the key challenges. The first application of ADSR will likely be the Belgian MYRRHA transmutation project

Intense accelerator sources of neutrons are also proposed as a testbed for the materials and construction methods required to support the development of nuclear fusion reactors such as ITER. The International Fusion Materials Irradiation Facility (IFMIF) is designed to replicate the neutron irradiation spectrum expected in a future fusion reactor such as ITER, and STFC-funded researchers have engaged both in this project and in studies of nearer-term proposed alternatives such as the Culham-led FAFNIR proposal.

Accelerators have a significant potential role to play in environmental science. The application of electron beams to water, sewage, and flue gas treatment that eliminates biological activity and breaks down larger organic molecules for subsequent filtration has been established at pilot-plant scale in several locations including in South Korea and in Poland. There is demand for both large-scale municipal systems for bulk treatment and smaller-mobile units to potentially deal with environmental spillage and localised remediation. Electron beams can also be used to enhance the efficiency of biogas production from biomass.

In the agri-tech sector, particle accelerators have been used to remove pathogens from the surface of seeds prior to planting, and this technology has been commercialised by the Fraunhofer in Germany. There are development programmes to extend this concept to the enhancement of soil to improve crop yield.

Opportunities for 1-5 years:

- Engagement in design of intense neutron sources for ADS and fusion irradiation applications
- Environmental remediation systems - validation and optimisation

ii. 5-10 years
Opportunities:

Industrial

- Widespread replacement of thermal and UV-light processes with electron beam sources
- Development of FEL-based EUV light sources for the semiconductor industry

Health

- Turn-key solutions for proton therapy and associated technologies (engagement with clinical and industrial partners); two NHS centres will provide suitable facilities for research (particularly Christie)
- Novel accelerator source development at Imperial, Manchester, QUB and Strathclyde
- Source development for future helium-ion or other ion treatment facility; many European collaborative partners
- VHEE – source development for future treatment demonstrator, likely with commercial partner. Governed by demonstration of clinical usefulness. Some VHEE techniques may be demonstrable at CLARA facility and using the Strathclyde plasma infrastructure.

Security and Defence

- X-ray systems for high resolution nuclear resonance fluorescence, and compact sources for tuneable gamma ray production
- Application of compact electron linac designs to commercial products

Energy and Environmental

- Water, sludge and flue treatment development systems with improved wall-plug efficiency. Pace of development will be driven by legislation (this may be a minor-interest activity in the short term but a critical societal impact opportunity over an extended timescale).
- Investigation of viability of soil remediation by medium energy electron beams

iii. 10-20 years
Opportunities:

Health

- Industrialisation of improved sources and methods for proton therapy
- Industrialisation of ion therapy and VHEE solutions
- Novel accelerator methods for radioisotope production, e.g. plasmas-based sources

Security and Defence

- Development of ultra-compact, low energy systems for bomb disposal imaging

Energy and Environmental

- Move towards proof-of-concept demonstration for ADSR and waste transmutation
- Serious engagement with the international fusion irradiation campaign
- Water, sludge and flue-gas economically viable at municipal-scale

1b. Please comment on the current UK position of each accelerator science and technology activity in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and capacity be exploited**

STFC-funded researchers are currently active in many of the identified application areas. STFC's expansion into specific application areas has hitherto been driven by synergistic technology developments of benefit to the development of STFC's large-scale facilities for scientific research and exploitation. Historically, this has relied on a relatively small number of significant interactions with a mix of academic and industry partners. This model has later expanded to cover a wider range of interactions enabled through the integration of business development activities within the STFC departmental structures.

STFC's accelerator application activities are not aimed toward mass production and have avoided direct competition with commercial service providers, accelerator systems manufacturers and integrators. However there are common manufacturing processes between scientific accelerators and industrial and medical accelerators. Having a strong industrial base can benefit all sides especially if it help maintain a critical mass in the very specialist supply chain.

STFC-funded researchers have been significantly involved in a number of pan-European initiatives to coordinate application activities, and to make test facilities and equipment more readily available to academic and industrial researchers across all application sectors. These activities include the research networks CARE, EuCARD, TIARA, EuCARD-2, AMICI and ARIES.

Industrial

Whilst often viewed as 'disruptive technologies' within their market sectors, the potential scale of their applications has led to the commercial development of robust, maintainable, integrated systems suitable for manufacturing environments. The majority of manufacturers of such systems are based outside of the UK, such as ebeam/COMET in Switzerland and SCIAKY in the US. The UK is active, but not world leading, in this sector.

Expertise in low-energy electron beams mainly lies within the commercial sector. Potential end users of the technologies engage with these technologies through direct contact with equipment suppliers or through bodies such as STFC, the Knowledge Transfer Network (KTN), the High Value Manufacturing Catapults, or the Manufacturing Technology Centre (MTC). STFC is expanding its influence in this sector through development programmes with suppliers (e.g. ebeam/COMET, Shakespeare Engineering) or through broader collaborative partnerships with industry-facing organisations (e.g. precision manufacture at MTC)

STFC can provide valuable design, engineering, test and validation capabilities such as the Versatile Electron Linear Accelerator (VELA) facility, whose high-quality, well-understood output is suitable for optimising processing conditions and challenging applications. Once the optimal parameter range is determined, more compact and efficient concepts can be developed and validated in the Linac Test Facility (LTF).

Health

The UK has significant involvement in accelerator applications within the healthcare sector. Commercial entities in the radiotherapy market (particularly Elekta and Varian) have R&D centres, market presence or installed systems within the UK. Researchers, including those within STFC and the Accelerator Institutes, play a major role in the development of X-ray radiotherapy and proton therapy systems, and their associated diagnostic and imaging systems. These include development of compact proton therapy sources (for example, PAMELA, NORMA, PROBE and the novel accelerator programmes at Huddersfield, Imperial, QUB and CI/Strathclyde). The UK is estimated to have the second largest number of commercial radiotherapy R&D professionals employed (after the USA). China is growing strongly in this area. The NHS has commissioned two national proton therapy centres currently under construction at the Christie Hospital in Manchester and University College London Hospital (UCLH), both of which offer opportunities and facilities for collaborative research.

There are extensive links between researchers within the Cockcroft Institute and Christie Hospital, particularly aligned with the research beamline being integrated as part of the new Christie proton facility. STFC-funded researchers are also involved with some of the UK's private healthcare proton therapy providers, for example aiding the adoption of alternative technology choices such as permanent magnet quadrupoles and FFAG gantry designs. Links with companies providing proton therapy sources may also give collaborative opportunities to develop future commercial ion therapy systems.

VHEE is another area of UK interest with researchers from STFC, academia and industry having formed networks to examine technology options (both conventional and novel acceleration) and their possible clinical effectiveness.

The above, leveraged in part by world-leading programme on FFAGs, means therefore that the UK is globally competitive in the application of particle accelerators to oncology.

STFC-funded researchers have assisted the UK government in investigating solutions for the supply of technetium for medical imaging, and recommended that off-the-shelf high-current cyclotrons would provide the most suitable immediate solution if UK supply was under threat; if this becomes the case, there are significant opportunities for STFC to assist in the maintenance of UK technetium supply. Elsewhere, STFC and its funded researchers continue to investigate clinical and technical solutions for the less-commonly-used radioisotopes, for example at RAL and at Strathclyde.

Security and Defence

The UK has a significant presence in security and defence applications of accelerators across government institutions, university research groups and industry. STFC has long-established links with groups in this application area, and in particular it has a record of project delivery with Rapiscan Systems (providers of hand baggage and cargo scanning systems). These developments have included system integration of baggage scanner systems, development of ultra-compact electron beam linacs within the Linac Test Facility, and validation of Compton Scatter Imaging using the VELA accelerator facility. These developments have been in conjunction with a number of university groups including those at Lancaster, Liverpool and UCL. STFC-funded researchers and the UK as a whole have made a significant impact in the global security and defence sector.

Energy and Environment

AEA Culham is the centre of activity in UK for material testing in fusion applications, and have made use of STFC researchers to progress their development programmes – for example in developing the FAFNIR irradiation proposal as an alternative to IFMIF.

Whilst lightly funded, STFC-funded researchers have been pivotal over the last decade in discussions on the applicability of ADSR to UK future nuclear energy needs, particularly in the issues of fuel breeding and waste transmutation.

STFC have played a role in the ongoing development of accelerator systems for waste water treatment, although the current centres of expertise in this sector are Poland (academic) and South Korea (technical demonstration).

2a. What enabling accelerator technologies/ capabilities (including computing, vacuum, RF, lasers etc.) are necessary to pursue each accelerator activity?

The following sector-specific technical challenges are highlighted:

Industrial

- Low cost, high wall-plug efficiency systems
- Mobile systems for on-site demonstration
- Superconductivity may provide compact, high power solutions (e.g. CIEMAT cyclotron)

Table 2. Key technology requirements mapped against particle accelerator applications.

Key technologies (Applications Theme)	Industrial, Medical, Defence and Security Applications														
	Industrial			Health				Security		Energy and Environmental					
	keV electron beams	MeV electron beams	Ion beams	X-ray radiotherapy	Proton therapy	Particle therapy	Radioisotope production	X-ray imaging	Nuclear security	ADSR	Transmutation	Nuclear fusion - material testing	Water/sludge treatment	Flue gas	Agri-tech
Diagnostics		X		X	X	X	X	X	X	X	X	X		X	
Front end	X	X		X	X	X	X		X	X	X				
Linac	X	X		X	X	X	X	X	X	X	X	X	X	X	X
RF Sources		X		X	X	X	X	X	X	X	X	X	X	X	X
FFAGs					X	X	X			X	X				
Superconducting/permanent magnets					X	X	X			X	X	X			
Large AC magnets						X									
Energy Efficiency	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Injection/extraction					X	X	X			X	X				
Superconducting RF						X	X	X	X	X	X				
Vacuum	X	X		X	X	X	X		X	X	X				
Controls and interlocks	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Computing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Targets and moderators							X	X	X	X		X			
Skills/retention/training/development	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
System integration	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Automation (Industry 4.0)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Compact/mobile systems	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cost reduction/ value engineering	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RAMI - Reliabiliy, Availability, Maintainability, Inspectability	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Health

- Rotatable superconducting magnet systems for gantries. Superconducting magnet technology is of pivotal importance for all future proton therapy systems, and probably most future ion therapy systems
- FFAG gantry designs for proton therapy
- Better beam positioning and imaging systems
- Software integration of X-ray system control, imaging and diagnostics (e.g. OMA network activity)
- Permanent dipole and quadrupole magnets for cost reduction; this is an area where the UK is world-leading
- Improved targetry and radio-chemistry for efficient isotope production

Security and Defence

- Improved timing diagnostics for CSI time-of-flight measurements
- Compact linacs with dual energy pulses close together, to aid material discrimination
- Improved control feedback to aid scanned image stabilisation
- Narrowband X-ray systems for high resolution nuclear resonance fluorescence

Energy and Environmental

- High power, high efficiency, high reliability systems required for environmental applications with accurate dosage control

2b. Please comment on the current UK position of each enabling technology/capability in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and/or capacity be exploited?**

STFC-funded researchers has been approached by academia or industry to develop solutions to most of the requirements highlighted in question 2a. Through over 50 years of experience designing, building and operating world-class accelerator-based facilities, STFC has developed a global reputation for advanced technology capability and solutions. Current highlights of the accelerator programme include superconducting RF cavity qualification for the European Spallation Source and accelerator system assembly for ELI-NP project. STFC has acknowledged global technology leads in vacuum system design and advanced magnets, illustrated by the recent licensing of permanent quadrupole magnet technology - developed at Daresbury Laboratory - to Danfysik. The majority of STFC contributions have been either one-off production of novel accelerator systems, or the development of innovative design prototypes which have then been licensed to commercial entities.

STFC is ideally positioned to deliver on the technical challenges posed, but the manpower demands required to fully support application development need to be tensioned against those available to deliver STFC core science and facility development. STFC is increasingly making use of the expertise and resources available within Industry to co-develop technology solutions.

3. Map the necessary enabling technologies/ capabilities required for activities within this theme against accelerator activities within the other accelerator themes.

From a technology development and support standpoint, what is good for the support of national laboratory scale research facilities is also good for accelerator application activities. The extensive technology portfolio and infrastructure required for the development of STFC's research facilities acts as a key attractor for academia and industry, and its effective exploitation can help drive application development. Table 3 illustrates the broad applicability of the technical disciplines across multiple thematic areas.

Where there is a notable disparity with other themes is in the areas which could be broadly described as 'industrialisation': the differences between producing one-off or few-off items for a research-type accelerator system, and those developing

Table 3. Activities mapped against key technologies for other thematic areas.

Key technologies (Neutron Theme)	Neutron Sources								Physics Machines					
	ISIS Operations	FETS	ISIS-II	Ion Sources	IBEX	ESS	PIP-II	Integrable Optics	Neutrino factory	LBNF/DUNE	Mu2e upgrade	Muon Ionisation Cooling	HL-LHC	CLIC
Diagnostics	x	x	x	x	?	x	x	x	x	x			x	
Front end	x	x	x	x		x	x		x	x			?	
Linac	x	x	x		x	x			x	x			?	
RF Sources	x	x	x	x	x	x	x		x	x			x	
FFAGs			x		x			x	x					
Superconducting/permanent magnets	?		x				?	?	x	?		x	x	x
Large AC magnets	x		x						x					
Energy Efficiency	?		x			x	x	?	x	x	x	x	x	x
Injection/extraction	?	x	x		?			?	x				?	
Superconducting RF			x			x	x		x	x			x	x
Vacuum	x	x	x	x	x	x	x	?	x	x	x	x	x	x
Controls and interlocks	x	x	x	x	?	x	x	?	x	x	x	x	x	x
Computing	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Targets and moderators	x		x				x		x	x	x	x		
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Key technologies (Neutron Theme)	Industrial, Medical, Defence and Security Applications															Light Sources			
	keV electron beams	MeV electron beams	Ion beams	X-ray radiotherapy	Particle therapy	VHEE	Radioisotope production	X-ray imaging	Nuclear security	ADSR	Transmutation	Nuclear fusion - material testing	Water/sludge treatment	Flue gas	Agri-tech	CLARA	UK-XFEL	DLS-II	EuPRAXIA
Diagnostics		x		x	x	x	x	x	x	x	x	x		x		x	x	x	x
Front end	x	x		x	x	x	x		x	x	x					x	x	x	x
Linac	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
RF Sources		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
FFAGs					x	x	x			x	x								
Superconducting/permanent magnets					x	x	x			x	x	x				x	x	x	x
Large AC magnets						x													
Energy Efficiency	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Injection/extraction					x	x	x			x	x					x	x	x	x
Superconducting RF						x	x	x	x	x	x						x	x	
Vacuum	x	x		x	x	x	x		x	x	x					x	x	x	x
Controls and interlocks	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Computing	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Targets and moderators							x	x	x	x		x							x
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

multiple units which can be economically produced and then deployed in the field. The differences are sometimes referred to as RAMI - reliability, availability, maintainability and inspectability. These systems may need to operate with very high duty cycles, with minimal maintenance and intervention, and be operated by non-specialists. This is not a weakness of STFC technology or design; it merely illustrates the differing drivers between national laboratory R&D and more commercial-facing products.

One response to this issue is that the burden for industrialising systems should lie with industry, since the expertise to do this more naturally lies within a commercial organisation rather than within an organisation such as STFC. Whilst this may be case, for STFC to maximise impact from accelerator applications it needs to develop systems which are made available and widely used. A better understanding of these RAMI requirements will likely encourage more external investment and at an earlier stage in the development process. It is also an area of development where the national laboratory facilities could stand to gain significantly by transferring knowledge from industry on reducing costs and maintenance requirements, and forming partnerships with key providers to aid in adoption of STFC-funded research.

Considerable progress is being made in the development of novel accelerator systems (e.g. laser wakefield, plasma wakefield accelerators) as identified in the Novel Accelerator theme roadmap. These developments, if successfully translated to practical, efficient and cost effective systems, have the potential to provide a 'disruptive technology' solution across a broad range of application areas currently dominated by conventional systems (e.g. linacs, cyclotrons), most likely on the extended 10-20 year timescale.

4a. What skills, experience and leadership is necessary to achieve each accelerator science and technology activity?

STFC has a remit to maximise the translation of its science, technology, skills and knowledge for the benefit of UK society and industry. At its core, STFC has a primary role to develop national and international scale facilities for academic and industrial use. It therefore follows that, for the majority of particle accelerator application areas, the overall leadership will reside externally to STFC. This may be with industry, with an external commissioning body (e.g. NHS or its hospitals) or potentially with a representative body of technique end-users. STFC is most likely to take an active leadership role in low Technology Readiness Level (TRL) applications where a scientific or commercial case is still under development. A degree of horizon scanning and seed funding is therefore likely to be required to kick-start new opportunities.

For STFC to be effective in identifying, interacting and understanding low-TRL needs, it needs to broadly engage with end-users, academia and industry. This is achieved both through the business development departmental functions and through the Cockcroft and John Adams Institutes. STFC is ideally placed to act as a conduit for government, academia and industry to combine to achieve maximum scientific, societal and ultimately economic impact for the UK.

A critical skills requirement is for application scientists, in a range of technical disciplines, who can support ideas beyond the initial conception, through the early development stages and experimental proof-of-concept and validation, and on to technology/skills transfer into academia or industry. Movement of staff between national facilities, industry and academia will benefit all three.

4b. Please comment on the current UK position regarding the necessary skills, experience, leadership and capacity in the international context.

Industrial

STFC has made in-roads into industrial market sectors (e.g. material modification, mass spectrometry) through the provision of test facilities, radiation enclosures and specific expertise in technology solutions such as vacuum system development, advanced materials analysis and RF system design. Although commercial systems are available for many end applications, significant opportunities exist for collaboration on technology developments.

As a potential model example, the development of ion beam systems in the UK is coordinated through the UK National Ion Beam Centre (UKNIBC), a collaborative delivery partnership between The University of Huddersfield, The University of Manchester's Dalton Cumbrian Facility and The University of Surrey.

Currently, for most electron-beam applications, the leadership and expertise resides within sector-specific OEM suppliers and end-users.

Health

The UK has considerable research and commercial activity in radiotherapy, proton and ion therapies and radioisotope production for imaging. STFC is actively involved through the research activities of the Cockcroft and John Adams accelerator institutes – for example two recent Cockcroft healthcare projects with industrial companies - and is closely involved in the development of new science areas such as VHEE. STFC also hosts the Medical Training and Research Laboratory, a joint SPECT/CT training initiative between the University of Liverpool, the Royal Liverpool University Hospital, and is a partner of the Optimization of Medical Accelerators Marie Curie Training Network.

Superconducting magnets and the associated skills have been identified as a critical UK development need in order to fully realise potential opportunities in proton therapy, particle therapy and radio-isotope production.

Security And Defence

The UK has a significant presence in security and defence applications of accelerators across government institutions, university research groups and industry. STFC has long-established links with Rapiscan Systems and Lancaster University (a Cockcroft Institute partner) who play a key role in the UK capabilities. As part of a postdoctoral training centre being established at STFC Daresbury, a student will be working on joint technology developments on linacs, with an extended placement at Rapiscan's UK cargo scanning design and production facilities. The requirements for security systems places high demands on the supply of skilled RF designers, engineers and controls personnel.

The nuclear material detection sector is also well represented in the UK with interest from organisations such as BNFL, NNL, AWE and the Dalton Nuclear Institute. Expertise regarding flash-radiography principally resides within AWE.

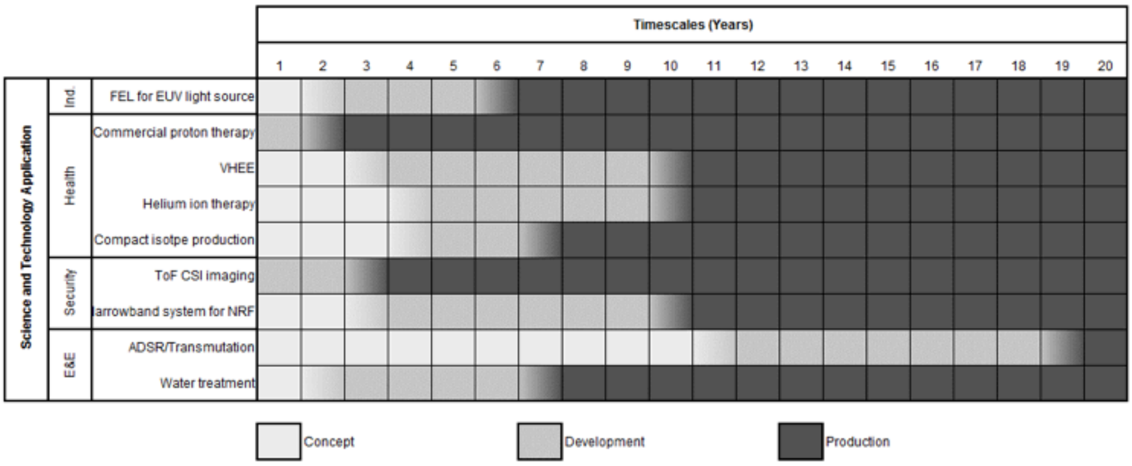
Energy And Environmental

Academics from Oxford, Bristol and Huddersfield universities are active in the application of electron beams to the treatment of waste water, industrial effluent streams and sludge. Proof of concept experiments assisted by STFC innovation funding have been conducted on the Linac Test Facility at Daresbury and further tests with a commercial partner are scheduled. STFC have also held workshops in conjunction with HEPTech to investigate the opportunities for particle accelerators in environmental applications, and also contributed to EuCARD-2 and IAEA activities in this research area. Industrial engagement from municipal water companies will likely be required to drive significant research activities.

5. What are the milestones, timescales and indicative costs for pursuing each accelerator science and technology activity?

Table 4 illustrates indicative timescales for the development of key accelerator application areas from conceptual design through to the production or commercialisation stage where impact can be quantified. The milestones, timescales and total costs of such activities will be determined by societal requirements, industrial needs and the level of external funding available; hence the table is for illustrative purposes only.

Table 4. Indicative development timescales for accelerator application activities.



6a. Map each accelerator science and technology activity and enabling technology/capability against potential impacts to:

i. ODA Strategic Objectives[1,2]

1 ODA Strategic Objectives: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/478834/ODA_strategy_final_web_0905.pdf
2 UN Global Goals: http://www.globalgoals.org/

The recently-introduced but large Global Challenges Research Fund (GCRF) in the UK - with its explicit link to providing direct, measurable impact in ODA listed countries - is currently focussing considerable attention on the Grand Challenge areas. Many accelerator science and technology topics where STFC-funded researchers have expertise are applicable to most of the challenges identified within the ODA strategy and by the UN development goals toward sustainable development. For illustration, STFC submitted (ultimately unsuccessful) GCRF bids regarding development of VHEE in India, and development of low cost accelerator systems in the Middle East.

We list below some of the areas with high potential for impact; whilst no opportunities should be excluded from these funding calls, some candidates look particularly well aligned to the requirements of GCRF funding; here we only highlight the need, rather than the UK group(s) that might contribute.

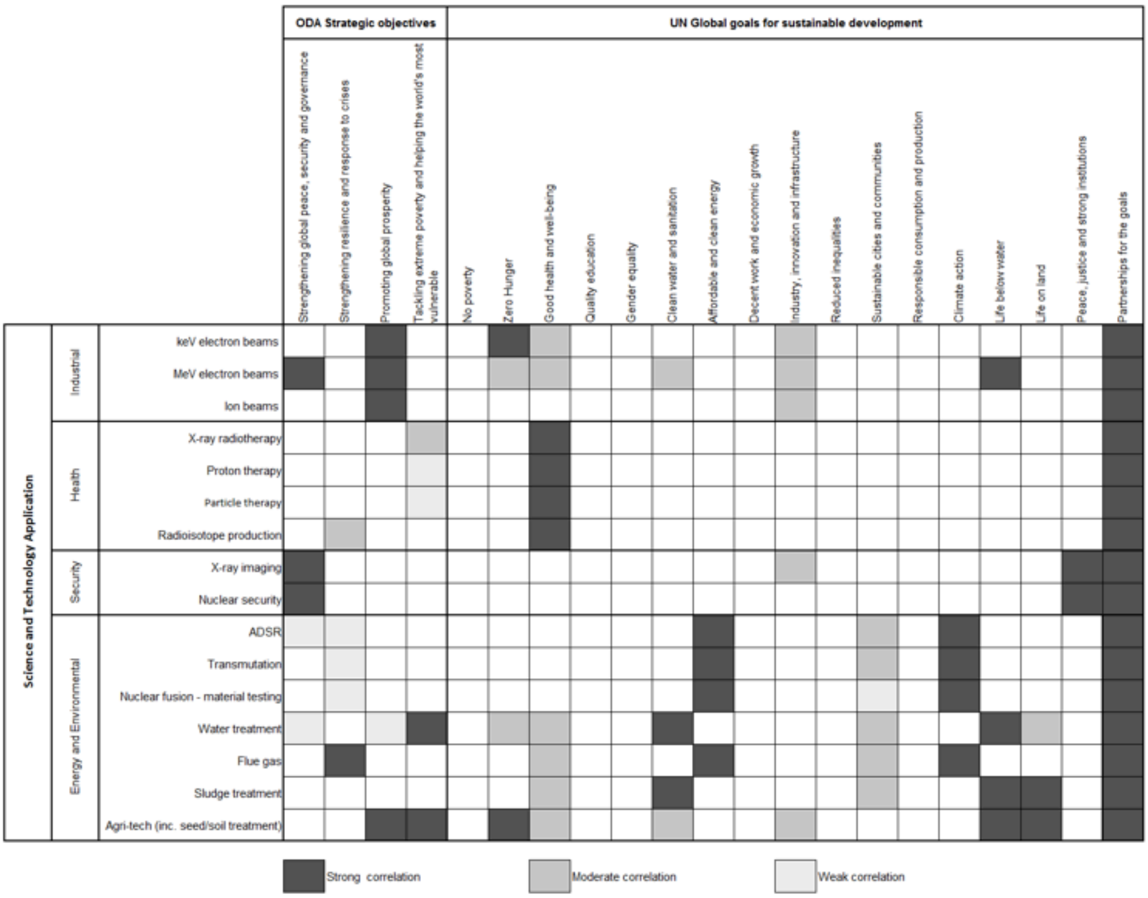
Industrial

- Medical equipment sterilisation in areas with contaminated water supplies
- Application of low-cost electron beam sources to mass manufacture (e.g. polymer cross-linking)

Medical

- Development of, and access to, X-ray and neutron science facilities for studies of ODA-relevant diseases
- Low-cost platforms for radiotherapy, initially

Table 5. Mapping of accelerator applications against ODA strategic objectives and UN global goals.



cheaper conventional X-ray systems but also novel platforms, protons, and VHEE

Security and Defence

- Border security in conflict zones, including defence of UK and UN troop deployments
- Detection of nuclear and other illicit materials, including impeding proliferation
- Promoting stable governance through anti-corruption measures - detection of illegal immigration, trafficking and tax/duty avoidance

Energy and Environment

- Flue gas treatment at conventional fossil-fuel power stations to reduce atmospheric pollution
- Low-cost electron-beam treatment of drinking water supplies for more effective reduction of contaminants
- Electron-beam treatment of industrial effluent, reducing its toxicity
- •Sewage and sludge treatment to reduce pathogens and provide potential for recycling as nutrient rich fertiliser
- Applications in seed treatment/dressing and soil remediation to promote increased crop yield.
- Development of accelerator-driven subcritical reactors for energy production to limit generation of greenhouse gases

It should be noted that the current GCRF regime seems focused towards the development of networks and people and for knowledge exchange, rather than to fund large experimental programmes or the establishment of capital-intensive infrastructure. The panel may therefore wish to consider whether STFC GCRF funding is best used to support medium-term projects where the technology impact is foreseen but considerable ground-work is still required to translate to a strategy and marketable product (e.g. VHEE in medical, nuclear detection in security), rather than as a mechanism to drive nearer-term technology development (e.g. proton therapy in medical, 3D ToF imaging in security). By implication, other funding mechanisms and models will be necessary to support these near-market solutions.

ii. Industrial Strategy Pillars[3]

3 Industrial Strategy Pillars: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/611705/building-our-industrial-strategy-green-paper.pdf

The broad base of application areas for accelerator science and technology is able to deliver the majority of pillars identified within the industrial strategy. As anticipated for an industrial strategy looking to support businesses with strong UK presence, the industrial strategy resonates most strongly with those applications that are near enough to market to identify clear economic and strategic impacts. From the market sectors under consideration, the following may be the highest rated candidates for ISCF funding:

Industrial

- keV electron beams for industrial processing (e.g. packaging, sterilisation, additive layer post-processing)

Table 6. Mapping of accelerator applications against industrial strategy pillars.

Science and Technology Application		Industrial Strategy Pillars: Investing in science, research and innovation	Developing Skills	Upgrading infrastructure	Supporting businesses to start and grow	Improving procurement	Encouraging trade and inward investment	Delivering affordable energy and clean growth	Cultivating world-leading sectors	Driving growth across the whole country	Creating the right institutions to bring together sectors and places
Industrial	keV electron beams	Strong	Moderate	Strong	Moderate		Moderate		Weak	Moderate	Moderate
	MeV electron beams	Strong	Moderate	Strong	Weak		Moderate		Weak	Moderate	Moderate
	Ion beams	Weak	Moderate	Weak	Weak		Weak		Moderate	Weak	Moderate
Health	X-ray radiotherapy	Weak	Strong	Weak	Moderate		Moderate		Strong	Strong	Strong
	Particle therapy	Weak	Strong	Strong	Moderate		Moderate		Strong	Strong	Strong
	VHEE	Strong	Strong	Strong	Moderate		Moderate		Strong	Strong	Strong
	Radioisotope production	Weak	Moderate	Weak	Moderate		Moderate		Moderate	Moderate	Moderate
Security	X-ray imaging	Strong	Strong	Strong	Moderate		Moderate		Strong	Strong	Strong
	Nuclear security	Weak	Moderate	Moderate	Moderate		Moderate	Weak	Moderate	Moderate	Moderate
Energy and Environmental	ADSR	Weak	Strong	Weak	Weak		Weak	Strong	Weak	Weak	Moderate
	Transmutation	Weak	Moderate	Weak			Weak	Moderate	Weak	Weak	Weak
	Nuclear fusion - material testing	Weak	Moderate	Weak	Weak		Moderate	Moderate	Moderate	Weak	Moderate
	Water treatment	Strong	Strong	Strong	Moderate		Moderate		Moderate	Moderate	Moderate
	Flue gas	Strong	Strong	Strong	Moderate		Moderate	Weak	Moderate	Moderate	Moderate
	Sludge treatment	Strong	Strong	Strong	Moderate		Moderate		Moderate	Moderate	Moderate
	Agri-tech (inc. seed/soil treatment)	Weak	Moderate	Moderate	Moderate		Moderate		Weak	Weak	Weak

Strong correlation Moderate correlation Weak correlation

Medical

- Proton therapy advancements (e.g. gantry design, application of permanent magnets)

Security and Defence

- 3D imaging using X-ray time-of-flight
- Technology developments (e.g. e-beam welding of RF cavities)

Energy and Environment

- Electron beam treatment of water supplies for more effective reduction of contaminants

Technology developments in areas such as SRF processing and e-beam welding of cavities can be incorporated in support of the above proposals, so long as they can be closely associated with a defined application, as opposed to generic capacity building.

iii. Other industrial applications and spin-out opportunities

The current preference within STFC is to encourage IP licensing, knowledge and technology transfer above the generation of spin-out companies. Innovation activities are currently supported by STFC innovation funding schemes such as the Industrial Partnership Scheme (IPS), Challenge-led Applied Systems Programme (CLASP) and Proof of Concept fund (PoC).

6b. How could STFC support the development of the potential impacts identified?

In the accelerator applications sector, STFC is already working in most of the potential impact areas to further develop technologies and solutions. STFC-funded accelerator scientists and engineers interact with academia and industry through a wide variety of mechanisms. The diversity of the technologies involved and the complexity of such systems means there is no one-size-fits-all solution.

STFC is able to provide extensive facilities, skills and infrastructure to support the development of accelerator applications. Specific examples include:

- The use of the VELA facility for the development of CSI 3D imaging with Rapiscan
- Dye water de-colourisation using the Linac Test Facility
- STFC innovation-funded development of superconducting RF cavities with Shakespeare Engineering

The formation of UK Research & Innovation and the availability of GCRF and ISCF provides new opportunities to maximise the impact of similar developments. There are a number of suggestions as to how this can be addressed. A key area of skills shortage in STFC is in superconducting magnet technology, which is a skill relevant both to applications and more generally to future research and facilities development relevant to STFC priorities.

One option is to form an STFC accelerator application centre to coordinate activities. Such an initiative has been tried elsewhere, such as the Industrial Accelerator Research Centre at Fermilab and the International Institute for Accelerator Applications at Huddersfield. Pre-existing facilities and infrastructure could be coordinated within a virtual centre, rather than physically co-located; this is relatively inexpensive to achieve. In order to attract significant inward investment, it is preferable to align the centre to a specific market sector, so as to clearly identify the centre's purpose and proposition. The selection of a suitable single theme may be difficult.

An example of this focussed approach is the National Centre for Electron Beam Research at Texas A&M University which investigates agri-tech and sterilisation aspects of low energy electron beams and X-rays. In addition to providing academic research facilities and commercial irradiation services, it also houses teams looking at the legal, PR/marketing and labelling requirements for food irradiation in the US.

An alternative approach may be to tackle issues which impact upon all accelerator applications, such as reliability, compactness or cost. This can potentially be an attractive proposition for industry but the expertise for such a centre currently lies to a greater extent within industry than within STFC.

New activities are currently underway to establish a postdoctoral training cohort within STFC and the Cockcroft Institute that will integrate training in some of the accelerator application activities. This is a positive step as it will raise the external profile of the skills and training available. If promoted successfully, such a source of talented engineers and researchers can act as a significant attractor to other industry partners, attracting inward investment. There will be opportunities to expand this scheme should it prove successful.

Success in generating new opportunities also brings with it added risks. The accelerator R&D facilities within STFC are not supported in the same way as user facilities and manpower resource currently has to be diverted from other projects to support applications development. Whilst this can typically be managed at departmental level, it can be difficult to deliver projects in timescales that align to industry expectations and budget spend profiles. Any significant endeavour to increase the development of accelerator applications will therefore need to be matched by allocations of suitable manpower and resource to support R&D programmes.

STFC, through the EU AMICI Horizon 2020 project, is investigating whether there are any common barriers to industry engagement, in areas such as intellectual property, regulation or communication. Any areas highlighted by the project should be addressed.

The benefits of an increased focus on accelerator applications goes beyond technology development and enhanced funding opportunities. Working with academia and commercial providers of accelerator systems and sub-systems transfers skills and knowledge back into STFC national laboratory facilities for the benefit of the UK science base.

7a. In a reduced funding environment, which accelerator activities would you prioritise within this theme?

- **What is the minimum activity level required to keep skills alive within this theme over the next 15-20 years?**
- **What are the wider impacts of maintaining skills within this theme?**

The determination of future priorities in this theme is driven less by the need to preserve 'minimum activity levels' and more by the need to reduce 'missed opportunities for impact'.

Accelerator application activities are, by their nature, less likely to be linked directly to the prioritisation of large-scale research accelerator projects which form the core of STFC's science and technology strategies, and more by the needs of academia, industry and funding bodies. Application-led developments are often supported fully or partially by external funding from Research Councils, governmental bodies or industry. However, application activities also often leverage pre-existing investments in STFC skills, facilities and infrastructure, so a reduction in funding across other particle accelerator themes can indirectly impact on the organisation's ability to pursue applications.

STFC has directly invested in business development and innovation activities to provide resource, infrastructure platforms and support funding as attractors to academia and industry to collaborate on particle accelerator application areas (e.g. water treatment, SRF cavity fabrication). STFC departments also make resources available to support application-led activities to achieve STFC's corporate impact targets. A flat-cash or reduced funding environment limits the organisation's opportunities to generate scientific, societal and economic impacts, and affects the external reputation of the organisation as a key partner to foster application-led innovation.

This is of particular concern during the formation of the over-arching UK Research & Innovation organisation since applications, which are typically cross-cutting and multi-disciplinary in nature, are the ideal platform for forging investment and development links between the various facets of the new organisation.

With reduced funding, priority should be given to application areas which are:

- Close to market (high TRL-level) and with a clear value/market proposition in order to attract external commercial investment
- Require minimal or incremental technology development requirements, rather than more costly fundamental developments or step-changes in design.
- Closely aligned to GCRF or ISCF priority requirements to increase non-STFC funding opportunities.
- Make use of pre-existing skills sets and infrastructure within STFC, enabling prompt achievement of milestones and deliverables within commercially-relevant timescales.

This approach favours established partnerships and well-categorised opportunities. Whilst this is prudent in a reduced funding environment, care needs to be taken to continue to support in innovative and high-risk opportunities. Commercial development timescales are typically much shorter than those for large-scale research accelerators and industry-critical opportunities which lie dormant for longer periods (say, greater than six months) are often difficult to restart.

From the opportunities identified in Q1a, the priority choices are:

- Industrial: collaborative technology R&D with OEM system suppliers
- Healthcare: development of proton therapy systems for private healthcare providers
- Security: ToF backscatter imaging for cargo scanning
- Energy and environment: optimisation of water, sludge and flue gas treatment processes

There are a number of STFC structure and process-type questions that can also be addressed with minimal funding. Re-branding of the existing facilities and skills as a centre-of-excellence for accelerator applications - and subsequent high-visibility promotion - could provide a focal point for driving further academic and industrial engagement. However, as stated previously, this risks being counter-productive if suitable resources for supporting experimental beamtime, analysis and project development are not made available.

Expanded use of UK and international institutions and networks could also be made to maximise technology co-development, collaboration on applications, proactive input into future STFC strategy and opportunities for cross-party funding. These could include representative groups for industrial applications (e.g. MTC), health (e.g. BNMS, NHS), security (e.g. AWE) and energy (e.g. BNFL, NNL) as well as pre-existing international links such as H2020 AMICI.

7b. In an environment of increased funding, what additional activities, enabling technologies/ capabilities – or enhancements to activities, enabling technologies/capabilities already specified – would it be desirable to pursue?

- **What aspirations exist for investment into nascent areas of research?**
- **How could current, planned or proposed activities be enhanced?**

With the support of additional funding, a more ambitious and expanded programme of work could be undertaken than highlighted in Q7a. Projects at lower–TRL levels or those with higher technology risks (i.e. requiring step-changes in development for economic viability) could be pursued as part of broadened range of activities.

Greater pump-prime funding, such as STFC's proof-of-concept programme would be required to kick-start development and enable the securing of external funding to support longer-term project development. A general increase in available funding would not only help to instigate more ambitious development programmes, but would also help expedite activity and technology development in timescales that industry can equate to a reasonable return on investment, and therefore support financially.

Some examples of programmes that could be pursued in this environment include:

- Healthcare: rotatable SC magnets for gantry design, designs for ion therapy treatment
- Security: ultra-compact accelerator designs for bomb disposal imaging
- Environmental: establishment of pilot scale water treatment in the UK, develop designs for waste transmutation

Enhanced funding could also be used to expand the scope of an STFC centre-of-excellence for particle accelerator-based applications, providing dedicated office space, personnel and supporting infrastructure to assist in the development of new activities and technologies. Additional investment could be used to provide facilities, environments and branding more appropriate for generating inward investment from industry in order to develop commercially-viable products. In addition, the additional capacity would allow for a more adaptable and flexible organisation, better able to meet the rapidly-changing needs of industry.

Light Sources

Executive Summary

Accelerator driven light sources have not only greatly improved the technology and applications of accelerator science, they continue to develop our knowledge of the natural world, from the subtle workings of life to the extreme conditions matter experiences at the centre of gas giant planets. This knowledge has had, and is having, a profound impact on our industrial, societal and economic evolution. Synchrotrons operating in the X-ray, such as the Diamond facility, have driven this progress over the past nearly 40 years[1]. The provision of high average brightness, high flux, ultra-stable X-rays in synchrotron light sources have supported the advances in Life Science, Physical Science, and Technology in many well documented ways. The development of synchrotron light sources shows no sign of slow-down. In recent years a whole host of new projects have been funded, or proposed, targeting quasi-diffraction limited light sources, enhancing the brightness and the transverse coherence of the X-rays[2]. In parallel, Free Electron Lasers (FELs) have been able to increase the X-ray pulse brightness by a factor of approximately one billion and reduced pulse durations to the femto-second level[16]. The number of useful photons available in pulses of such short durations is, for the first time, enabling the dynamics of molecular processes to be followed. It is also becoming feasible to follow how charge flows during such processes, so opening up yet further new observation windows on the scientific landscape at the fundamental atomic and molecular levels.

The universal nature of these systems will undoubtedly lead to a more profound understanding of fundamental processes across the natural sciences. The knowledge gained offers the potential to ultimately control these processes. Such advancements are expected to yield significant technological, economic and thence societal impact, for example in energy sources and storage, which ultimately may affect the direction and sustainability of human evolution[3].

Given the historical and on-going importance of ever more advanced synchrotron sources and in particular the impact that X-ray FELs (XFEL) offer, it is of little surprise that there is an ongoing programme of investment in diffraction-limited light sources[4] and XFEL user facilities worldwide[5].

With storage rings, the UK has a long-standing tradition in delivering state-of-the-art facilities with the operation of the Synchrotron Radiation Source, at Daresbury (from 1981 to 2008) and the Diamond Light Source since 2007, at the Harwell Campus. Diamond provides high brightness synchrotron light source supporting a national and international community of more than 4000 users/year served by 30 beamlines operating 5000h/year. The 3 GeV booster and synchrotron are the largest accelerators ever built in the UK. The user community ranges from the Life Sciences, Physical Sciences to Industrial Users. Since the start of operations in 2007 the scientific throughput has increased in all common metrics adopted by STFC (number of publications, number of protein depositions, income from industrial users) and on average the beamlines are oversubscribed by a factor 2.5. Underpinning this exploitation is the exquisite quality of the electron and photon beam generated, sustained by a continuous improvement of the machine operation to match the ever-increasing demands of the user community. The 10-year vision[6] for Diamond sets out a number of developments across many of its core activities including accelerator R&D aimed at:

- improving reliability and stability of the existing accelerators
- full upgrade to an ultra-low emittance lattice, Diamond-II, and correlated R&D

Diamond is already developing a Science Case and the Conceptual Design for a comprehensive upgrade is to be completed by March 2019. The corresponding R&D activities will cover the next few years until the procurement phase is launched. The whole project aims at restoring light for users of Diamond-II by the autumn of 2025. The Diamond upgrade will open a new wealth of capabilities in photon science underpinned by higher coherence, and outstanding control of the photon transverse phase space, with nano-focus, ultra-low divergence X-rays as exemplified in the science cases for MAX IV, SIRIUS, ESRF-EBS, APS-U, ALS-U and SLS-II.

To date, the UK has not invested in a national short wavelength FEL facility despite having produced two facility designs: 4GLS[7] and NLS[8]. UK scientists are able to access and utilise such facilities in the USA at LCLS and will shortly do so at the XFEL.EU in Hamburg, which has recently been commissioned and which the UK has now joined. However, as noted in the recent STFC FEL Strategic Review[9], the capacity at such facilities will not be adequate to meet the growing needs of the UK. Furthermore, new and emerging FEL output capabilities will attract new users, further increasing the demand and urgency for a UK XFEL facility.

While synchrotron development builds upon the experience cumulated over many decades of operations, XFELs are still at the relatively early stages of development. In particular, temporal coherence and pulse durations can be expected to improve towards their theoretical limits by orders of magnitude to create Fourier-transform limited pulses and down to few cycle hard X-ray pulses, which at 1Å wavelength corresponds to sub-attosecond pulse durations[30]. Further novel output types are also possible, with highly separated multi-colour pulses, higher harmonic output, multi-pulse, variable polarisations, orbital angular momentum output, etc all being feasible. The CLARA FEL test facility is designed to prove these novel outputs, pushing FEL capability towards its theoretical limit. In this respect, the UK has a real opportunity to skip the current generation of XFEL facility design and move directly towards novel capability and applications in a future UK XFEL that would be a world-leading, international facility. This leap in capability will not be possible without CLARA, making it an essential step on the road to the UK having its own world class XFEL facility. The key objectives of the CLARA programme are:

- Develop new methods for improving the quality of the light output from FELs.
- Prove next-generation XFEL technologies.
- Develop the UK's science and engineering skills base in FEL design and construction.
- Position UK XFEL researchers as global leaders in their field.
- Lower the cost and risks associated with the delivery of a UK XFEL.

In short, CLARA will facilitate a superior, more cost effective, UK XFEL which will enable UK HEIs and industry to lead the world in research on ultrafast atomic and molecular processes which underpin our daily lives. In addition to this core mission of CLARA, there is also great potential and demand for cross-fertilizing exploitation of CLARA for Novel Accelerator concepts and technology.

Given the ability of CLARA to prove new FEL capabilities and technologies it is not surprising that it is of great international relevance and interest. Many overseas laboratories and facilities are eager to collaborate on the exploitation of CLARA, examples being SwissFEL, SLAC, CERN, FERMI@Elettra, and INFN Frascati. The coordination of the European light source facilities under the LEAPS initiative has highlighted the need for a European FEL Test Facility and CLARA is the obvious candidate to take on this role. This would formalise the international user access, ensure that the facility is exploited fully with the highest possible impact, and provide access to additional resources for enhancing and upgrading the facility as required for cutting edge accelerator research.

In the last few years, the UK has also had a substantial interaction with industry and has designed a FEL facility for a leading industrial company in X-ray semiconductor lithography. This process has developed skills which will serve any UK XFEL facility design by building in, where appropriate, the rigorous stability, reliability, and tolerances required in an industrial context. It also positively sets up the UK for future expected industrial developments in this field.

At this stage of design of a future UK XFEL, and given the present unknown funding position, it is felt it would be premature to make decisions upon whether to use normal conducting or Super-Conducting RF (SCRF) accelerating structures. Without funding constraints, the preferred option would be for a dedicated SCRF, high rep-rate (~1MHz) facility based in the UK. The trend towards SCRF, e.g. at LCLS-II, is driven in part by the approximately order of magnitude improved energy stability of these accelerators over normal conducting RF and the improved temporal synchronisation. The recently launched UK XFEL accelerator underpinning technology programme will consider both options including examining a cost effective recirculating SCRF energy recovery solution with superior parameters to existing XFELs by using hands-on knowledge gained from the SCRF ALICE and EMMA test facilities.

Given the increase in capability that XFELs have generated and the emergence of new user groups as the facilities come online, it would be prudent to try to identify and engage with the new potential users who would wish to utilise the greatly improved capability (shorter pulses, multi colours, Fourier transform limited pulses etc) that is being proposed for a UK XFEL. This would best be managed centrally by STFC rather than expecting it to happen on an ad-hoc basis.

In summary the roadmap strategy can be summarised by 3 main objectives:

- Construction and operation of CLARA (2022; £19M)
- Construction and operation of the UK XFEL (2026; £500M+)
- Construction and operation of the Diamond II upgrade (2025; £200M)

1a. Map current, planned and proposed accelerator science and technology activities within this theme against the science priorities (supported by STFC) they will enable over the next:

i. 1-5 years

ii. 5-10 years

iii. 10-20 years

Science Priorities

Science and Technology Activity	Prepare to construct a UK XFEL [1, 2]	Define UK XFEL specification [1, 2]	Develop a fully coordinated UK XFEL R&D plan [1, 2]	Develop the skills required to deliver UK XFEL [1, 2]	Complete CLARA as an R&D test facility [1]	Collaborate internationally with FEL facilities [1]	UK XFEL Construction, operation and upgrade [1, 2]	IR-FEL?	Demonstration of lasing of novel accelerator based FELs	Development of novel accelerator compact FEL photon facilities	CLARA as a light source user facility	Continue R&D at Diamond [3, 4, 6, 7, 8, 9, 10]	Conceptual desing for Diamond II [6, 7, 8, 9, 10]	Construction and operation of Diamond II [6, 7, 8, 10]
Design, construct, commission CLARA	x	x	x	x	x	x	x				x			
Exploitation of CLARA	x	x	x	x	x	x	x		x	x	x			
Upgrade CLARA to a light source user facility						x			x	x	x			
UK XFEL Underpinning Technology Programme	x	x	x	x	x	x	x				x			
UK XFEL Design, construction, commissioning	x	x	x	x	x	x	x				x			
UK XFEL operation and upgrades						x	x				x			
SwissFEL Commissioning (Aramis, Athos, Porthos)	x	x	x	x		x	x				x			
CLARA as European FEL Test Facility	x	x	x	x	x	x	x		x	x				
EuPRAXIA Design and Construction				x		x			x	x	x			
FEL for 13.5 nm Lithography	x			x		x								
CompactLight Design Study	x	x	x	x		x	x				x			
DLS Operations and Sustainability												x		
DLS-II underpinnign R&D												x	x	x
DLS-II Design, construction, commissioning													x	x
DLS-II operation and upgrades													x	x
ESRF-EBS commissioning												x	x	

Science and Technology Activity	Focus on R&D for UK-based facility [2]	Daresbury as key location for accelerator R&D [2]	Support areas of STFC leadership [3]	High impact in global challenges and industrial strategy [3]	Reflect needs of other RCs [3]	Collaboration with universities [3]	Economic and campus impact [3]	Inspire training, STEM development and public awareness [3, 4]	Fully exploit synergies with different branches of science and technology [3, 7, 9]	Integrate STFC's international activities [3, 7, 9]	Technology capability development with industry [3, 4]	Exploit our unique strengths and capabilities [3]			Timescale: 1 to 5 years	5 to 10 years	10 to 20 years
Design, construct, commission CLARA	x	x	x		x	x	x	x		x	x	x			x		
Exploitation of CLARA	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x
Upgrade CLARA to a light source user facility	x	x	x		x	x	x	x	x	x	x	x					x
UK XFEL Underpinning Technology Programme	x	x	x		x	x		x	x	x	x	x			x	?	
UK XFEL Design, construction, commissioning	x	x	x		x	x	x	x		x	x	x			x	x	
UK XFEL operation and upgrades	x	x	x	x	x	x	x	x	x	x	x	x				x	x
SwissFEL Commissioning (Aramis, Athos, Porthos)	x		x		x					x		x			x	x	
CLARA as European FEL Test Facility	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x
EuPRAXIA Design and Construction	x	x	x		x	x	x	x	x	x	x	x			x	x	x
FEL for 13.5 nm Lithography		x	x	x			x	x			x	x			x	x	x
CompactLight Design Study	x	x	x		x	x	x	x	x	x	x	x			x		
DLS Operations and Sustainability	x			x	x		x	x	x		x	x			x	x	
DLS-II underpinnign R&D	x		x			x	x	x	x		x	x			x	x	
DLS-II Design, construction, commissioning	x		x		x	x	x	x	x	x	x	x			x	x	
DLS-II operation and upgrades	x		x	x	x	x	x	x	x		x	x				x	x
ESRF-EBS commissioning			x							x		x			x		

1. FEL Review 2016
2. Annex A produced by Executive Board for this Review
3. STFC Corporate Strategy 2010-2020
4. STFC Delivery Plan 2016-2020
5. STFC Impact report (2016)
6. Accelerator Review Panel Report (2014)
7. STFC Programmatic Review (2013)
8. Diamond Ten-Years Vision 2015-2025
9. Accelerator Institutes Review (2016)
10. Accelerator Review Framework (2017)

Light Sources: Free Electron Lasers

Design, construct, commission CLARA. CLARA[26] is an FEL Test Facility at Daresbury Laboratory and is an essential stepping stone towards UK XFEL. Phase 1 (400Hz photoinjector and 50 MeV linac) is installed and under commissioning now. Phase 2 (high brightness 250MeV electron beam) is being assembled offline and will begin installation in 2019. Phase 3 (100nm FEL) requires funding to allow procurement of undulators to begin, first lasing is possible in Jan 2022 (funding profile dependent). CLARA will be able to prove a number of novel FEL schemes for the generation of increased FEL capability for UK users. CLARA will also prove new accelerator technologies and develop a UK skillbase in preparation for UK XFEL. Since XFELs are a rapidly advancing area all current XFEL facilities have been preceeded by similar test facilities.

Exploitation of CLARA. CLARA will allow the demonstration of new FEL concepts yet to be proven, which can then be implemented on UK XFEL with confidence. These schemes will generate much increased longitudinal coherence, multiple pulses of very different colours, attosecond pulse capability, and so on. The bright electron beam is already being exploited to develop and prove new accelerator technologies (400Hz photoinjector, new low level RF systems, single shot diagnostics, ultrastable RF modulators, very high gradient linacs, superconducting undulators, etc) for UK XFEL and will also be exploited for non-FEL R&D such as novel acceleration experiments (plasma, THz, dielectric), VHEE therapy, beam instrumentation developments, etc.

Upgrade CLARA to a light source user facility. Other FEL Test Facilities have transitioned into user facilities once the national FEL facility project has been firmly established. Examples include FLASH in Germany (European XFEL test facility) and SCSS in Japan (SACLA test facility). It is therefore natural to consider this as a possible outcome for CLARA in the future. An increase in beam energy (1 to 2 GeV), by implementing a high gradient linac or possibly a novel acceleration technique, would shift the CLARA output wavelength range into an area of significant user interest (few nm).

UK XFEL Underpinning Technology Programme. In response to the 2016 FEL Review the UK accelerator community (ASTeC, CI, DLS, & JAI) has generated a UK XFEL R&D programme[10] to develop the skills and technology required in preparation for the UK XFEL in order to rapidly make well informed decisions on layout and have solutions to all major technical issues. The four year programme, funded by core allocations, started on 1st April 2017. The heart of the R&D programme is the detailed design, assembly, commissioning, development, and exploitation of the CLARA FEL Test Facility. A very important aspect of the overall programme will be strong connections to the UK XFEL user community. As the programme is core funded it is somewhat constrained with no explicit resources available for building prototypes, unless funded by CLARA directly for example.

UK XFEL design, construction, commissioning. The 2016 FEL Review envisaged defining the final specification for UK XFEL in around 2020, with the facility itself open for first users in around 2026. There is no explicit design study activity at present although the Underpinning Technology Programme will be developing strawman designs as part of the activities.

UK XFEL operation and upgrades. The 2016 FEL Review envisages UK XFEL operations starting in around 2026 with an ongoing programme thereafter of operations and upgrades.

SwissFEL Commissioning (Aramis, Athos, Porthos). ASTeC and SwissFEL have worked closely for a number of years under an MoU. ASTeC have led a number of work packages for SwissFEL, including supplying equipment for the project. ASTeC is currently supporting the commissioning on the ground of SwissFEL and the first FEL, Aramis. ASTeC expect to continue this relationship into the future with the subsequent FELs (Athos and Porthos). It is noteworthy that the physical layout and capability of Athos has been strongly influenced by the UK contribution already. The skills and experience gained by working on SwissFEL will be extremely valuable for the UK XFEL project.

CLARA as European FEL Test Facility. LEAPS, the League of European Accelerator-based Photon Sources, is a strategic consortium initiated by the Directors of the Synchrotron Radiation and FEL user facilities in Europe. The consortium is developing long term plans for coordinated European accelerator and FEL technology R&D including access to world leading test facilities, such as CLARA. Once completed CLARA will be the primary FEL test facility within Europe and so strong consideration should be given to establishing the project as a European resource to maximise it's impact for the UK. Such a facility would be of interest, for example, in carrying out feasibility studies towards novel accelerator driven FELs.

EuPRAXIA Design and Construction. Several UK institutions are part of the ongoing H2020 EuPRAXIA Design Study, which will result in a CDR for the worldwide first high energy plasma-based accelerator that can provide industrial beam quality and user areas, including an FEL capability. It is planned for the project to be accepted onto the ESFRI roadmap in the near future and for the test facility to be subsequently funded and constructed within Europe. The UK is one possible location for this project (Daresbury or Harwell).

FEL for 13.5nm Lithography. ASTeC staff have already made major contributions to the design of a possible new FEL-based light source for next generation lithography. Whilst this major industrial initiative is currently on hold, it is expected to be restarted in the near term and to be implemented on a worldwide scale.

Compact Light Design Study. Several UK institutes are part of the recently approved H2020 Compact Light Design Study, led by FERMI@Elettra, with ASTeC leading the FEL design and integration work package. It is expected to start early in 2018 and run for three years. The project will design a hard X-ray FEL facility beyond today's state of the art, using the latest concepts for bright electron photo injectors, very high-gradient X-band structures at 12 GHz, and innovative compact short-period undulators. The user specification for the hard X-ray FEL will be based upon UK XFEL requirements and so will effectively provide an advanced X-band design for the UK XFEL, which will able to be compared against other options developed as part of the UK XFEL initiative.

Light Sources: Storage Rings

Diamond Operation and Sustainability. The ever-increasing demands of the users' community, in terms of reliability and stability, have driven a strong R&D effort in the improvement of the RF system and the diagnostic and feedback systems for both electron and photon beams. The current aim is to increase the reliability of the RF system by including redundancy with the installation of HOM damped normal conducting cavities and migrating to solid state amplifiers sources. In terms of stability Diamond is proposing an integrated system where the photons and electron stability is controlled from the source to the sample. Likewise, the improvement of the photon sources is driving R&D in novel optics concepts and (in-house) development of CPMUs and SCUs (with ASTeC). These are considered the minimal R&D activity to maintain the facility competitive in the landscape of third generation light sources. The STFC Corporate Strategy and Delivery Plan strongly support this development.

Diamond II Upgrade. Diamond has put forward a design study for the realisation of an ultra-low emittance ring reducing the beam emittance by a factor 20 over the existing machine. Such small emittance beam, improved coherence and smaller focus size are key enabler of a large number of new scientific applications that cannot be carried out with the existing machines. The Diamond upgrade is part of the STFC Programmatic Review Report (2013), the Diamond 10-years vision (2015). The Diamond II CDR is supported by the Diamond SAC and the Diamond board. The users' community is putting together the scientific case extending the existing science case for MAX IV, SIRIUS and ESRF-EBS where applicable.

Diamond is coordinating a design team with input from ASTeC, CI, JAI. The present milestones are a complete CDR by March 19, TDR by September 20, followed by procurement and start of shutdown in April 24, resuming user operation in April 25.

Diamond II underpinning R&D. The Diamond II project will be underpinned by strong R&D in accelerator physics (AP), magnets, vacuum and diagnostics. Although no technical showstoppers are foreseen many subsystems are pushed to the boundary of the present technological limits. High Gradient magnets, possibly permanent magnet based (ASTeC), NEG coating of small chamber (ASTeC), novel IDs, alignment and measurements, ultra-fast kickers for novel injections schemes. This programme cover approximately the first 4 years of the project, up to the procurement phase.

ESRF-EBS commissioning. The Diamond and the ESRF team have a strong collaboration in the past on the design of novel lattice cells for ultra-low emittance ring, dating back to the time of the Super-B project. Many of the novel optimisation tools for lattices and low emittance tuning were developed together by the AP teams. Magnets construction, measurement and alignment, Vacuum and Diagnostics are also area of strong collaboration.

1b. Please comment on the current UK position of each accelerator science and technology activity in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and capacity be exploited**

Light sources: Free Electron Lasers

Given the historical and on-going importance of synchrotron sources and in particular the impact that X-ray FELs (XFEL) offer, it is of little surprise that there is an ongoing programme of investment in XFEL user facilities worldwide[11]. To date, the UK has not invested in such a national facility despite having produced two facility designs: 4GLS[12] and NLS[13]. UK scientists are able to access international facilities in the EU and USA and potentially elsewhere. However, the capacity at such facilities will not be adequate to meet the growing needs of the UK[9]. New and emerging FEL output capabilities will undoubtedly attract new users further increasing the demand and urgency for a UK XFEL.

As noted in the FEL Strategic Review[9] and elsewhere[14,15], once new facilities begin to come online, new user groups ‘come out of the woodwork’[14]. Henry Chapman, a prominent XFEL facility user, said, ‘When we look back at the initial list of experiments made before the LCLS was built, it seems we weren’t dreaming big enough, but once the machines turned on it stimulated the community to think of new possibilities’ [15]. Such increased demand is further amplified by new capability, such as the increased pulse rate at XFEL.EU. It can therefore be expected that further new capability, such as the generation of few-cycle pulses and FT limited pulses to be developed at CLARA for inclusion in UK XFEL design proposals, will further broaden the user base and increase XFEL facility demand.

UK based FEL user facility provision has so far been limited to the ALICE energy recovery SCRF linac infra-red FEL oscillator at Daresbury. While this facility had international users it does not fall within the scope of the disruptive user facilities currently on offer and being developed at short wavelengths into the hard X-ray in other countries. However, ALICE has provided an excellent resource for the development of skills in SCRF accelerating systems which would be utilised in a high rep-rate XFEL. The UK currently has no short wavelength FEL user facility either operational or funded for construction, therefore lagging by up to a decade behind other leading scientific and industrially innovative countries who have such provision in hand[16] (China; Germany; Italy; Japan; South Korea; Switzerland; USA).

However, the UK is driving world-leading, active FEL research activities with partners from SLAC, SwissFEL, CERN, FERMI@Elettra, INR, Colorado State, Berkeley, & Argonne, which should lead to the development of user facilities with greatly increased capability in output pulse quality and flexibility[17,18,19,20,21,22,23,24,25,29,30,31,32,35]. This research is now focused on experimental testing at the CLARA FEL test facility at Daresbury Laboratory[26] for inclusion in a UK XFEL design. The FEL demonstrations on CLARA will be internationally leading and advance FEL output from the equivalent of 1960’s lasers towards the multitude of conventional laser output options available today. Current generation XFEL output can be improved upon by orders of magnitude in key areas such as the temporal coherence, peak power and pulse duration. Important novel output properties of potential interest to users include pulses with multi-colour, variable polarisation, Orbital Angular Momentum and Frequency Modulated output. Such improved output will create the ability to investigate new areas of science that have until now been inaccessible. How this may develop has recently been reviewed by UK users and FEL scientists[27]. CLARA will also directly lead to enhanced accelerator technologies in areas including photo-injectors, normal conducting linacs (S-band and X-band), deflecting cavities, laser-electron interactions, timing and synchronisation, low level RF, single pass and low charge diagnostics, and femto-second timescale photon diagnostics. Such technologies will be essential for any future national XFEL facility, but are also applicable across a very wide range of advanced accelerators which are relevant to STFC's mission.

CLARA is of great interest internationally as any new technique proven or technology developed can be applied to new and existing FELs. CLARA has established formal links with SwissFEL, SLAC/LCLS-II, CERN, INFN, INR, and FERMI@Elettra. Examples of these collaborations include the following:

- SwissFEL has provided in the region of 1M£ of equipment for CLARA in exchange for future beam time access, and support from STFC expertise in the design of various SwissFEL systems and FEL commissioning.
- LCLS-II wants to use CLARA to develop new FEL concepts beyond the capability of their test facility.
- CERN and Italy are developing advanced accelerator technologies for more cost effective FELs and plan to prove this technology on CLARA (CompactLight H2020 project).

LCLS-II, SwissFEL and MAX IV are also looking closely at using the following ideas developed by the UK:

SwissFEL[28]: SwissFEL has implemented novel FEL methods developed in the UK[29,30,31] to improve its ATHOS soft X-ray FEL for improved output over the normal SASE. This will include improved temporal coherence towards the Fourier transform limit and the opportunity to generate few-cycle pulse trains. Joint research has also been conducted to investigate simultaneous two-colour output[32]. Furthermore, SwissFEL are assessing the application of UK superconducting undulator technology[33] to their PORTHOS FEL.

SLAC/LCLS-II: Collaborative research has been ongoing with Stanford University into FEL methods which may be employed at LCLS-II towards improved and novel FEL output (FT limited; few-cycle generation; multi-colour generation; output with Orbital Angular Momentum (OAM)). This has been driven both by the novel methods for improved output and improved FEL simulation software developed in the UK required to model such methods[34]. This software is now being used by Stanford in its research towards improvements of LCLS-II. Following some initial research progress[35], a joint PhD programme with Strathclyde/Cockcroft has now been funded with Stanford to further develop this research.

MAX IV: This group is now working with the Swedish FEL user community to design their soft X-ray FEL. Their current baseline solution is for an HB-SASE FEL[31], an idea developed in the UK.

The FEL Strategic Review[9] considered high rep-rate superconducting RF to have relatively high capital and operations costs. However, recent advances in beam dynamics and superconducting RF technology in a multi-pass recirculation and energy recovery configuration, mean that an up to multi-MHz repetition rate machine capable of driving a FEL amplifier with output of ~20 keV photons at the fundamental is likely to be significantly more affordable. Such a configuration also affords access to multiple beams at multiple energies allow synchronised output spanning a wider range of photon energies. In addition to the 1MHz CW pulse train designed for LCLS-II, the XFEL.EU is also now considering such an upgrade[36]. High rep-rate, CW pulses also allow the consideration of low feedback cavities which simulations show can generate stable few femto-attosecond pulse output[37,38].

13.5nm Lithography FEL: ASTeC has worked under contract to an industrial company to develop an advanced FEL for future lithography facilites. This ambitious and challenging programme led to a number of deep insights which are now being applied to UK XFEL. ASTeC was the supplier of choice due to the broad skills range and expertise in relevant accelerator and FEL areas. When this project is restarted, as anticipated, then the company has made clear that securing ASTeC's services will be their priority.

Light sources: Storage Rings

At the beginning of operation in January 2007 the Diamond storage ring provides the smallest electron beam emittance in medium energy light source. Since then many light sources upgrade or started operation providing better beam quality to their users (PETRA III, ALS, NSLS-II, MAX IV). The landscape of third generation light source have been decisively modified in the last 5 years by the funding and construction of the first ultra-low emittance rings (MAX IV, ESRF-EBS, SIRIUS) which promise to reduce the electron beam emittance to quasi-diffraction limited values. A large effort toward the design of ever more aggressive lattices is ongoing, notably led by the US with the APS-U, ALS-U, and followed by many European national laboratories (Diamond, SOLEIL, SLS, ELETTRA, DESY PETRA IV) and Asian (HEPS Beijing, HEFEI diffraction limited light source and Spring8-II, Japan). It is foreseeable that in the next years Diamond will continue to lose competitiveness in the international area, if no upgrade programme is launched.

The Diamond team has a well visible track record in the construction and running of a large facility and its upgrades. In collaboration with the large engineering expertise present at ASTeC and the academic support of the Accelerator Institutes a UK wide team led by Diamond is in an ideal position to drive the upgrade project to Diamond II.

International capabilities will continue to be exploited, notably at the ESRF-EBS, however they will concentrate on different photon spectral ranges and will not cover the whole of UK users' demands.

2a. What enabling accelerator technologies/ capabilities (including computing, vacuum, RF, lasers etc.) are necessary to pursue each accelerator activity?

FELs and storage ring light sources require a broad range of technologies and capabilities (see mapping table), in order to have the capability to design, construct, commission, and operate a user facility. Many of these capabilities are common, not only between FEL and rings, but also with other types of accelerators. Therefore, the UK must have access to all the required capabilities as each one is an essential element to a user facility. This does not mean that the UK needs to be world leading in every area but it does mean that it is essential that STFC maintains skills and capability across the full range, and this should be recognised as a priority.

Science and Technology Activity

Key technologies & capabilities	Design, construct, commission CLARA	Exploitation of CLARA	Upgrade CLARA to a light source user facility	UK XFEL Underpinning Technology Programme	UK XFEL Design, construction, commissioning	UK XFEL operation and upgrades	SwissFEL Commissioning (Aramis, Athos, Porthos)	CLARA as European FEL Test Facility	EuPRAXIA Design and Construction	FEL for 13.5 nm Lithography	CompactLight Design Study	DLS Operations and Sustainability	DLS-II underpinnign R&D	DLS-II Design, construction, commissioning	DLS-II operation and upgrades	ESRF-EBS commissioning
Beam Instrumentation and feedabacks	x	x	x	x	x	x		x	x	x		x	x	x	x	x
High Brightness Sources	x	x	x	x	x	x		x	x	x	x		x	x	x	
Normal conducting RF	x	x	x	x	x	x		x	x		x	x		x	x	
Superconducting RF				x	?	?		?		x				x	x	
Lasers	x	x	x	x	x	x		x	x	x						
Timing and Synchronisation	x	x	x	x	x	x		x	x	x						
Permanent Magnets	?		?		?	?		?	?			x	x	x		
Resistive Magnets	x	x	x	x	x	x		x	x	x		x	x	x		
Pulsed Magnets													x	x	x	
Undulators	x	x	x	x	x	x		x	x	x	x		x	x	x	
Energy Efficiency	x	x	x	x	x	x		x		x	x			x		
Linacs	x	x	x	x	x	x		x	x		x					
ERLs				x	?	?				x						
FFAGs				x	?	?				?						
Vacuum	x	x	x	x	x	x		x	x	x			x	x	x	
Surface Technology	x	x	x	x	x	x		x		x	x		x	x	x	
Simulations and Modelling	x	x	x	x	x	x	x	x	x	x	x	x				x
HPC	x	x	x	x	x	x	x	x	x	x	x	x				x
Beam Dynamics	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
FEL expertise	x	x	x	x	x	x	x	x	x	x	x					
Wakefields	x	x	x	x	x	x		x	x	x	x		x	x	x	x
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	

Nevertheless, there are some key technological challenges, specific to FELs and storage rings which must be pursued.

Light Source: Free Electron Lasers

Beam Instrumentation: FELs have very challenging requirements for diagnostics as most of them need to be single shot. Bunch length and profile must be diagnosed accurately with fs resolution, bunch arrival time also needs to be recorded at the fs level. Beam position within the FEL itself is required at sub-micron resolution.

High brightness sources: FELs are very demanding in terms of the electron source. Low emittance, high RF gradient, long lifetime photocathodes, stable laser performance with adjustable transverse and longitudinal profiles are all important features of a high performance source.

Lasers: there are numerous lasers built into FEL facilities (source, laser heater, seed, timing system, beam arrival monitoring, end station, etc) and their performance is crucial in defining the overall performance of the facility.

Undulators: these are at the heart of both types of light source. The performance of the undulators defines the output of the light source. Advances in this area can have major benefits for the end user.

Energy recovery linacs (ERLs): these are well suited to light source applications and have been pursued by numerous facilities. A multi-pass ERL may make a MHz FEL (using SRF) much more affordable and offer superior beam properties to a single pass linac.

FFAGs: the FFAG capability of transporting electron beams with a broad range of energies is likely to be important for the ERL system mentioned above.

Simulations and Modelling and HPC: FELs are particularly challenging to simulate, from the cathode to the FEL. Significant expertise is required to carefully model the beam dynamics and FEL process involved. The more advanced simulations require access to HPC. The data acquisition rates in FELs are demanding both for exploitation and accelerator operation. Facilities to store, analyse and visualise large data sets will be required and application of machine learning both in optimisation and simulation will be technology areas that can be explored in the CLARA facility and implemented in the realisation of a large scale facility

FEL expertise: clearly this is specific to FELs and is essential throughout the FEL user facility project life cycle.

Wakefields: these are an important issue for FELs and so the capability must be available to carefully model and understand them as they can have a significant influence on the FEL performance.

Light Source: storage rings

RF: improvement in Diamond reliability operation concentrate on guaranteeing reliability and stability. Area of improvement are RF, cavities and sources, with the migration from Klystrons/IOTs to Solid state amplifiers.

Diagnostics and feedback: the improvement on the stability requires both with passive measures and better feedback to cope with the ever increasing demands of sub-microns stability up to 1 kHz, both in electron and photon beam.

Undulators and sources: Light source improvement is focussed in the study of novel insertion devices. Diamond has in-house capabilities for building CPMUs and a strong R&D programme is in place for the construction of SCUs in collaboration with ASTeC and STFC Technology department.

Simulations and modelling: The Diamond II upgrade is based on a skilful set of accelerator designers, versed in modern computational approaches to the lattice optimisation and supported by adequate computing cluster infrastructure. The most modern multi-objective optimisation run typically for many weeks in large clusters.

Novel magnets: aggressive lattice design call for the construction of novel magnets like longitudinal gradient bends and high gradient quadrupoles. Strong focussing magnet push the boundaries of the existing technology with large gradient demanding very accurate machining, measurement and alignment procedures. The interest in green, low power consumption magnet will benefit from the approaches based on permanent magnets where ASTeC has produced many innovative concepts, e.g. high gradient tunable permanent magnet quadrupoles.

Pulsed magnets: novel injection scheme in small aperture rings require the use of fast pulsed magnets

(1 ns rise-fall time). These are demanding in terms of pulser performance and are the object of strong R&D worldwide.

Vacuum systems: the small aperture magnet will demand small aperture pipes. The increase use of NEG coated structures will require strong collaboration and R&D labs presently pursued by Diamond and ASTeC. Other areas will be Diagnostics and feedback systems to guarantee the stability of such an ultra-small beam up to 1 kHz. Novel insertion devices will play a key role with ever smaller gaps in the new facility.

2b. Please comment on the current UK position of each enabling technology/capability in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and/or capacity be exploited?**

Free Electron Lasers and Storage Rings

As explained above, FELs and storage ring light sources require the full range of technologies and capabilities in order to have the capability to design, construct, commission, and operate a user facility. This is currently the case but in many areas the level of resources is spread very thinly and there are many potential single points of failure where particular expertise is only held by one or two people within the UK accelerator community. The level of staffing, especially in the engineering areas (e.g. magnets, mechanical, electrical, and so on) might prove critical if no action is taken upfront in a timely manner, to carry out the upgrade project. Particular comments on the key technological challenges highlighted above are given below:

Simulations and Modelling and HPC: the UK is recognised as an international leader in FEL modelling and a number of high profile FEL concepts have been developed by UK researchers and adopted by others. The PUFFIN code[22,34] from CI has unique capabilities and is used by several international groups. XFEL modelling requires significantly more HPC capacity than normal accelerator design work due to the much finer sampling of the electron beam required. Diamond, ASTeC and the accelerator institutes is well placed in the international landscape having all the necessary key expertise in house to design a UK XFEL and a lattice upgrade for Diamond II. The use of artificial intelligence and other big data analytical techniques require development of systems and expertise to support their implementation on existing and future light source facilities. FELs will present a particular challenge in data quantity and acquisition rates.

Beam Instrumentation: The UK has an international standing within this area. The CI and JAI make significant contributions as well as the national labs. Specific examples include cavity BPMs, electro-optic bunch profiling, and coherent Smith-Purcell monitors.

High brightness sources: ASTeC has designed a 400Hz high brightness source for CLARA, this is internationally leading. Sources appropriate to a high repetition rate SC national facility will be challenging but the UK has significant experience in exploring design solutions for 4GLS and NLS and ASTeC has international standing within this area and supports an advanced cathode laboratory which can facilitate the realisation of a suitable injector for future facilities.

Lasers: significant growth is required in this area to meet the needs of UK XFEL.

Undulators: The UK has international standing in superconducting undulators and cryogenic permanent magnet undulators. The latest SCU developments from ASTeC are being considered for application on SwissFEL and elsewhere.

Energy recovery linacs (ERLs): the UK has international leadership in this area largely due to the ALICE test facility and subsequent application of ERL principles to other designs.

FFAGs: the UK has international leadership in this area largely due to the EMMA test facility and PAMELA design and subsequent application of FFAG principles to other designs.

FEL expertise: as above.

Wakefields: there are a number of UK researchers who contribute to this area largely applying theory developed elsewhere.

3. Map the necessary enabling technologies/ capabilities required for activities within this theme against accelerator activities within the other accelerator themes.

The proposed Light Source roadmap is based on the construction of major accelerator facilities and builds upon core STFC technical skills. The scientific and technology expertise required cuts across many other accelerator themes, and a non-exhaustive list is given below. One example is that the combination of accelerator expertise in light sources has already proven to be relevant for high energy physics in the collaboration between damping rings and synchrotrons in the production of ultra-small vertical emittance beams. Another example is the SCRF expertise gained from the ALICE test facility, which was a prototype for the proposed 4GLS FEL, has directly led to the capability to support the ESS neutron facility high beta cavity in-kind contribution by the UK and the HEP HL-LHC crab cavity cryomodule delivery. Furthermore the LINAC expertise from CLARA and UK XFEL will in turn be highly relevant to the HEP projects like linear colliders (CLIC or ILC). The same applies to the field of radiation therapy and novel acceleration schemes which will benefit enormously from the expertise of technical staff involved in the commissioning and running of operational facilities, capable of generating and handling high charge ultra-short pulses and the associated diagnostics and technical systems.

Underlying light source development, and in particular FELs, is the requirement for computational modelling and its optimisation in an HPC environment. There are clear synergies across the accelerator themes which also require HPC modelling and which could be exploited to enhance all.

Synergies with storage rings and FEL

- Beam dynamics
- Diagnostics and feedbacks
- Magnets (design, materials, …)
- Undulators (technology, schemes, gaps, …)
- vacuum (engineering and coatings)
- NC & SC RF cavity design and operation
- Simulations and modelling
- Wakefields

Synergies with other roadmaps themes

- Beam dynamics, high level applications
- Diagnostics and feedbacks
- Magnets (design, materials, …)
- Vacuum (engineering and coatings)
- NC & SC RF cavity design and operation
- Big data, software development and HPC facilities
- Simulations and modelling
- Wakefields
- High brightness sources
- Laser-based systems (diagnostics, sources, etc)
- Linacs, ERLs, FFAGs
- Novel Accelerator R&D - Requires large HPC resources for simulation and CLARA offers an opportunity for future engagement in Novel Accelerator research for light sources.

4a. What skills, experience and leadership is necessary to achieve each accelerator science and technology activity?

Free Electron Lasers and Storage Rings

Clearly the key areas identified in Q2a & b require the necessary skills to meet these needs. While the UK does not lack leadership and scientists with high international standing in many of these areas, the projects highlighted will require a solid base of highly trained scientists, engineers and expert technical staff in all areas of accelerator technology. As mentioned previously the UK is spread thinly in many of these areas and does not have the necessary resources to deliver major new user facilities such as UK XFEL or Diamond II. Some specific examples are highlighted below:

Experimental, theoretical and simulation physicists: International level experts in the general field of accelerator physics, able to conceive, design and implement a user facility with world leading capabilities and participate and lead international level collaborations. Specialist leaders in specific areas able to innovate, design, simulate, specify, procure and implement systems at or beyond state of the art in areas such as electron beam sources, beam dynamics, collective effects, static and RF electromagnetics, short pulse and high power laser systems, photon science, advanced diagnostics, synchronisation, feedback, longitudinal and transverse dynamics, FEL radiation physics. A team of graduate and postgraduate level physicists able to support the above specific specialist areas.

Radiofrequency engineers: International level expertise in the general field (NC and SC), able to conceive, design and implement high power and low level RF systems with state of the art capabilities and participate and lead international level collaborations. Specialist leaders in specific areas able to innovate, design, simulate and implement systems at or beyond state of the art in areas such synchronisation and low-level RF control and feedback. Experienced RF systems engineers in RF cavity, distribution and low level controls system able to innovate and develop to meet the exacting demands of state of the art FEL systems. Graduate level RF or electronic engineers to support all of the above activities.

Vacuum Engineering and Science: High level expertise in material, surface and vacuum science and technology able to design and manage, implement and maintain operation of whole facility system and meet the challenges associated to operation with very small aperture pipes. High level scientific expertise to enable the research and develop of advanced solutions delivering improved vacuum and surface properties in the areas of cathode science (XUV) and small aperture vessels. Vacuum engineers, technician and graduate level scientist to support the above facility, research and development activities.

Computer Scientist/Engineers: High level expertise in the design and develop of whole system solutions for accelerator facilities and for accelerator modelling and simulation. Specialist in hardware and software controls utilised routinely and extensively in accelerators. Software engineering expertise to support physicist in high-performance computing including artificial intelligence, machine learning, and advanced feedback processes to optimise and control complex accelerator systems, management of large-scale and variable source sensor and experimental data sets and visualisation. Technicians to support the above activities

Mechanical Design engineering: Design engineers with extensive experience of producing and implementing advanced technology facilities with highly specialist engineering component systems, requiring specific experience of such systems and expertise of system integrated into the complex arena of accelerator facilities. Engineers and technical staff from technicians, designers, graduates and professional engineers to support all levels of mechanical design engineering.

Magnets (DC and pulsed): the UK has maintained a good level of magnet design expertise especially in conventional and permanent magnet with the project of CLIC, EMMA and the DDBA upgrade of Diamond. The challenges posed by the requirements of ultra-fast ns pulsed kicker magnets are however relatively new and increased capabilities need to be developed.

Mechanical systems assembly and integration: Senior engineering staff with extensive experience of the variety and complexity of mechanical systems within accelerator facilities. Engineers and technical staff from technicians, graduates and professional engineers to support.

Electrical and electronic systems design engineering, including high power systems, and high-performance (low noise, high bandwidth) electronics: Senior engineers with extensive knowledge of state of the art accelerator system. Engineers and technical staff from technicians, graduates and professional engineers to support.

High precision survey and alignment¬: the tight constraints on alignment of accelerator components (e.g. magnets in storage rings, RF cavities and undulators in FELs, and so on) requires a set of trained engineers mastering the latest techniques in survey and alignment and capable of liaising with magnet designers and integration engineers.

Health and Safety and Operations Management of Complex Radiations Facilities: An experienced engineering skills base with a broad knowledge of accelerator operations and component systems together with significant experience in managing H&S within this field.

4b. Please comment on the current UK position regarding the necessary skills, experience, leadership and capacity in the international context.

Free Electron Lasers and Storage Rings

User Facility Design Skills: The UK team has designed two FEL user facilities, 4GLS and NLS, and a major upgrade to the Diamond lattice with the DDBA, so it has demonstrated the essential requirements for designing UK XFEL and a lattice upgrade for Diamond II. The UK position in this field is widely considered to be world-leading. FEL simulation tools developed in the UK[34] are now being used in design studies towards international facilities like LCLS-II[35] and SwissFEL[32].

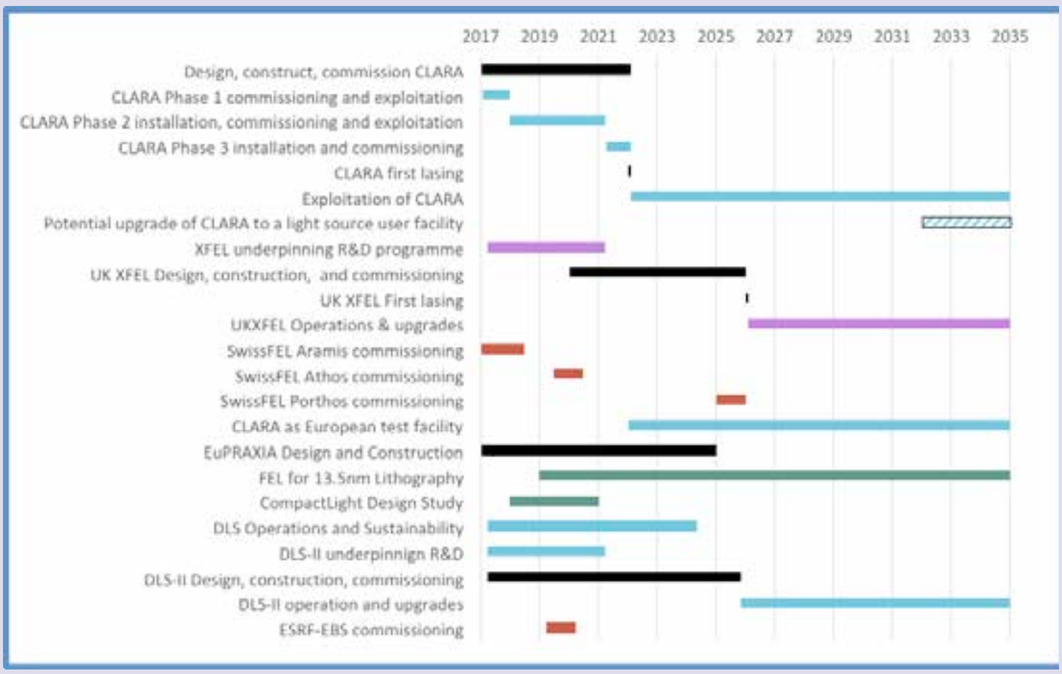
FEL commissioning: there is little genuine practical experience of developing and exploiting the necessary technologies to be applied to state of the art FELs or of commissioning and operating a single pass FEL. This lack of state of the art skills and technologies will be remedied by completing the full aims of the CLARA project (by the whole team of over 100 people) and this will then ensure that the UK XFEL user facility is world leading with output performance optimised for the UK user base. A small number of UK staff are also actively taking part in the commissioning of SwissFEL which is giving them very valuable direct experience of an XFEL.

RF: One area that CLARA will not address is SCRF should that be required for the UK XFEL. However, the UK has gained significant SCRF expertise via the ALICE test facility design and operation, the 4GLS and NLS designs, and through other projects such as ESS high beta cavity in-kind delivery and the HL-LHC crab cavity cryomodule collaboration. Practically trained RF engineers with experimental expertise are extremely difficult to recruit within the UK and internationally.

Magnets (AC and pulsed): the UK has retained some expertise in conventional and permanent magnet design with work on CLIC, EMMA and the DDBA upgrade of Diamond. However, in the field of pulsed magnet the existing expertise is too thin to cope with the challenges and the R&D required for both spreader systems for FEL and for swap out injection in ultra-low emittance rings.

5. What are the milestones, timescales and indicative costs for pursuing each accelerator science and technology activity?

The current timeline for the Light Source roadmap covering the Free Electron Lasers and the Storage ring activity is summarised in the attached Gantt chart. The main milestones and indicative cost estimate are reported below.



Light Source: Free Electron Lasers

The current timeline for the FEL activity is based on the following milestones

- CLARA commissioning and first lasing February 2022
- UK XFEL design and construction 2020-2026
- UK XFEL first lasing February 2026

Remaining capital funding to complete CLARA to the end of phase III is approximately 19M£. The cost of the UK XFEL will strongly depend on the final energy reach and the RF technology used. It was estimated that the costs of constructing and commissioning a normal conducting RF XFEL facility is of the order of 500M£[9] while a superconducting machine with the same energy could be expected to be around 25% higher without recirculation, with the precise increase dependant on the practical implementation of facility. A superconducting facility based on recirculation is expected to be more affordable.

Light Source: storage rings

The current timeline for the Diamond II upgrade activities is based on the following milestones

- CDR completed by March 2019
- TDR completed by September 2020
- Procurement phase 2020-2024
- Start of shutdown April 2024
- Resume normal user operation October 2025

The preliminary estimated cost of the lattice upgrade is within 100 M£ (scaled from ESRF-EBS). If the beamline upgrade will be included, it is foreseeable that the cost will be nearly doubled.

6a. Map each accelerator science and technology activity and enabling technology/capability against potential impacts to:

i. ODA Strategic Objectives[1,2]

1 ODA Strategic Objectives: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/478834/ODA_strategy_final_web_0905.pdf
2 UN Global Goals: http://www.globalgoals.org/

Free Electron Lasers and Storage Rings

Light sources can contribute significantly to the ODA Strategic Themes. These activities have a longer-term reach to ODA recipient countries as well as providing solutions to a specific, often acute, short term objective. The impact of light sources in e.g. biology, has provided much of our understanding of how biochemical processes function allowing solutions to specific human health problems to be developed. In this way light source can tackle specific issues of direct relevant to the ODA recipient countries like the efficient delivery of a particular drug for prevention of e.g. ebola (in Africa), zika-virus (in Brazil), directly contributing to the ODA strategic objective of 'Strengthening resilience and response to crises'. If the longer-term benefits of investment can be made, then funding opportunities certainly exist from the 1B£ 'Ross fund' committed to improving global public health.

Another exemplar topic which contributes to this theme is in the development of new or more efficient methods of energy production to help mitigate and adapt to the effects of climate change. Light sources play a pivotal role in materials science research (e.g. to create more efficient solar panel technology) and in synthetic biology (e.g to create a synthetic form of photosynthesis.) It is worth noting and emphasising that the middle east, which has several ODA compliant countries, has already recognised these longer term benefits via its investment programme in its SESAME light source. Africa also has a consortium of countries which are looking at the development of an African Light Source[39]. As part of a shorter term impact approach, access for training and research to DIAMOND and the CLARA test facility could be provided.

A recent call to the Global Challenge Research fund (GCRF) has seen five bids based on application related to light sources, with one from Diamond being shortlisted for interview, in an extremely competitive environment. In addition, three full scale GCRF bids were submitted which were based upon electron accelerators (VHEE therapy in India, FEL and other accelerators in the middle east, and storage ring enhancements in Thailand). The skills and capabilities generated as a consequence of light source activities are broadly applicable to electron beam applications and indeed have been applied already within the UK to several security cargo scanning developments, water treatment experiments, and VHEE radiotherapy system design.

A measure of the economic benefit of a light source facility to a local economy may be obtained from the SRS Light Source at Daresbury where 300 local businesses benefited, with 600M£ awarded in contracts – the financial impact on the local economy throughout its lifetime is estimated to be almost 1B£[40]. Similarly, more than 1000 companies have benefited from construction or technology contracts for the Diamond Light Source and a quarter of the science carried out at the ESRF links directly to industry[1]. This scale of economic impact, or probably greater with a need for service industries to be created, may also be expected to occur in ODA countries.

The UK can facilitate the training of solid base of scientists, engineers and technicians that will be able to operate and develop light sources (be it free electron lasers or storage rings). Before light source facilities can be built, however, they need to be designed. This aspect light source science requires the use of many computer simulation codes on High Performance Computing facilities. The training and set-up of access to design software and HPC facilities by UK researchers would give ODA countries the ability to contribute to the design of large accelerator and light source facilities and also to smaller local facilities e.g. in the medical accelerator field. The generic HPC skills and the principles of sustainable software development that would be learned would then be transferable to a much wider range of social and economic tasks in ODA countries. With remote access to HPC resources now available, either commercially via Amazon or using STFC resources such as DiRAC or Hartree. Likewise, access to Diamond beam time can be guaranteed to support and promote research programme of direct relevance to ODA themes. This has the potential to have a shorter term impact under the ODA strategic objective of 'Promoting global prosperity'

ii. Industrial Strategy Pillars[3]

3 Industrial Strategy Pillars: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/611705/building-our-industrial-strategy-green-paper.pdf

Free Electron Lasers and Storage Rings

The breadth spanned by light source facility science means that it has impact across a wide range of high-tech industry and potential industrial applications. One of the three overarching criteria the industrial strategy should satisfy is to 'close the gap between the UK's most productive companies, industries, places and people and the rest'. With many top industrial countries now investing in advanced light sources, the UK is now falling behind and the gap needs closed if we are to remain competitive.

In this context, Diamond is already strongly engaged with industrial partners with 22 beamlines operating also to serve industrial users. As for 2016-2017 Annual Report , 112 industrial users from 12 countries around the world used 250 beam time sessions. The net revenue for Diamond is 1.35 M£, corresponding to a 15% increase over the previous year. For the Diamond II upgrade, the user community is putting together a science case for industrial application as part of the core science case for Diamond II. At this stage of development, the design of the new lattice will guarantee the continuation of the existing engagement. With a suite of sources that will cover the necessary photon range.

With 4.7B£ being invested in R&D funding by 2020-21 and with light sources contributing significantly to our science and technology base, there is a very strong case to obtain funding for design and facility build. Of the ten Industrial Strategy Pillars, light sources can support and may benefit from the following five:

- Investing in science, research and innovation: as discussed in previous sections, synchrotrons and XFELs are a crucial tool in enabling exploration of new science across many fields.
- Developing skills: investment in STEM skills is to be promoted at early career stage level.
- Delivering affordable energy and clean growth: research in materials science and (synthetic) biology may make breakthroughs in improving solar energy capture
- Driving growth across the whole country: The broad range of science that can be researched and the high level of industrial use already demonstrated at Diamond should benefit companies across the UK.

There is a suit of electron accelerators at Daresbury directly underpinned by the light source activities and expertise (VELA, Compact Linac and the E-Beam facilities) which supports a range industry research and development (security, instrument and engineering).

- Creating the right institutions to bring together sectors and places: the light source R&D activity at Daresbury creates the critical mass in engineering, technology and instrumentation valued as part of the SciTech Daresbury ecosystem which supports more than 100 high tech businesses on campus. The Diamond facility is part of the Harwell innovation campus.

The foundation of a light source institution would enable further engagement with industry and promote the use/development of new capability. While Diamond has already demonstrated success in this area, there is certainly scope for extension, in particular for FELs where new industrial applications that result from new capability have yet to develop. Identification and early engagement with potential users of the new capability, both research and industrial, should be made in a strategic and managed way. There is a clear opportunity to address one of the Industrial Strategy Pillars of 'build on our strengths and extend excellence into the future', in a managed way. For example, preferential access/rates could be agreed with industries which already or may utilise light sources for research towards technologies identified (e.g. batteries) in the Industrial Strategy Green Paper.

iii. Other industrial applications and spin-out opportunities

The R&D in light sources presents many opportunities for establishing spin-out companies. The experience of other light sources provides a large number of examples of local industries that have been commercially successful, especially when support from the major international lab was available in the initial stages. Beam instrumentation (I-Tech), undulators (Kyma), and so on. The Cockcroft Institute has already generated one spin-out company, D-Beam[42], which markets advanced diagnostics for charged particle beams, and has already made use of CLARA for product development.

6b. How could STFC support the development of the potential impacts identified?

STFC could have a clear role in supporting the development of the identified impact by fostering the engagement with the Users' community by means of workshops and dedicated liaisons offices. This will enable the definition of a strong Science Case for the next facilities, both on storage ring and FEL front, engaging with and building consensus across the community, possibly across different research councils.

Similar support should be provided by STFC, in the engaging with industrial partners and with the ODA stream of funding. The STFC should not have a passive role but proactively, surveying industrial users and partners, helping with grants applications, managing or supporting access to facilities, identifying and targeting specific industrial and manufacturing problems that can be targeted with storage ring and FELs, involving the industries in the early stage of the design and development of the facility, even at prototype level.

The IoP's Particle Accelerators and Beams Group recently conducted a survey (as yet unpublished) of its members on whether they should seek to form a Collaborative Computational Project[43] in Accelerator Science, which would include all of the accelerator themes of the STFC Roadmap. The result was a strong 'yes'. The formation of such a CCP would help enable synergies across themes to be exploited and help themes gain access to computer science experts and HPC resources. STFC and its partner EPSRC are urged to help facilitate the setting up of such a CCP. From 6 a) i above, it may be possible to include an international ODA element to such a partnership from the outset, perhaps enabling access to GCRF resources.

7a. In a reduced funding environment, which accelerator activities would you prioritise within this theme?

- **What is the minimum activity level required to keep skills alive within this theme over the next 15-20 years?**
- **What are the wider impacts of maintaining skills within this theme?**

The light source roadmap is articulated in three main topics

- Construction and operation of CLARA
- Construction and operation of the UK XFEL
- Construction and operation of the Diamond II upgrade

STFC has clearly stated that the priority of the R&D should be in support of the UK XFEL via CLARA, while at the same time does not put the UK XFEL and the Diamond upgrade as either/or alternatives. In a scenario of reduced funding therefore it is important that the potential realization of both the UK XFEL and Diamond II is maintained so R&D must continue towards both facilities, though at a reduced pace, with the priority being the completion and exploitation of CLARA.

It is conceivable to establish a user facility priority according to the level of investment that will be available. However, we should notice that the consultation of the corresponding users community needs to be carried out in much more depth and the ultimate priorities should be determined strategically by all of the research councils, UKRI, the relevant user communities, and other stakeholders. Keeping alive these R&D activities in the longer term will require the funding of at least one of these major projects. While Diamond can still operate for the next 15-20 years in a scenario of much reduced competitiveness, it is easy to predict that the technical level of the machine and of the staff will lose any competitive edge in an international environment. The situation is even more evident in the case of FELs, where the present lack of a funded user facility means that CLARA and UK XFEL R&D activities are critical to ensuring the development and sustainability of much of the expertise and capability to deliver an eventual UK XFEL facility.

7b. In an environment of increased funding, what additional activities, enabling technologies/ capabilities - or enhancements to activities, enabling technologies/capabilities already specified - would it be desirable to pursue?

- **What aspirations exist for investment into nascent areas of research?**
- **How could current, planned or proposed activities be enhanced?**

Given the scenario described in Q7a, it is natural that in a scenario of increased accelerator R&D funding that the pace of research should be increased towards realization of both user facilities. Investing in the completion of CLARA in the shortest timescale and securing the resource to underpin CLARA as a European FEL test facility would raise CLARA from a National Test Facility of significant international relevance to an International Test Facility with significant national relevance and boost the ultimate capabilities of any UK XFEL delivered in the future. This scenario is already under consideration with significant interest from international facilities as discussed earlier (see 1a and 1b). Increasing the resource to progress a UK XFEL facility science case in parallel with significant analysis of FEL technology capabilities and costings, to the stage where a design specification and technology choices could be made at the earliest time, would ensure that a full facility design study and additional prototyping of key components could be initiated in the timeliest fashion.

References

1 Synchrotron Light, IoP publication, 2010
2 Mikael Erikson et al., Diffraction Limited Storage Rings – a window to the science of tomorrow, http://journals.iucr.org/s/issues/2014/05/00/vv0002/vv0002.pdf
3 John C Hemminger et al., Challenges at the Frontiers of Matter and Energy: Transformative Opportunities for Discovery Science, U.S. Department of Energy, 2015
4 Mikael Erikson and J Friso van der Veen, Diffraction limited storage rings and new science opportunities, Journal of Synchrotron Radiation, September 2014, http://journals.iucr.org/s/issues/2014/05/00/
5 Persis S Drell & Helmut Dosch, X-ray Light Sources: An International Perspective, presentation to the US DoE, Office of Science, 2017
6 A Ten Years Vision for Diamond Light Source, http://www.diamond.ac.uk/Home/Company/Vision-and-Strategy.html
7 4GLS Conceptual Design Report, CCLRC, 2006
8 New Light Source (NLS) Project: Conceptual Design Report, STFC, 2010
9 FEL Strategic Review, STFC, 2016.
10 The UK XFEL Underpinning Accelerator & FEL Technology Programme, July 2017.
11 Persis S Drell & Helmut Dosch, X-ray Light Sources: An International Perspective, presentation to the US DoE, Office of Science, 2017
12 4GLS Conceptual Design Report, CCLRC, 2006
13 New Light Source (NLS) Project: Conceptual Design Report, STFC, 2010
14 M Mitchell Waldrop, Nature, 505, 604-606, 2014
15 Journal Highlights X-ray Laser Impacts on Biological Science
16 Brian WJ McNeil and Neil R Thompson, Nature Photon., 4, 814, 2010
17 BWJ McNeil & GRM Robb, Phys. Rev. E 70 035501(R), 2004
18 BWJ McNeil, GRM Robb, MW Poole & NR Thompson, Phys. Rev. Lett. 96, 084801, 2006
19 BWJ McNeil, NR Thompson, DJ Dunning, JG Karssenberg, PJM van der Slot & K-J Boller, New Journal of Physics 9, 239, 2007
20 E Kur, DJ Dunning, BWJ McNeil, J Wurtele & AA Zholents, New Journal of Physics 13, 063012, 2011
21 DJ Dunning, BWJ McNeil, NR Thompson & PH Williams, Physics of Plasmas 18, 073104, 2011
22 BWJ McNeil & NR Thompson, Europhysics Letters, 96, 54004, 2011 & 98 29901, 2012
23 LT Campbell & BWJ McNeil, Phys. Plasmas 19, 093119, 2012
24 JR Henderson, LT Campbell & BWJ McNeil, New J. Phys., 17, 083017, 2015
25 JR Henderson, L T Campbell, HP Freund & BWJ McNeil, New J. Phys., 18, 062003, 2016 (Fast-Track)
26 JA Clarke et al., JINST, 9, T05001, 2014
27 EA Seddon et al., accepted for publication in Reports on Progress in Physics
28 https://www.psi.ch/swissfel/
29 NR Thompson & BWJ McNeil, Phys. Rev. Lett. 100, 203901, 2008
30 DJ Dunning, BWJ McNeil & NR Thompson, Phys. Rev. Lett., 110, 104801, 2013
31 BWJ McNeil, NR Thompson & DJ Dunning, Phys. Rev. Lett., 110, 134802, 2013
32 LT Campbell, BWJ McNeil & S Reiche, New J. Phys., 16, 103019, 2014
33 JA Clarke et al, WEC02, Proc. of FEL 2017, Santa Fe.
34 http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/M011607/1
35 B Garcia, E Hemsing, T Raubenheimer, LT Campbell & BWJ McNeil, Phys. Rev. Accel. Beams 19, 090701, 2016
36 J Sekutowicz et al., PRAB 18, 050701, 2015
37 DJ Dunning, BWJ McNeil & NR Thompson, Nucl. Inst. Meth. Phys. Res., A593, 116, 2008
38 BWJ McNeil & NR Thompson, Europhysics Letters, 96, 54004, 2011 & 98 29901, 2012
39 https://www.aps.org/units/fip/newsletters/201603/africa.cfm
40 New Light on Science, The Social & Economic Impact of the Daresbury Synchrotron Radiation Source, (1981 - 2008) STFC.
41 Diamond Annual Report 2016-2017, to be published.
42 http://d-beam.co.uk/
43 http://www.ccp.ac.uk/

Neutron Sources

Executive Summary

Current Landscape

The current landscape for accelerator activities associated with neutron production is dominated by operation of the world-class ISIS spallation neutron source at STFC's Rutherford Appleton Laboratory and management and delivery of the UK's in-kind contributions to the accelerators for the new European Spallation Source (ESS) under construction in Lund, Sweden.

ISIS accelerator science and technology activities facilitate day-to-day facility operation and the programme of equipment renewal and upgrades required to keep the present ISIS accelerators running optimally and sustainably for the lifetime of the facility. For accelerator and target business as usual ~135 FTE (120 FTE accelerator, 15 FTE target) and ~£9M per year (£8M accelerator, £1M target) is required.

The UK is making significant in-kind contributions to the ESS accelerators (ASTeC, Technology Department and Huddersfield University). The combined High Beta Cavity, Linac Warm Unit and RF Distribution accelerator delivery programme for ESS equates to 75 FTE and almost £42M of hardware costs, with delivery timescales of end 2020, mid 2019 and end 2018 respectively.

Other accelerator activities currently being pursued in this theme include:

- The Front End Test Stand (FETS), which is a generic proton accelerator R&D programme (ISIS, ASTeC, JAI, Imperial College London, University College London, Huddersfield University, Warwick University and ESS Bilbao) which could enable a significant increase in the flux of neutrons available for the neutron user community on ISIS and at similar facilities worldwide.
- Ion source development plasma studies fill a vital scientific knowledge gap for ISIS and the international ion source plasma community, and are applicable to newly funded industrial collaborations (UK Space Agency, Added Value Solutions, Surrey Satellite Technology Ltd and the University of Southampton) on space thrusters.
- The Intense Beam EXperiment (IBEX) (ASTeC, ISIS, JAI, Hiroshima University), which has recently been built and commissioned at STFC Rutherford Appleton Laboratory to study the intense beam dynamics of a non-neutral plasma confined in an electrodynamic trap, which is equivalent to that in an accelerator focusing channel.

Future Horizon

Central to all the options for the future horizon is the need to maintain the UK's internationally competitive ISIS facility. In light of the significant changes anticipated over the coming years as reactor-based sources close and ESS comes on line, there should be further detailed evaluation of the UK's neutron needs in the mid-2020s. In readiness for this, at the start of 2016 ISIS launched a new ISIS-II feasibility study in order to refocus on facility upgrades with the intention of designing a major ISIS facility replacement or upgrade which would be complementary to ESS and provide enhanced neutron capacity in Europe beyond 2030. Predicted activity for ISIS-II can be readily split into three distinct phases:

- Feasibility, design studies and R&D (2017-2027).
- Integrated facility technical design (2027-2031).
- ISIS-II construction (2031-2040).

Other accelerator activities are expected to contribute directly to ISIS-II development:

- SRF cavity fabrication, preparation and testing for ESS by ASTeC at Daresbury Laboratory, building on ASTeC expertise, industrial contacts and collaboration with CEA, INFN and DESY, development of the ESS RF distribution system at Huddersfield University and discussion of the UK contribution to PIP-II at Fermilab are all intended to maintain continuity of UK capability on the timescale of a UK facility such as ISIS-II being built.
- FETS will be used by ISIS for further accelerator R&D and is eventually intended to be the injector for a small-scale FFAG test ring as part of ISIS-II R&D.
- H– ion source R&D at ISIS is important as many new and existing facilities (including ISIS-II) are looking for the best H– source.
- IBEX will address issues which will help to design better optimised high intensity rings for ISIS-II.

- Involvement in international studies of integrable optics would be linked to current IBEX work and may expose interesting alternative possibilities for ISIS-II designs.

The roadmap set out herein to maintain ISIS operations and sustainability, promote involvement with ESS and work towards ISIS-II is intended as a sensible, achievable vision for UK neutron provision over the next 20 years, in line with the findings of the recent report from the STFC Advisory Panel – Neutron & Muon Science and Facilities, A Strategic Review and Future Vision.

1a. Map current, planned and proposed accelerator science and technology activities within this theme against the science priorities (supported by STFC) they will enable over the next:

i. 1-5 years

ii. 5-10 years

iii. 10-20 years

Science and Technology Activity	Science Priorities: Maintain ISIS as core of neutron provision for the UK [1,2,3,4]	Maintain ongoing support for ESS operation [1,4]	Not close off major ISIS upgrade in 2020s complementing ESS [2]	Europeanisation/internationalisation of ISIS [1,4]	Business oportunities arising from neutron science [2,3,4]	Focus on investment for UK facilities [1,2]	Support areas of STFC scientific leadership [1,3]	High impact in Global Challenges and Industrial Strategy [3]	Reflect needs of Research Councils [3]	Collaboration with universities [1,3]	Economic and campus impact [1,3]	Inspire training, STEM development and public awareness [3,4]	Fully exploit synergies with different branches of science and technology [3]	Integrate STFC's international activities [3]	Technology capability development with industry [1,3,4]	Timescale[†]: i. 1 - 5 years	ii. 5 - 10 years	iii. 10 - 20 years
ISIS Operations and Sustainability	x		x	x	x	x	x	x	x	?	x	x	x	x	?	x	x	x
FETS	?		?			x	x			x		x	x		?	x		
ISIS-II	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ion Source Development	x		?				x			x		x				x	x	?
IBEX	?		?			x	x			x		x	x	x		x		
ESS		x		x	x		x	x	x	x	x	x	x	x	x	x	x	x
PIP-II at Fermilab*	?		?				x		x	x		x	x	x	x	?	x	?
Integrable Optics*			?				x			x		x	x	x		x	x	?

[1]STFC Neutron & Muon Science and Facilities
– A Srategic Review and Future Vision

[2]Appendix A produced by Executive Board for this review

[3]STFC Corporate Strategy 2010-2020

[4]STFC Delivery Plan 2016-2020

*Potential future activity

[†]See Q5 for detail on timescales for individual activities

Brief Science and Technology Activity Descriptions:

ISIS Operations and Sustainability. The ISIS neutron and muon source (which is a short-pulse source driven by the UK's only large proton accelerator, based on a 800 MeV rapid cycling synchrotron) supports a national and international community of more than 3000 scientists and gives unique insights into the properties of materials on the atomic scale, providing information which complements that provided by photon-based techniques. ISIS accelerator science and technology activities facilitate day-to-day facility operation and the programme of equipment renewal and upgrades required to keep the present ISIS accelerators running optimally and sustainably for the lifetime of the facility. Current high profile sustainability projects include replacement of the Target Station 1 target and services area (the TS-1 Project) and replacement of linac tank IV (both intended to be completed during a year-long shutdown in 2020), a new resonant magnet power supply, installation of a MEBT and replacement of RF valves in the linac and synchrotron with more reliable (and available) alternatives.

FETS. The Front End Test Stand (FETS) project is a generic proton accelerator R&D programme (ISIS, ASTeC, JAI, Imperial College London, University College London, Huddersfield University, Warwick University and ESS Bilbao). The production of beams as envisaged with FETS could enable a significant increase in the flux of neutrons available for the neutron user community on ISIS and at similar facilities worldwide. At the conclusion of Scientific Programmes funding FETS will be used by ISIS for further accelerator R&D and is eventually intended to be the injector for a small-scale FFAG test ring as part of ISIS-II R&D.

ISIS-II. At the start of 2016 ISIS launched a new ISIS-II feasibility study in order to refocus on facility upgrades in light of the advent of ESS and new forecast scenarios for neutron provision in Europe with the intention of designing a major ISIS facility replacement or upgrade which would be complementary to ESS and provide enhanced neutron capacity in Europe beyond 2030. The ISIS Facility Board and Scientific Advisory Committee have endorsed the recommendation that development of RCS, accumulator ring and FFAG based optimal beam dynamics designs is kept active to the point where a well informed decision can be made on which option to pursue based on technical merit and lifetime cost. The FFAG option will require R&D, with the initial proposal being the development of a prototype magnet (and later an RF system and diagnostics). If this is successful then the aim will be to incorporate these as part of a small FFAG on the end of FETS in order to explore the beam dynamics fully. A full Technical Design Report is anticipated in the period 2027-2030, in preparation for ISIS-II construction.

Ion Source Development. H– ion source R&D at ISIS is internationally important as many new and existing facilities are looking for the best H– source, including possible ISIS upgrades. Plasma studies fill a vital scientific knowledge gap for ISIS and the international ion source plasma community, and are applicable to newly funded industrial collaborations on space thrusters.

IBEX. The Intense Beam EXperiment (IBEX) experimental demonstrator (ASTeC, ISIS, JAI, Hiroshima University) has recently been built and commissioned at STFC Rutherford Appleton Laboratory. In this experiment, the intense beam dynamics of a non-neutral plasma confined in an electrodynamic trap is equivalent to that in an accelerator focusing channel. IBEX will address issues which will help to design better optimised high intensity rings for ISIS-II.

ESS. The European Spallation Source started construction in Sweden in 2014 and aims to produce first neutrons in 2020. Like ISIS the ESS will be an accelerator-based facility, but will be a high-power long-pulse source based on a 2 GeV superconducting linac. The UK is making significant in-kind contributions to the ESS accelerators (ASTeC, Technology Department and Huddersfield University) and may be expected to provide continued support in the operational phase.

PIP-II at Fermilab. This project is to replace the existing 400 MeV Fermilab linac with an 800 MeV superconducting linac capable of CW operation for the Long Baseline Neutrino Facility (LBNF). UK involvement would help to maintain the SRF linac skills and infrastructure capabilities built up from accelerator activities for ESS and develop UK fabrication capability for multi-cell SRF structures in preparation for ISIS-II.

Integrable Optics. The novel accelerator concept of non-linear integrable optics relies on non-linear magnetic fields and non-linear dynamics. This is an area of interest to the UK accelerator community in general and could provide a major area of overlap across UK programmes. In the context of neutron production involvement in international studies would be linked to current IBEX work and may expose interesting alternative possibilities for ISIS-II designs.

1b. Please comment on the current UK position of each accelerator science and technology activity in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and capacity be exploited?**

ISIS Operations and Sustainability. The ISIS International Review held in 2013 noted that 'it is remarkable that ISIS, although a primarily nationally funded facility, compares, in all aspects, favourably to the international facilities', that 'it continues to set the standard for operation and user support' and that 'a proton accelerator running recently with average efficiencies higher than 90% will place ISIS in the top league of proton accelerators if maintained'. ISIS provides support for all comparable international neutron production facilities (SNS, ESS, J-PARC, LANSCE, PSI, CSNS, ILL, NIST) with expert membership of numerous Technical Advisory Committees and leading contributions to global development of neutron instruments, detectors, data acquisition and sample environment techniques. In an accelerator context ISIS has recently been involved in close collaboration with international facilities on novel beam diagnostics (SNS, GSI, CERN), ion sources (SNS, CERN, CSNS, Fermilab, LANSCE), injection beam dynamics (J-PARC, CERN), stripping foils (J PARC, CSNS, CERN), swept-frequency RF systems (J-PARC, CSNS), ring instabilities (GSI) and resonant magnet power supplies (CSNS). ISIS remains a world leading facility and accelerator operations and sustainability are critical to its ongoing success, with particular importance having to be placed on the challenging requirements of running a mature machine with many older components. Other facilities (particularly SNS) are keen to learn from this experience at ISIS. Close connection of the ISIS accelerator team to major international laboratories working in the field and a number of collaborations on topical subjects should be sufficient to cover some gaps in the UK knowledge and expertise base.

FETS. The FETS RFQ design includes the development of new techniques in the design as well as in the manufacturing process and the international community has expressed strong interest in the forthcoming results. FETS has a strong collaboration with CERN on beam instrumentation and cavities, and an ongoing collaboration with ESS Bilbao. The production of beams as envisaged with FETS, with high brilliance, large duty factor and 'ideal' chopping will provide world leading performance for neutron production, high-energy physics and other applications requiring a high-intensity proton driver.

ISIS-II. Designs for a major ISIS facility replacement or upgrade are unsurprisingly not intended to support international projects or facilities, but close connection of the ISIS accelerator team to major international laboratories working in the field (see examples quoted for ISIS Operations and Sustainability above) greatly strengthens ISIS-II efforts and will ensure that design study results are freely disseminated to all interested parties. The UK has world leading capability, particularly in beam dynamics expertise, but also in most aspects of the design and operation of proton accelerators for neutron production. However, for ISIS-II it will be necessary to build capability in some areas by carrying out appropriate R&D, potentially exploiting UK capability in the institutes and academia (e.g. for FFAGs) and in others by participating in international projects (e.g. superconducting RF for ESS and PIP-II). ISIS-II is already exploiting international capability and capacity by, for instance, keeping a watching brief on SNS and J-PARC exploration of short-pulse target operation above 1 MW. As has been the case for ESS it is fully anticipated that in the technical design and construction phases of ISIS-II international partners will become involved in various development aspects and potential in-kind contributions.

Ion Source Development. Facilities worldwide are still looking for the ideal H– ion source, with current performance not yet meeting requirements for reliability, lifetime and output. For many years ISIS has been at the centre of international efforts to develop better H– sources, collaborating closely with CERN, Fermilab, LANSCE, SNS, CSNS and others on simulation, design and test of various source types. The UK has world leading expertise and experience of Penning surface plasma sources, plasma modelling and beam transport. After development of a scaled Penning source (primarily intended to achieve the full specification for FETS) ISIS intends to exploit source development at SNS and CERN to produce an RF volume source suitable for use on ISIS-II.

IBEX. This experiment allows UK researchers ready access to an electrodynamic trap of the type originally developed at Hiroshima University. As this is one of the few experiments of its type in the world it has generated a great deal of international interest, with Fermilab keen to collaborate.

ESS. The UK's in-kind contributions for the ESS accelerator encompass the following project delivery areas:

a) All high-beta, Superconducting RF accelerating cavities.

b) All Linac Warm Units (LWU) located between each SRF linac cryomodule.

c) All RF waveguide distribution systems for the SRF linac.

The UK has unique SRF capabilities in Europe, having developed linac technologies and operated SRF linac systems over many years at Daresbury Laboratory. For the high-beta cavity project ASTeC is collaborating with CEA-Saclay (France), INFN-Milan (Italy), DESY (Germany) and the ESS Linac group (Sweden) to procure and test all 84 SRF accelerating cavities for the high-energy stage of the ESS linac, taking proton beam energies from 570 MeV to 2.0 GeV. For the LWU project, a total of 74 integrated modules, in addition to 48 beam-pipe units will be prepared and tested in collaboration with ELETTRA (Italy) and DESY (Germany) who are respectively providing the magnets and beam position monitors which form major parts of the LWU integration. For the RF Distribution project, STFC is collaborating with Huddersfield University to provide the 'passive' RF distribution network for the SRF spoke and elliptical linac systems, which comprise waveguide, circulators, loads, couplers, arc detectors and all installation support infrastructure. Any gaps in UK knowledge and/or experience are being sourced through collaborations with other leading international groups e.g. JLab (USA) for SRF vertical test RF controls and commissioning of high beta cavities. The scope for each of these ESS in-kind projects is well-defined and agreed with ESS as Technical Annexes to the formal UK-ESS in-kind agreement.

PIP-II at Fermilab. Potential UK contribution for the PIP-II accelerator would comprise procurement, test and cryomodule integration of 24 SRF accelerating cavities into four dedicated cryomodules, which would then be tested at Fermilab to PIP-II specifications. The project would follow-on from the ESS high-beta cavity testing programme, taking advantage of Superconducting RF assembly and testing capabilities built up over many years for the linac system delivery for ESS and HL-LHC cryomdoule integration. Collaboration with UK industry is envisaged in order to demonstrate first UK fabrication capability for multi-cell SRF structures, which are compliant with the high performance specification envisaged for PIP-II.

Integrable Optics. As a relatively new idea, but with great potential to change current thinking on accelerator design this is an activity in which the UK accelerator community intends to participate along with the international community.

2a. What enabling accelerator technologies/ capabilities (including computing, vacuum, RF, lasers etc.) are necessary to pursue each accelerator activity?

Key technologies	Science and Technology Activity: ISIS Operations and Sustainability	FETS	ISIS-II	Ion Source Development	IBEX	ESS	PIP-II at Fermilab	Integrable Optics
Diagnostics	x	x	x	x	?	x	x	x
Front end	x	x	x	x		x	x	
Linac	x	x	x		x	x	x	
RF Sources[1]	x	x	x	x	x	x	x	
FFAGs[1] and high intensity rings	x		x		x			x
Superconducting/permanent magnets	?		x				?	?
Large AC magnets	x		x					
Energy Efficiency[1]	?		x			x	x	?
Injection/extraction[1] and beam dynamics	x	x	x	?	x			x
Superconducting RF[1]			x			x	x	
Vacuum	x	x	x	x	x	x	x	?
Controls and interlocks	x	x	x	x	?	x	x	?
Computing	x	x	x	x	x	x	x	x
Targets and moderators[1]	x		x				x	
Skills/retention/training/development[1]	x	x	x	x	x	x	x	x

[1]Identified in 'Applications of Particle Accelerators in Europe' as a key area for development for neutrons

2b. Please comment on the current UK position of each enabling technology/capability in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and/or capacity be exploited?**

Diagnostics. High resolution diagnostics, data acquisition and correction systems are increasingly important for high-intensity applications such as neutron production, where control of beam losses is of paramount importance for optimisation of machine performance and protection. The UK produces world leading diagnostics (often in collaboration with international partners) such as the strip-line monitors, fast, non-destructive residual gas profile monitors with space-charge correction and localised scintillator beam loss monitoring at ISIS, laser diagnostics for H– photo-detachment profile monitoring developed for FETS and tested at CERN, and development of diagnostics at the Cockcroft Institute suitable for future research infrastructures including ESS. The UK (CI Liverpool) is involved in development of high power target profile monitoring for ESS. Halo monitoring will need to be improved for next generation high-intensity machines.

Front End. Covered by FETS and Ion Source Development discussion in Q1b.

Linac. Recent investment at ISIS in replacement of linac tank IV has re-established the current UK manufacturing base for linac tanks and drift tubes at 202.5 MHz, but more work would be required to produce similar structures at the 324 MHz expected for ISIS upgrades. As 324 MHz is the frequency in use at J-PARC, CSNS and ESS international capability could be exploited. ASTeC production of warm linac modules for ESS is clearly an area where the UK has demonstrated world leading capability. Regarding superconducting linac stages see the discussion of Superconducting RF below.

RF Sources. Efforts to ensure ISIS linac and synchrotron RF sustainability have led to recent exploration of alternative valves, possible solid-state valve replacements and a general push towards digital low-level RF, which has involved discussion and collaboration with J-PARC, CERN, CSNS, LANSCE and others. However the eventual goal of this work is to attain sustainable operation with 'industry standard' technology rather than to be world leading. RF technology readiness for normal conducting systems for ISIS upgrades will require development of an FFAG RF system and increased familiarity with IOT and klystron sources. ISIS has a watching brief on magnetic alloy cavity operation and development at J-PARC.

FFAGs and high intensity rings. The UK has a strong reputation in FFAG design, with expertise within National Laboratories, Institutes and University groups. International collaboration in this area is strong and the UK has been a leading participant in experimental FFAG work at KURRI and in international FFAG workshops. The PAMELA and NORMA medical FFAG designs and the realisation of 'serpentine channel' acceleration with EMMA at Daresbury Laboratory are evidence of world leading capability in the UK. If an FFAG test ring as part of ISIS-II R&D becomes a reality this will provide a focus for UK and international efforts and will have distinct overlap with other applications (neutrino physics, medical, etc.). Likewise a long tradition of ISIS expertise in RCS and accumulator ring high intensity beam dynamics and experimentation places the UK at the forefront of international R&D in this area.

Superconducting/permanent Magnets. STFC ASTeC/ Technology Department and CERN have created a project to develop steering and focusing magnets that draw no power. The project is named ZEPTO (Zero-Power Tuneable Optics) and achieves power savings by using large, strong permanent magnets which move to adjust the field strength. These are intended as a demonstrator for CLIC, but could be applicable to power saving in fixed field magnets for ISIS-II designs. In parallel ISIS has engaged Technology Department to look at other possibilities for superconducting and permanent magnets for ISIS and ISIS-II, and is testing samples of permanent magnets from ZEPTO for radiation hardness. It is likely that increased UK expertise in superconducting magnets will be required for ISIS-II and for developments in other roadmap themes.

Large AC Magnets. ISIS has recently designed and procured many new DC and pulsed electromagnets for its extracted proton beam lines, but there is currently a requirement to re-establish large AC normal conducting magnet production for ISIS sustainability and any new RCS based facility. As no such magnets have been manufactured for a UK application for over 30 years it is reasonable to say that the UK is world lagging in this area. The ISIS team has established links with their counterparts at CERN, and have contacts with CSNS (who have had similar magnets manufactured recently in China).

Energy Efficiency. Establishing that any accelerator design for a new neutron production facility is as energy efficient as possible will be increasingly important when bidding for funding, both in terms of operational running costs and environmental impact. Initiatives with superconducting and permanent conducting magnets are already underway in ASTeC at STFC, and FFAG and accumulator ring designs are being pursued at least in part because they present the opportunity to use fixed field magnets. Clean energy sources and energy recycling as promoted by ESS will be high on the agenda for definition of a new facility. STFC has participated in a number of international accelerator energy efficiency workshops and expects to take a full part in future.

Injection/extraction and beam dynamics. ISIS is involved in international collaborations on injection beam dynamics (J-PARC, CERN) and stripping foils (J-PARC, CSNS, CERN) and other key areas of beam dynamics such as ring instabilities (GSI). World leading beam dynamics expertise has allowed ISIS to propose novel solutions for efficient multi-turn injection without the requirement of charge exchange (therefore removing the need for H– injection or a stripping foil) which will be pursued as part of ISIS-II design studies, along with efficient extraction schemes, possibly using superconducting or permanent magnets. Overlap with work at J-PARC, SNS and CSNS will be exploited wherever possible.

Superconducting RF. New large scale facilities currently envisaged for neutron production (and ADS, neutrino physics, etc.) will require a large superconducting linac. If the UK is to participate in these projects (or build a new facility itself) an increase in UK expertise, technology capability and manufacturing base is desirable. SRF cavity fabrication, preparation and testing for ESS at ASTeC, building on ASTeC expertise, industrial contacts and collaboration with CEA, INFN and DESY, development of the ESS RF distribution system at Huddersfield University and discussion of the UK contribution to PIP-II at Fermilab are all intended to maintain continuity of UK capability on the timescale of a UK facility such as ISIS-II being built. Considerable expertise in this area has also been built up in CI for the LHC upgrade and could be exploited for ISIS-II. Applicability of such SRF capabilities will also be a requirement for other roadmap areas, in particular Frontier and Nuclear Physics and Light Sources themes.

Vacuum. Most accelerator vacuum requirements for neutron production are well covered by currently available technology, however there is a requirement to re-establish technology for ceramic vacuum vessel manufacture which ISIS is addressing as part the sustainability programme. The UK industrial supply and manufacturing base is particularly strong in the vacuum field, with more than 20 UK companies active. For ISIS-II it will be interesting to investigate whether to exploit new RF screening techniques being used at J PARC and CSNS.

Controls and Interlocks. Controls and interlocks requirements are covered by currently available technology. For a new facility the likelihood is that an EPICS control system would be adopted as this is the current ‘industry standard’ and a transition towards EPICS on ISIS in anticipation of this will probably occur over the next few years. A fully IEC61508 compliant interlock system should also be expected.

Computing. The world-leading high intensity beam dynamics now required for neutron facility development requires access to appropriate computing resources. For ISIS-II the emphasis needs to be on space charge issues and the development of codes especially for FFAGs and long-term tracking. There are also other modelling (as well as technical) issues in relatively small high intensity machines like the heavy beam loading, CW operation, etc. Development of really fast codes (with space-charge) that can be used during machine operation (for instance to reset parameters to ensure continuous operation if a cavity fails) will be increasingly important to optimise availability. Provision of continued access to parallel computing infrastructure (which is currently provided by local clusters) is vital for a variety of beam dynamics simulations. The UK has a long history of leading international collaboration on beam dynamics, simulation and computing, and continuation of this tradition is to be expected.

Targets and Moderators. The ISIS Target Engineering Group and Neutronics Group lead target and moderator design work for ISIS and ISIS-II, with significant contributions from the Target Studies Group in Technology Department. The Target Studies Group itself provides world leading contributions to neutron capture and moderation systems to 0.5, 1 and 5 MW and has contributed to studies of the 5 MW ESS target, as well as having an interest in particle production targets for neutron production for medical, security and energy applications, including ADSR. Huddersfield University’s range of target simulations includes backgrounds from targets and beamlines, possible activation in FETS, and studies for ESS. ISIS-II is already exploiting international capability and capacity by keeping a watching brief on SNS and J-PARC exploration of short-pulse target operation above 1 MW and novel ESS moderator configurations.

Skills/retention/training/development. See Q4.

3. Map the necessary enabling technologies/ capabilities required for activities within this theme against accelerator activities within the other accelerator themes.

Key technologies (Neutron Theme) — Light Sources

Key technologies (Neutron Theme)	Design, construct, commission CLARA	Exploitation of CLARA	Upgrade CLARA to a light source user facility	UK XFEL Underpinning Technology Programme	UK XFEL Design, construction, commissioning	UK XFEL operation and upgrades	SwissFEL Commissioning (Aramis, Athos, Porthos)	CLARA as European FEL Test Facility	EuPRAXIA Design and Construction	FEL for 12.4nm Lithography	CompactLight Design Study	DLS Operations and Sustainability	DLS-2
Diagnostics/Instrumentation	x	x	x	x	x	x		x	x	x			
Front end (Sources, injectors)	x	x	x	x	x	x		x	x	x	x		
Linac	x	x	x	x	x	x		x	x		x		
RF Sources	x	x	x	x	x	x		x	x		x		
FFAGs and high intensity rings				x	?	?				?			
Superconducting/permanent magnets	?		?		?	?		?	?				
Large AC magnets	x	x	x	x	x	x		x	x	x			
Energy Efficiency	x	x	x	x	x	x		x		x	x		
Injection/extraction and beam dynamics	x	x	x	x	x	x	x	x	x	x	x		
Superconducting RF				x	?	?		?		x			
Vacuum	x	x	x	x	x	x		x	x	x			
Controls and interlocks (Timing)	x	x	x	x	x	x		x	x	x			
Computing	x	x	x	x	x	x	x	x	x	x	x		
Targets and moderators													
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x		

Frontier and Nuclear Physics Machines* / Novel Accelerators

Key technologies (Neutron Theme)	Neutrino factory	LBNF/DUNE	Mu2e upgrade	Muon Ionisation Cooling	HL-LHC	CLIC	LWFA	PWFA	Hybrid LWFA-> PWFA	Laser ion/proton acceleration	Dielectric e-beam driven	Dielectric laser-driven	THz-driven
Diagnostics/Instrumentation	x	x			x		x	x	x	x	x	x	x
Front end (Sources, injectors)	x	x			?								
Linac	x	x			?			x			x		
RF Sources	x	x			x			x			x		x
FFAGs and high intensity rings	x												
Superconducting/permanent magnets	x	?		x	x	x	x	x	x				
Large AC magnets	x												
Energy Efficiency	x	x	x	x	x	x							
Injection/extraction and beam dynamics	x				?		x	x					
Superconducting RF	x	x			x	x		x					
Vacuum	x	x	x	x	x	x	x	x	x	x	x	x	x
Controls and interlocks (Timing)	x	x	x	x	x	x	x	x	x	x	x	x	x
Computing	x	x	x	x	x	x	x	x	x	x	x	x	x
Targets and moderators	x	x	x	x						x			
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x	x	x

Industrial, Medical, Defence and Security Applications

Key technologies (Neutron Theme)	keV electron beams	MeV electron beams	Ion beams	X-ray radiotherapy	Particle therapy	VHEE	Radioisotope production	X-ray imaging	Nuclear security	ADSR	Transmutation	Nuclear fussion - material testing	Water/sludge treatment	Flue gas	Agri-tech
Diagnostics/Instrumentation		x			x	x	x	x	x	x	x	x		x	
Front end (Sources, injectors)	x	x			?	x	x		x	x	x				
Linac	x	x			?	x	x	x	x	x	x	x	x	x	x
RF Sources		x			x	x	x	x		x	x	x	x	x	x
FFAGs and high intensity rings					x	x				x	x				
Superconducting/permanent magnets					?	?				?	?	?			
Large AC magnets															
Energy Efficiency	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Injection/extraction and beam dynamics					x		x			x	x				
Superconducting RF							x			x	x				
Vacuum	x	x			x				x	x	x				
Controls and interlocks (Timing)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Computing	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Targets and moderators							x	x	x	x		x			
Skills/retention/training/development	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

*NB no information was received directly from the Frontier and Nuclear Physics Machines theme roadmap coordinators

4a. What skills, experience and leadership is necessary to achieve each accelerator science and technology activity?

General. For the purpose of this review the following resource categories have been identified as important for the neutron theme (see Q2a for enabling capabilities):

- Accelerator Physics
- Mechanical Engineering
- Mechanical Technical
- Electrical/Electronics Engineering
- Electrical/Electronics Technical
- RF Engineering
- Neutron/Muon Science
- Neutronics
- Civil Engineering and Architecture
- Project Management
- Other (for instance project administration, procurement and legal services, etc.)

These are the categories used in the resource graphs for Q5, which give an indication of how many FTEs in each category are required for the delivery of each activity.

ISIS Operations and Sustainability. As with all large accelerator facilities ISIS has a strong need for experienced professional physicists, engineers and technicians. At ISIS many of these staff members are former STFC sponsored PhD students, former STFC Graduate Trainees and former STFC/Harwell Apprentices. For current business as usual activities it has been possible, but is becoming increasingly difficult, to maintain adequate skills levels as positions are often in direct competition with industries where more competitive salaries are on offer. Due to these difficulties with both recruitment and retention there is evidence that although FTEs at ISIS have remained stable the average age and hence experience of the workforce has dropped significantly as it becomes more difficult to attract mid-career engineers. Nonetheless, ISIS currently has strong leadership and adequate capacity to deliver sustainable operations.

FETS. FETS draws on a strong UK base of national laboratory and university skill, experience and leadership in accelerator physics and front end design. However it is probably a reasonable observation that it has not always had enough mechanical and electrical engineering and technical effort at its disposal, and this has been an important point to address as FETS has drawn closer to ISIS.

ISIS-II. The skills, experience and leadership required to deliver the feasibility, design studies and R&D phase for ISIS-II have a high degree of overlap with ISIS Operations and Sustainability, and should prove adequate provided there is access to some additional effort from the Target Studies Group in Technology Department, university engineering departments and contract effort, as discussed in Q5. Likewise ISIS has appropriate test stands and build areas which can be used for this phase. For the integrated facility technical design and construction phases the increase in staff numbers required would be extremely challenging to achieve by drawing on the present skills pool and in light of current difficulties in recruitment and retention at the national laboratories (this is not specific to ISIS-II and would apply to any similarly large technical project).

Ion Source Development. This activity has an appropriate balance of skills, experience, leadership and capability provided by ISIS staff.

IBEX. This activity has an appropriate balance of skills, experience, leadership and capability provided by ISIS staff and JAI staff, PhD students and placement students.

ESS. For the contracted areas of technology delivery for ESS, both STFC ASTeC and Technology Departments are providing all of the necessary leadership and technical skills over the timescales envisaged for achieving milestones. The investment being implemented to support SRF cavity testing is envisaged to be utilised for other SRF related projects, not only in terms of the qualification infrastructure, but also in terms of the skilled staffing resource developed over the 5-year duration of the project delivery to ESS.

PIP-II at Fermilab. A primary example for UK opportunity development in the field of SRF technology delivery, taking advantage of UK SRF capabilities, is for the PIP-II SRF linac at FNAL in the USA. Following on from the ESS delivery which is expected to conclude in early 2021, the PIP-II SRF cavity fabrication and testing, with subsequent cryomodule integration is expected to transition seamlessly starting in 2020/21 and utilising the same leadership and technical skills developed for ESS, but applied to delivering the four integrated cryomodules for PIP-II by 2024/25.

Integrable Optics. This activity has an appropriate balance of skills, experience, leadership and capability provided by ISIS and JAI staff.

4b. Please comment on the current UK position regarding the necessary skills, experience, leadership and capacity in the international context.

Accelerator Physics. UK skills, experience, leadership and capability remain strong for physics design of neutron production facilities. ISIS and ASTeC have been in demand to provide underpinning work for ESS. The J-PARC RCS was designed by a current ISIS (formerly ASTeC) staff member. ISIS has a strong accelerator physics team with many years' experience in operations, R&D, experiments, code development and PhD supervision and is now developing further expertise on core topics of impedance, instabilities, space-charge loss, etc. This activity trains and develops excellent physicists who will sometimes go on to work elsewhere. ISIS is still able to attract accelerator physicists of international standing, despite salaries being uncompetitive, but this is unlikely to remain the case indefinitely. There is also considerable relevant UK expertise available in academia (particularly in the institutes and Imperial College London) generated by recent/current projects such as HL-LHC-UK and the Neutrino Factory International Design Study.

Mechanical Engineering, Mechanical Technical, Electrical/Electronics Engineering, Electrical/Electronics Technical. All present a clear and present challenge for recruitment, retention and maintenance of the skill and experience base in the UK. Internationally comparable facilities (SNS, J-PARC, ESS) appear to have less of a problem as salaries are relatively higher (and in the case of SNS the cost of living is lower).

RF Engineering. RF engineers globally are an extremely scarce resource and so are particularly difficult to recruit and retain. ESS and SNS have similar difficulties to ASTeC and ISIS in this area, despite the much higher salaries on offer.

Neutron/Muon Science. ISIS neutron and muon scientists have world leading expertise in instrument specification and design and are in great demand, for instance to participate in ESS instrument builds. Sharing of this expertise between neutron facilities (in particular ISIS, ILL, SNS) is relatively common. CSNS are very keen to build their expertise and neutron scattering community through interaction with ISIS scientists.

Neutronics. The type of neutronics specific to neutron production targets, reflectors and moderators is a very niche area, where ISIS has significantly strengthened its team recently and is now in a position to collaborate more effectively with e.g. SNS and ESS.

Civil Engineering and Architecture. No obvious comparison.

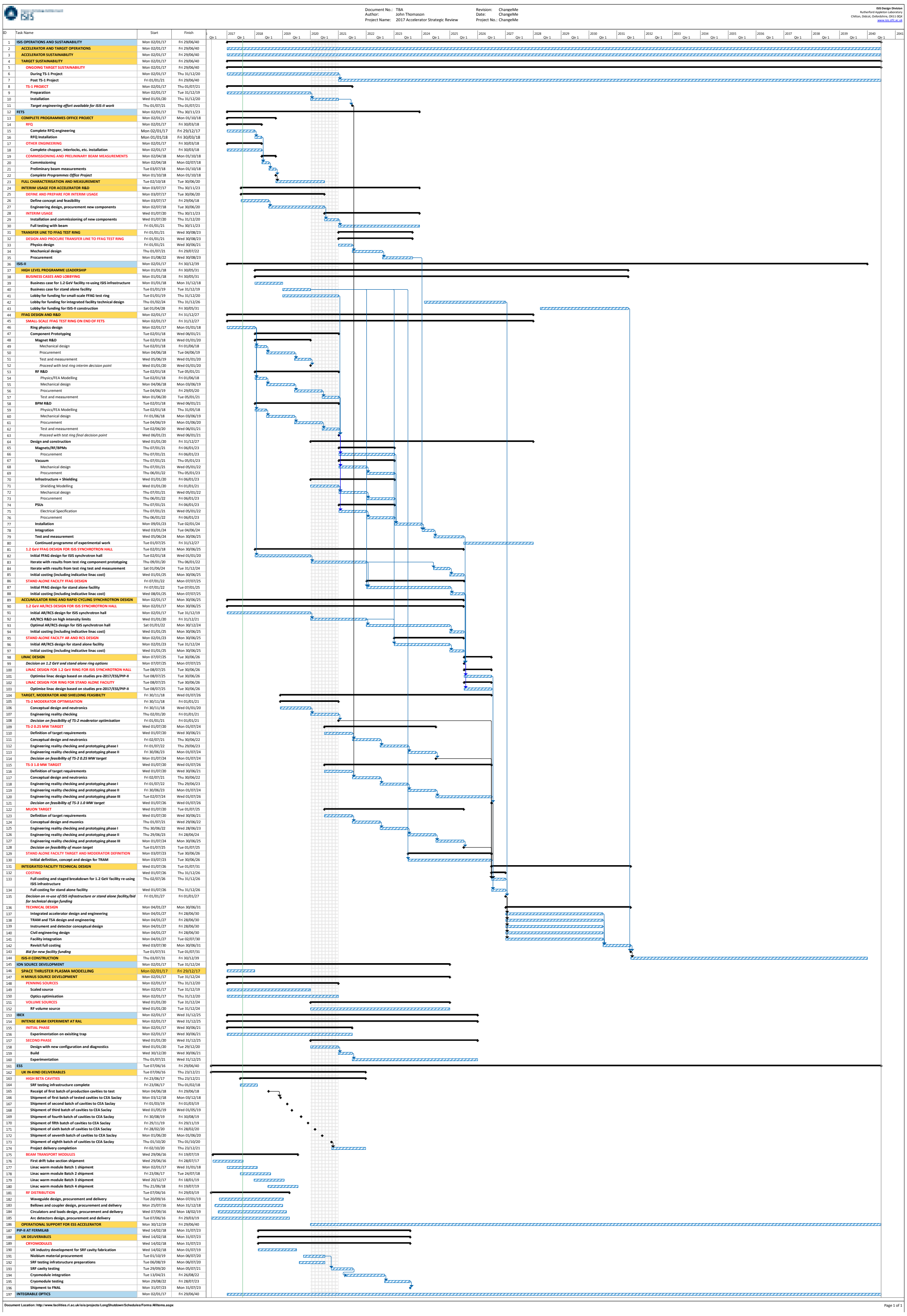
Project Management. SNS are interested in learning from ISIS project management and prioritisation techniques, particularly in the context of managing an ageing facility and of cost effective project delivery. Similarly STFC project management expertise is recognised as part of the UK's programme delivery for ESS, with strategic project management responsibility being undertaken by STFC for all of the accelerator delivery projects.

Other (for instance project administration, commercial and legal services, etc.). ESS will provide valuable lessons learnt in preparation for ISIS-II.

Test Stand Capability. ISIS and ASTeC test facilities for magnets, RF systems, front ends, ion source, etc. are broadly comparable with those at SNS and J-PARC, but typically have fewer dedicated staff associated with them, both for operation and development.

Build Space Capability. Will be greatly enhanced on completion of the Harwell Facilities Building at RAL, which will provide space for ESS instrument build, the TS-1 Project, ISIS-II R&D and enhanced active waste management. This is comparable with similar pre-construction provision made at CSNS and post-construction provision at SNS.

5. What are the milestones, timescales and indicative costs for pursuing each accelerator science and technology activity?




Accelerator Physics
Mechanical Engineering
Mechanical Tech
Electrical/Electronic Engineering
Electrical/Electronic Tech
RF Engineering
Neutron/muon Science
Neutronics
Civil Engineering and Architecture
Project Management
Other
In-year Spend (£m)
Cumulative Costs
ISIS Operations & Sustainability
FETS
ISIS II
Ion Source Development
IBEX
ESS
PIP-II at
Integrable Optics
Resource FTEs
Millions

Commentary:

General. In all of the above resource estimates:

- FTEs are per year and the cost of these FTEs is not included in in-year spends.
- In-year spends are for the sum of capital and resource.
- No attempt has been made to apply inflation to any of these indicative figures.

ISIS Operations and Sustainability. FTEs and in-year spends include figures for both accelerator and target activities. For business as usual ~135 FTE (120 FTE accelerator, 15 FTE target) and ~£9M per year (£8M accelerator, £1M target) is required. Increased resource in the period 2017-2020 is associated with the TS-1 Project, on completion of which ISIS target engineering and neutronics effort will become available for target, moderator and shielding feasibility studies for ISIS-II. All of this activity is covered by the ISIS facility budget.

FETS. In general resource levels for the continuation of this activity are within the envelope of the ISIS facility budget. However, interim usage for accelerator R&D would probably require additional funding (~£2M) during the period 2018-2020. After 2023 the intention is that FETS becomes the injector for a small-scale FFAG test ring as part of ISIS-II activity.

ISIS-II. This activity can be readily split into three distinct phases:

1) Feasibility, design studies and R&D (2017-2027). In general resource levels for this activity are within the envelope of the ISIS facility budget. However, in the period 2023-2025 requirements for mechanical engineering towards FFAG design and target, moderator and shielding feasibility studies become larger than ISIS can provide. This issue could be addressed by increased (and earlier) involvement of the Target Studies Group in Technology Department, university engineering departments and contract effort. The main requirement for additional funding is associated with building a small-scale FFAG test ring (~£10M) during the period 2021-2024.
2) Integrated facility technical design (2027-2031). Following the decision on exactly what should be built a largely new team of ~150 FTE will be required to produce a full 'shovel-ready' design. This will require significant recruitment in all key technical areas. It should be noted that for phases 2) and 3) indicative FTEs and costs now reflect design and build of the whole facility rather than just accelerators and targets.
3) ISIS-II construction (2031-2040). Indicative FTEs reflect the effort currently involved in ESS construction, which is on a similar scale. For simplicity the breakdown in effort of various types has been taken as constant throughout the build – the reality would obviously be somewhat different. The cumulative cost of the project has been given as a round figure of ~£1B (excluding FTEs), but this is only intended as a very early indication of the actual cost.

Ion Source Development. Resource levels for this activity are within the envelope of the ISIS facility budget, including the cost of development of an RF volume source in the period 2020-2023.

IBEX. Resource levels for this activity are within the envelope of the ISIS facility budget, including provision for a new configuration and diagnostics in the period 2019-2021.

ESS. The combined High Beta Cavity, Linac Warm Unit and RF Distribution accelerator delivery programme for ESS equates to 75 FTE and almost £42M of hardware costs, with delivery timescales of end 2020, mid 2019 and end 2018 respectively. No estimate of any ongoing contribution to ESS accelerator operations has been included.

PIP-II at Fermilab. Resourcing levels for the delivery of four integrated Superconducting RF cryomodules have been determined based on existing resourcing provision of SRF cavity procurement, manufacture and testing of cavities for ESS and also by extrapolation of the resources anticipated for completion of the pre-series crab cavity cryomodule integration for HL-LHC, both of which are expected to conclude by the end of 2020. The total scale of this project, which includes demonstration of SRF cavity fabrication capability with UK industry, is £14.6M hardware costs and 40 FTE of manpower resource over a 4 year programme.

Integrable Optics. Resource levels for this activity, which is likely to be ongoing for a number of years, are within the envelope of the ISIS facility budget.

6a. Map each accelerator science and technology activity and enabling technology/capability against potential impacts to:

i. ODA Strategic Objectives[1,2]

1 ODA Strategic Objectives: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/478834/ODA_strategy_final_web_0905.pdf
2 UN Global Goals: http://www.globalgoals.org/

a) The ISIS facility and the neutron science it enables score very highly in this area. The STFC impact study Neutron scattering Materials research for modern life demonstrates the strong impact of neutron science on energy, environment and climate, medicine and health, electronics and IT, manufacturing and industry, natural world and heritage science, all of which can be readily

		ODA Strategic Objectives																				
		Strengthening global peace, security and governance [1]	Strengthening resilience and response to crises [1]	Promoting global prosperity [1]	Tackling extreme poverty and helping the world's most vulnerable [1]	No poverty [2]	Zero hunger [2]	Good health and wellbeing [2]	Quality education [2]	Gender equality [2]	Clean water and sanitation [2]	Affordable and clean energy [2]	Decent work and economic growth [2]	Industry, innovation and infrastructure [2]	Reduced inequalities [2]	Sustainable cities and communities [2]	Responsible consumption and production [2]	Climate action [2]	Life below water [2]	Life on land [2]	Peace, justice and strong institutions [2]	Partnerships for the goals [2]
Science and Technology Activity	ISIS Operations and Sustainability		a	a	a	a	a	a			a	a	a	a		a	a	a	a	a		
	FETS											b										
	ISIS-II	a	a	a	a	a	a	a			a	a	a	a		a	a	a	a	a		
	Ion Source Development																					
	IBEX																					
	ESS	a	a	a	a	a	a	a	a		a	a	a	a		a	a	a	a	a		
	PIP-II at Fermilab																					
	Integrable Optics																					
Key technologies	Diagnostics																					
	Front end											b										
	Linac											b										
	RF Sources																					
	FFAGs and high intensity rings											b										
	Superconducting/permanent magnets																					
	Large AC magnets																					
	Energy Efficiency																					
	Injection/extraction and beam dynamics																					
	Superconducting RF											b										
	Vacuum																					
	Controls and interlocks																					
	Computing																					
	Targets and moderators											b										
	Skills/retention/training/development	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c

[1] UK aid: tackling global challenges in the national interest
[2] The global goals for sustainable development

mapped onto ODA strategic objectives. This impact is directly dependent on the continued development and operation of the accelerator.

b) Application of these key technologies to ADSR.

c) Naturally.

ii. Industrial Strategy Pillars[3]

3 Industrial Strategy Pillars: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/611705/building-our-industrial-strategy-green-paper.pdf

a) See argument for ODA above.

b) Application of these key technologies to ADSR.

c) Naturally.

iii. Other industrial applications and spin-out opportunities

a) Ion source development plasma modelling techniques applicable for space thrusters.

		Industrial Strategic Pillars									
		Investing in science, research and innovation [1]	Developing skills [1]	Upgrading infrastructure [1]	Supporting businesses to start and grow [1]	Improving procurement [1]	Encouraging trade and inward investment [1]	Delivering affordable energy and clean growth [1]	Cultivating world-leading sectors [1]	Driving growth across the whole country [1]	Creating the right institutions to bring together sectors and places [1]
Science and Technology Activity	ISIS Operations and Sustainability	a	c					a	a		
	FETS		c					b			
	ISIS-II	a	c					a	a		
	Ion Source Development		c								
	IBEX		c								
	ESS	a	c					a	a		
	PIP-II at Fermilab		c								
	Integrable Optics		c								
Key technologies	Diagnostics		c								
	Front end		c					b			
	Linac		c					b			
	RF Sources		c								
	FFAGs and hig intensity rings		c					b			
	Superconducting/permanent magnets		c								
	Large AC magnets		c								
	Energy Efficiency		c								
	Injection/extraction and beam dynamics		c								
	Superconducting RF		c					b			
	Vacuum		c								
	Controls and interlocks		c								
	Computing		c								
	Targets and moderators		c					b			
	Skills/retention/training/development	c	c	c	c	c	c	c	c	c	c

[1]Building our Industrial Strategy

6b. How could STFC support the development of the potential impacts identified?

Impact of neutron science. Clearly neutron science is a major factor in STFC's impact towards ODA and industrial strategy. STFC can continue to support the development of this impact by appropriate investment in UK neutron provision in the short, medium and long term.

Impact on ADSR. Should be covered under the Industrial, Medical, Defence and Security Applications theme of this review.

Impact on development of space thrusters. Two funded space thruster projects have brought collaboration between the UK Space Agency, the ISIS Low Energy Beams Group, Added Value Solutions, Surrey Satellite Technology Ltd and the University of Southampton. The collaboration aims to design and test two game-changing ion thruster technologies: Impulse and Aquajet. The initial stage of the project will deliver thrusters at technology-readiness level (TRL) 3. With growing commercial demand and public awareness of ion thrusters, development towards a first space-based demonstration at TRL7 of either of these thrusters would have significant industrial impact. STFC could support this development by increasing inter-departmental collaboration and enhanced investment into cutting-edge space propulsion technologies.

7a. In a reduced funding environment, which accelerator activities would you prioritise within this theme?

- **What is the minimum activity level required to keep skills alive within this theme over the next 15-20 years?**
- **What are the wider impacts of maintaining skills within this theme?**

ISIS Operations and Sustainability. This would be the clear priority as the primary provision for UK neutron science. The recent BEIS Review of Facilities Operations 2016/17 (yet to be published) is expected to report that ISIS is already being run very efficiently. As the current ISIS operating marginal cost is a small percentage of the overall cost, even a modest cut in facility funding would result in a drastic and immediate reduction in facility availability, capacity and capability. However, simply maintaining the status quo will gradually lead to a decrease in the skills base (no longer able to attract new staff) which, over a 15-20 year period, would likely lead to a premature end to the activity.

ESS. The UK is obliged to deliver on its 10% commitment to ESS build (and presumably operating) costs. Failure to do so would result in reputational and political damage.

ISIS-II. Unless ISIS-II work is pursued at a suitable level there will be no possibility of beginning to build a new neutron facility in the UK by ~2030 and the UK would probably lose the initiative, opportunity and capability to establish such a facility. The rates of progress indicated in Q5 are already challenging with the resources currently available and any reduction in funding would at very least prolong the feasibility, design studies and R&D phase significantly beyond 2027. In extremis it would be possible not to pursue the FFAG strand (which involves the only significant investment in R&D), but this would not be consistent with exploring possibilities for a more energy efficient facility and would also result in a significant likelihood of loss of current UK leadership and expertise in the area.

FETS, Ion Source Development, IBEX and Integrable Optics. Although not mainstream all these activities are interesting, challenging and help to maintain the UK position a key part of the international high-intensity accelerator community generating innovative ideas for leading edge technologies and facilities. Possibly more importantly work of this type is one of the few means we have of encouraging highly skilled and experienced staff to stay at STFC, where business as usual at a large facility such as ISIS could otherwise become routine. The same argument applies for work on ISIS-II.

PIP-II. In a reduced funding scenario, external funding to secure technology delivery for PIP-II would seem highly advantageous, as this would safeguard critical UK skills capabilities within the context of a limited internal priority to develop existing SRF capabilities and/or utilisation of SRF infrastructure.

General Comments. The minimum activity level required to keep skills alive within the neutron theme over the next 15-20 years is to maintain at least the current level of support for ISIS and enough additional activities to ensure retention of skilled and experienced staff. However, even this would certainly compromise any possibility of ISIS-II as, for instance, skills and experience currently being built up in superconducting RF for ESS and PIP-II (and intended to benefit ISIS-II) could not be maintained indefinitely without relevant projects to work on.

The wider impacts of maintaining skills within the neutron theme are in the ability for the UK to contribute effectively to international accelerator projects and activities. Responses to Q2, Q3 and Q4 make it abundantly clear that accelerator skills, expertise and technology developed within the neutron theme are widely applicable across the breadth of UK and international accelerator activities and particularly within ASTeC and the Institutes these transferable skills are extremely important.

7b. In an environment of increased funding, what additional activities, enabling technologies/ capabilities - or enhancements to activities, enabling technologies/capabilities already specified - would it be desirable to pursue?

- **What aspirations exist for investment into nascent areas of research?**
- **How could current, planned or proposed activities be enhanced?**

The roadmap set out herein to maintain ISIS Operations and Sustainability, promote involvement with ESS and work towards ISIS-II is intended as a sensible, achievable vision for UK neutron provision over the next 20 years, in line with the findings of the recent report from the STFC Advisory Panel – Neutron & Muon Science and Facilities, A Strategic Review and Future Vision. However, this will require increased funding if the FFAG option is to be properly explored. The funding for an ISIS-II itself will be justified on the basis of its broader scientific contribution, rather than as an accelerator project and is therefore considered to be outside the scope of this strategy.

Novel Accelerators

Executive Summary

Novel Accelerators have emerged as a strong theme within accelerator physics in the last decade, thanks to a continuing stream of high profile results demonstrating their potential. Whilst Novel Accelerators are not as mature as those based on conventional technology as yet, they possess a number of specific advantages which invite further development, such as:

- Extremely high gradients (>100 GV/m) that facilitate compact and cost effective solutions for applications where their beam properties are appropriate or favourable.
- Adaptable with schemes suggested for applications ranging from medical and security to fundamental science and high-energy physics applications in a compact footprint compared to conventional devices.
- Societal impact such as early diagnosis and treatment of cancer, by enabling affordable advanced accelerator technology for widespread use.
- Being ultrafast and versatile, capable to provide simultaneous multimodal radiation sources; enabling new applications in science and technology.
- Generating economic development in ancillary technology and aid the knowledge-based economy through potentially transformative applications and training of skilled labour.
- Augmenting STFC's future accelerator infrastructures such as the UK-XFEL with novel diagnostics and beam manipulation building blocks, with the potential to extend their parameter range significantly.
- Enhancing the funding base of STFC to GCRF and Industry Strategy Funds via ODA and industry relevant applications of novel accelerators.

Novel accelerator schemes come under a number of different guises: those which aim for electrons, and those which aim for ions; those driven by lasers or Terahertz sources and those driven by particle beams; and those which use plasma or dielectric structures as a medium for acceleration. UK groups are active in all of these areas and indeed in many cases have made seminal contributions to the field.

Of these, the most advanced and active research in the UK is presently directed towards laser wakefield acceleration (LWFA), both in terms of improving accelerator performance and as regards uses for applications. The major centre for UK LWFA research is the Gemini Laser in the Central Laser Facility at Rutherford Laboratory (RAL), but supplementary developments exist in Strathclyde at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA), Queen's Belfast (X-Taranis), Oxford's ASL and ICL. As well as a source of electrons, LWFA produce compact sources of secondary radiation, such as high quality betatron x-rays, positrons and inverse Compton scattered (ICS) γ-rays.

Particle beam driven plasma wakefield acceleration (PWFA) is the sibling of LWFA and has until recently been less studied inside the UK, even though UK investigators have been leaders of international programs. This has been due to a lack of available sites for this research locally. This is about to change with the VELA/CLARA facility, the Compact Linear Accelerator for Research and Applications at Daresbury Laboratory (DL). Though not at the forefront of energy, high beam quality and repetition rate, coupled with a collocated laser and the noted advantage of accessibility will allow innovative approaches to PWFA to be performed on CLARA. In particular, PWFAs are known to be able to multiply the energy, and improve the emittance or brightness available in existing electron accelerators by orders of magnitude. In addition to CLARA, there are emerging schemes which hybridize LWFA and PWFA and therefore allow PWFA research also at LWFA-capable facilities by using intense LWFA electron output for PWFA.

However, electrons are not the only particle drivers of plasma wakefields. The AWAKE experiment at CERN is a unique proton driven wakefield experiment that (presently) uses self-modulation of the SPS beam to drive a wakefield suitable for accelerating electrons. The high energy contained within the proton beam allows one to consider almost limitless acceleration of particles. The co-location of the existing high energy proton beam with a proton beam driven electron accelerator allows the theorising of novel collider schemes such as a wakefield based e-p collider.

The lasers at the CLF have also been used for pioneering work in developing laser-driven high energy hadron sources. Present work is focussed on using novel techniques such as radiation pressure acceleration and shock acceleration to enable hadron beams suitable for near-term applications such as determining radiobiological effects of different species, and in the long-term as a possible source for hadron therapy.

A more recent advance in the UK Novel Accelerator field is the use of dielectric structures as hosts for particle acceleration. Similar to a conventional cavity, these structures can be driven by particle beams or electromagnetically, though due to their smaller size, the suitable frequency range now comprises Terahertz and laser radiation. The UK involvement in dielectric accelerators is clustered around the effort in DL, using CLARA. Recent results with low-energy laser-driven structures have demonstrated impressive acceleration gradients; with low energy, these laser drivers would allow novel accelerators operating at multi-kHz rates.

As well as these national programs, UK researchers in these fields are actively engaged with major developments in this field at labs such as CERN, SLAC FACET, DESY, ELI etc., often in project leadership positions.

Novel Accelerators are indeed a worldwide growth field, characterised by intense collaboration of research centres and universities, as there is enormous potential with regards to transformative applications that can be realized even in university-scale laboratories. Other countries continue to invest increasingly into Novel Accelerators, and it is now apparent that the comparatively modest investments made in the UK increasingly endanger the leadership position of UK R&D. In order to remain a strong player in this field and in order to harness first mover advantages e.g. for industrial exploitation, it is envisaged that:

- The UK needs to intensify its investment in its national facilities which enable Novel Accelerator techniques; this means overdue upgrades to the high-power lasers at the CLF (Gemini and Vulcan), the further development of CLARA e.g. to higher energy and current, and the implementation of dedicated beamlines for and user stations at these national facilities.
- The UK needs to invest substantially into Novel Accelerators to remain competitive internationally, both through the Accelerator Institutes as well as through additional projects in order to exploit local capabilities and capacities at centres such as SCAPA, TARANIS, ASL. Notably there is now a pan-UK Plasma Wakefield Accelerator Steering Committee (PWASC) that coordinates the activities in this area.
- STFC should exploit the huge potential of this work for ISCF, since compact and versatile accelerators are desirable for industrial applications, and in context of the GCRF, since many developing countries do not have the technological infrastructure required for conventional accelerator systems.
- STFC should also exploit the suitability for cross-council/RCUK/UKRI support, since it involves technologies such as novel lasers, photonics, and plasmas, and has direct applicability to engineering, material and life sciences.

A substantial investment in form of a “Novel Accelerator Action Plan” could be a potential pathway to deliver the required funding allocation as this may open up broader funding options and could deliver the funding more targeted, more synergistic and more efficient than by attempting to fund a multitude of smaller projects.

1a. Map current, planned and proposed accelerator science and technology activities within this theme against the science priorities (supported by STFC) they will enable over the next:

i. 1-5 years

ii. 5-10 years

iii. 10-20 years

STFC currently invests directly in Novel Accelerator technology via its funding of the Accelerator Institutes (Cockcroft and John Adams Institute and ASTEC), in which this work plays an ever-increasingly important role, and via a direct PPRP grant allocation to the AWAKE-UK consortium. It has also made capital investments such as the Cockcroft beamline on SCAPA (Strathclyde) and the laser developments in the JAI-Oxford.

STFC also indirectly funds Novel Accelerator R&D through its support of the facilities, in particular the Gemini and Vulcan Lasers in the CLF and the CLARA development at Daresbury Laboratory. Indeed, Novel Accelerator research has played a pivotal role in the programme at the CLF for nearly 30 years, and many of the ground-breaking achievements that have taken place at the laboratory, such as the step-change from producing extremely broadband to quasi-monoenergetic electron beams as reported in the Nature "Dream Beam" Issue (2004)[1] – the highest cited publication across the national STFC facilities portfolio – were made possible by STFC's commitment to make sure the facilities are at the leading edge of performance, and that there is the necessary support for plasma acceleration research.

The UK has been at the forefront of studies on Novel Accelerators2, especially laser-plasma driven schemes, almost since the inception of the field (as outlined in part 2). We, now, routinely produce GeV-energy, multi-kA electron beams in cm-scale distances, in fields exceeding 100 GV/m. As well as the facilities, much of this pioneering work has been driven by university-based groups. For plasma based electron acceleration, this effort is now increasingly coordinated by a consortium, the UK Plasma Wakefield Accelerator Steering Committee (PWASC). PWASC has 11 key partners including both STFC facilities, Accelerator Institutes and universities (CI-Lancaster, CI-Liverpool, CI-Manchester, CI-Strathclyde, JAI-ICL, JAI-Oxford, STFC-ASTeC, STFC-CLF, QUB, UCL, York). PWASC is currently preparing a roadmap for developing this field, which has provided input to this report. EPSRC ASAIL (QUB, CI-Strath, JAI-ICL, STFC-CLF) represents major efforts in laser-hadron acceleration, and has been particularly directed towards developing ion accelerators for medical applications, and EPSRC Lab in a Bubble (CI-Strath, CI-Lanc, U Glasgow, U St. Andrews, NPL) represents another major UK research thrust in LWFA, as a follow-up programme to the ALPHA-X programme on LWFA-driven light sources. Dielectric and THz-driven wakefield acceleration are a new field in the UK. Most of the setup will be developed at the CLARA test facility, and at CERN CLEAR for beam diagnostics with participation from CI-Lanc, CI-Liv, CI-Man, CI-Strath, and STFC-ASTeC, and also at SLAC FACET. Although not at the same energy levels, acceleration using dielectric structures has made promising advancements in recent years[3].

The work in novel accelerators will greatly influence STFC's priorities, since it promises next-generation capabilities that will have an impact in almost all areas of STFC's mission. For example, plasma based particle accelerators could form the basis of next generation light sources[28,29,30], accelerators for high-energy physics applications including the generation of novel beams such as gamma and positron beams or even linear colliders[4], compact and versatile accelerators for biomedical research, VHEE[13], synchronised ion and gamma sources for nuclear physics[9], versatile high brightness neutron sources, radiation fields relevant to radiography, laboratory astrophysics and space radiation[5,6] and compact accelerators for uses in medicine and industry. The application of acceleration to these societal challenges, through the development of compact accelerators, make this theme particularly relevant to ODA challenges, and also in context of industrial exploitation.

We list below the major activities in this area for the next several years, which represents the breadth of the field. Table 1 in this section shows how the proposed activities relate to STFC's priority areas such as World-class Research (green), Innovation (purple) and Skills (beige).

References:
a) Annex A from Executive Board for this review
b) Accelerator Review Panel Report 2014
c) STFC Corporate Strategy 2010-2020
d) STFC Delivery Plan 2016-2020
e) STFC Impact Report 2016

Accelerator Science and Technology Activities				World Class Research					Science Priorities (supported by STFC)						Innovation						Skills		Timescale		
				Leadership in accelerator physics	International competitiveness in plasma acceleration[a,b]	Develop next-generation accelerators and light sources	Support UKRI and UK science priorities	Focus on R&D for world class UK based facilities[a]	Enabling world-class UK facilities[a]	Complementary programmatic research in Universities	Cross-disciplinary synergies[a,b]	Assist and improve performance of UK-FEL[a]	Development of novel acc. based photon sources/facilities	Demonstration of lasing of novel accelerator based FEL's	Campuses as focal points for innovation	Economic and Societal Impact & Industrial engagement	High Impact in Global Challenge Areas	Collaboration with universities[c]	Develop coordinated approach e.g. via PWASC[d]	Building International Influence	STEM training	Critical mass of core skills of national importance	1-5 years	5-10 years	10-20 years
Science Activities	Laser-driven plasma	Beam improvements	Extreme beams	x	x	x	x	x					x	x				x	x		x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	Phase space control & stability	x	x	x	x	x	x	x		x	x	x				x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	Plasma injection techniques	x	x	x	x	x				x	x	x				x	x		x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	External injection & staging	x	x	x		x	x	x		x	x	x				x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	Multi-pulse wakefields	x	x	x	x	x		x			x			x	x	x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	Ion/proton acceleration R&D	x	x		x	x	x	x						x	x	x			x	x	x	x	x
Science Activities	Laser-driven plasma	Beam improvements	Extraction, capture & transport	x	x	x	x		x	x		x	x	x				x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Beam improvements	Hybrid LWFA→PWFA	x	x	x	x	x				x	x	x				x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Applications	Radiobiology & therapy		x		x				x				x	x	x	x		x	x	x	x	x	
Science Activities	Laser-driven plasma	Applications	HVM, RHA, security	x	x		x	x			x	x			x	x	x	x		x	x	x	x		
Science Activities	Laser-driven plasma	Applications	x - γ - rays from betatron & ICS	x	x	x	x	x	x	x			x		x			x	x	x	x	x	x	x	
Science Activities	Laser-driven plasma	Applications	LWFA-driven FEL	x	x	x	x	x	x	x		x	x	x		x		x	x	x	x	x		x	x
Science Activities	Laser-driven plasma	Applications	Collider design & R&D			x		x										x	x	x		x			x
Science Activities	Laser-driven plasma	Applications	Positrons, pions, muons	x															x		x	x		x	x
Science Activities	Laser-driven plasma	Applications	EuPRAXIA R&D		x	x					x		x	x	x		x	x	x	x	x	x	x	x	x
Science Activities	Particle-beam driven plasma	Beam improvements	head/tail & driver/witness PWFA	x	x	x		x		x			x			x		x	x	x			x	x	
Science Activities	Particle-beam driven plasma	Beam improvements	Plasma photocathode R&D	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x
Science Activities	Particle-beam driven plasma	Beam improvements	AWAKE	x	x	x	x			x							x	x	x	x	x	x	x	x	x
Science Activities	Particle-beam driven plasma	Beam improvements	FACET-II, DESY, ATF-II, INFN, CLEAR	x		x	x			x			x	x			x	x	x	x	x	x	x	x	
Science Activities	Particle-beam driven plasma	Beam improvements	Extreme beams, TeV/m etc.	x	x	x	x	x		x		x						x	x		x	x		x	x
Science Activities	Particle-beam driven plasma	Applications	PWFA-based FEL & photon sources	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x		x		x	x
Science Activities	Particle-beam driven plasma	Applications	Radiobiology & therapy		x		x				x				x	x	x	x		x	x	x	x	x	x
Science Activities	Particle-beam driven plasma	Applications	Material testing, RHA, security		x		x	x			x	x			x	x	x	x		x	x	x	x		
Science Activities	Particle-beam driven plasma	Applications	HEP applications & design	x	x	x	x	x										x	x	x	x				x
Science Activities	Particle-beam driven plasma	Applications	EuPRAXIA R&D		x	x					x		x	x	x		x	x	x	x	x	x	x	x	x
Science Activities	Dielectric and THz based	Beam improvements	DWA with CLARA	x		x	x	x	x	x		x				x		x		x	x	x	x	x	
Science Activities	Dielectric and THz based	Beam improvements	DWA-based THz sources	x		x	x	x	x	x	x					x	x	x			x	x	x	x	
Science Activities	Dielectric and THz based	Beam improvements	High gradient & efficient structures	x		x		x	x	x	x	x				x		x			x	x	x	x	
Science Activities	Dielectric and THz based	Beam improvements	Collinear staging schemes	x		x	x	x	x	x						x		x			x	x		x	
Science Activities	Dielectric and THz based	Beam improvements	Multi-MeV demonstration	x		x	x	x	x	x		x	x					x			x	x	x	x	
Science Activities	Dielectric and THz based	Applications	DLA-based light sources	x		x	x	x	x	x			x	x	x	x	x	x		x	x	x			x
Science Activities	Dielectric and THz based	Applications	Applications, e.g. THz deflector	x		x	x	x	x	x		x				x		x		x	x	x	x	x	
Science Activities	Dielectric and THz based	Applications	HEP applications & design			x		x										x		x	x	x			x
Technology Activities	Access to HPL & linacs		Upgrade to CLF Gemini	x	x	x	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x		
Technology Activities	Access to HPL & linacs		Additional target areas for Gemini	x	x	x	x	x	x		x		x		x	x	x	x	x	x	x	x	x		
Technology Activities	Access to HPL & linacs		Upgrade to CLF Vulcan		x		x	x	x		x				x	x		x		x	x	x	x		
Technology Activities	Access to HPL & linacs		Programmatic beamlines at SCAPA	x	x	x	x			x			x	x		x	x	x	x	x	x	x	x		
Technology Activities	Access to HPL & linacs		Support and exploit CLARA	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x	x	x	x		
Technology Activities	Access to HPL & linacs		CLARA test facility upgrade	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x		
Technology Activities	Access to HPL & linacs		Exploitation of University HPL (Strathclyde, Imperial, Oxford, Queens)		x	x	x	x		x	x		x			x	x	x	x	x	x	x			
Technology Activities	Driver technology		Diode-pumped, 10Hz PW laser	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x		
Technology Activities	Driver technology		mid-to far IR lasers		x	x				x			x			x		x					x		
Technology Activities	Driver technology		PW-class lasers at 100 Hz	x	x	x	x	x		x		x	x	x	x	x	x			x	x	x		x	
Technology Activities	Driver technology		Thin-disc and fibre technology		x	x															x	x		x	
Technology Activities	Driver technology		20PW technology development		x		x	x	x		x				x			x		x	x		x		
Technology Activities	Driver technology		High-kA linac R&D, photocathodes	x	x	x	x	x			x	x	x	x		x		x	x	x		x	x		
Technology Activities	Ancillary technologies		Feedback optimisation			x			x	x	x	x	x	x		x	x	x			x	x	x		
Technology Activities	Ancillary technologies		Spatiotemporal alignment			x			x	x	x	x	x	x		x	x	x			x	x	x		
Technology Activities	Ancillary technologies		High-gradient plasma structures	x	x	x			x	x	x	x	x	x		x	x	x			x	x	x		
Technology Activities	Ancillary technologies		Plasma chanels and structures	x	x				x	x	x	x	x	x		x	x	x			x	x	x		
Technology Activities	Ancillary technologies		High-repetition rate diagnostics	x	x		x	x	x	x	x	x	x	x	x	x		x		x	x	x	x		
Technology Activities	Ancillary technologies		High-resolution x-ray detectors	x	x		x	x	x	x	x	x	x	x	x	x		x		x	x	x	x		
Technology Activities	Ancillary technologies		High repetition rate targetry	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		

i. 1-5 years

LWFA and driver technologies:

- Development of a new target area on the Gemini laser at CLF dedicated to the development of laser wakefield acceleration and it uses in radiation generation
- Continue complementary high power laser developments and exploitation in universities (Imperial, Oxford, Queens and Strathclyde) including the Cockcroft beamline at SCAPA and its 40 and 350TW lasers with beamlines in three shielded bunkers
- Exploitation of enhanced injection mechanisms to improve properties of injector stages (charge, energy spread, brightness…)
- Generate attosecond-scale bunches and bunch trains[7,8]
- Staged acceleration to enhance maximum energy gain, and provide control on energy spread, pulse length…
- Continue investigation in to the generation of secondary sources such as high quality gamma or positron[21] beams
- Development of LWFA-based radiation sources such as betatron[9,10] ion channel laser (ICL)[11], inverse Compton scattering (ICS)[12], undulator radiation[28,29,30]
- Continue development of high-rep rate compact accelerators for societal applications, such as VHEE therapy[13] and isotope production
- Develop novel laser technology for LWFA applications; including diode-pumped solutions, multi-pulse-excitation, thin-disk, fibre lasers and mid/far IR laser systems
- Upgrade to the Gemini laser in CLF: increase energy and repetition rate to 10Hz for one Gemini beam for optimising applications
- Continue to engage in international projects such as ELI(s), Laserlab Europe, EuPRAXIA, DESY SINBAD, Helmholtz ATHeNA, BNL ATF(-II) (CO2-laser)

PWFA & hybrid LWFA→PWFA:

- First acceleration experiments in a proton driven plasma wakefield on the CERN AWAKE[14] experiment
- Preparation for a multi-stage self-modulation experiment with CERN AWAKE
- Exploit current and upcoming capacities and capabilities e.g. at VELA/CLARA and SCAPA for first experimental realisation of PWFA in the UK: plasma glow synchronization first, then plasma lensing, then head/tail PWFA and broadband space radiation production spin-off, in agreement with CI plans
- Improve CLARA's electron beam capabilities (in particular high peak current) and laser pulse capabilities for preionization, timing and injection
- Measure and improve fs-scale synchronization of CLARA electron and laser beams
- Realise first (externally injected) driver/witness acceleration and energy doubling
- Continue development of plasma photocathodes and ultrahigh 5d/6d-brightness electron beams[15,16] if necessary using downramp-assisted schemes
- Continue or begin projects on international facilities such as at SLAC FACET-II, DESY FLASHForward and Helmholtz VI, INFN and CERN CLEAR, including UK pioneered projects (e.g. E210: Trojan Horse PWFA, plasma torch at DESY)
- Develop ultrahigh current electron beams from LWFA at SCAPA and CLF to realize hybrid LWFA→PWFA[17]
- Explore and control/mitigate instabilities such as hosing, explore tailored bunch profiles, enhanced transformer ratios, beam loading etc.

Laser proton-ion acceleration:

- Continue to develop laser-driven proton and heavy ion acceleration to beyond 100 MeV per nucleon
- Explore novel regimes of proton/ion acceleration (e.g. radiation pressure acceleration, shock acceleration) to produce narrow energy spread, extreme high current ion sources
- Continue exploring novel secondary structures and staging for focussing, increasing energy, or better phase space control of ion & proton beams.
- Continue exploring laser driven neutron generation as a means of developing compact, portable neutron sources.

- Upgrading Vulcan (to 20-PW) and Gemini lasers (2 PW in one beam) to access favourable intensity regimes for laser-driven hadron acceleration.

Dielectric-based acceleration: wakefield (DWA), THz, and dielectric laser (DLA) acceleration:

- Exploitation of current and upcoming capabilities at VELA/CLARA and establishment of CLARA as internationally competitive test facility for dielectric wakefield acceleration.
- UK-led demonstration of 100 MV/m gradient acceleration DWA on CLARA, multi-MeV energy gain on CLARA.
- Dielectric dechirper on CLARA
- Development of DWA-technology based THz sources
- Exploration of feasibility Trojan Horse-type plasma photocathodes in dielectric structures in collaboration with RadiaBeam Technologies / DoE.
- Demonstration of terahertz driven transverse deflector on >100MeV beam at CLEAR
- Measurements of acceleration at PSI and at DL with and without laser.

Technology and Applications:

- Exploitation of plasma based radiation sources for applications such as imaging, material testing and security, radiobiology, and further industrial uses.
- Continued exploitation of laser generated ion and electron beams in radiobiological studies.
- Develop and utilise advanced plasma optics for laser beam control (e.g. staging, contrast)
- Realise a plasma based platform for space radiation reproduction and radiation hardness assurance.
- Continued development of plasma targetry for advanced injection schemes, and efficient acceleration of electrons and positron, including plasma capillaries and hollow waveguides[18].
- Continue development of novel targetry to allow accessing novel schemes for hadron beam acceleration with lasers such as cryogenic, gas or isolated (floating) targets.
- Continue developing novel, high-repetition rate targetry for both electron and hadron beam acceleration.
- Continued development of plasma diagnostics[19] including ultrafast imaging of plasma waves
- Femtosecond and μm-scale spatiotemporal synchronization of relativistic electron and laser beams
- Continued development of diagnostics of the extreme beams produced in wakefield accelerators especially in the ultrafast domain.

ii. 5-10 years

LWFA and driver technologies:

- Development of a higher repetition rate (>10Hz) higher energy (>30J) Dipole-based upgrade to both Gemini beamlines to enable > 5 GeV single stage and > 10 GeV staged acceleration of electrons for applications.
- Demonstrate high brightness beam production in laser wakefield acceleration using optimised injection/staging.
- Experimental tests of x-ray FEL using plasma generated beams.
- Experimental tests of high-energy positron acceleration, and production of γ beams of suitable energy and brightness for $\gamma\gamma$-collider
- Development of 100Hz, 100TW laser technology for applications
- Develop mid- and far-IR lasers for particle acceleration
- Pursue tests of acceleration schemes based on novel laser configurations (multi-pulse, coherent addition) to enable high rep-rate high-energy wakefield performance
- Single- stage acceleration >10 GeV using Vulcan 20PW beam
- Realise EuPRAXIA on ESFRI roadmap

PWFA:

- Investigations of acceleration in a multistage self-modulated proton driven accelerator (AWAKE-II).
- Exploration of design for AWAKE based high-energy physics experiments such as e-p collider[20] or fixed target searches of dark photons/ dark matter.
- Demonstrate routine control of electron beam

parameters in PWFA and LWFA/PWFA hybrid down to: nm-rad (normalised emittance), ~100 kA (peak current), multi-GeV (energy), resulting in 5d and 6d brightness orders of magnitude better than state-of-the-art.

- Develop tunable multibunch capability
- Conceptual design of a brightness amplifier for existing XFELs, including the ultrashort pulse driver expected on CLARA
- Develop PWFA-based betatron, ICL, ICS and undulator radiation
- Continue engagement an exploitation at SLAC FACET, DESY, INFN

Laser proton-ion acceleration:

- Extend laser-driven proton and heavy ion acceleration to beyond 250 MeV per nucleon on the 20 PW laser at CLF.
- Demonstrate active control of ion beam properties (e.g. spectrum, divergence, …)
- Implement cryogenic targetry to enable dense (solid density) high-energy proton beams to be generated using radiation pressure schemes at high repetition rates.
- Demonstrate coupling of laser-generated ion beams to conventional beamlines to allow phase-space preparation of the beams.
- Produce extremely narrow energy spread ion beams coupled to secondary sources of radiation (electrons, gammas, positrons[21]) for applications in nuclear physics and mixed-modal oncology.
- Demonstrate high repetition-rate compact, portable neutron sources for neutron imaging and nuclear applications.

Dielectric electron and laser driven, and THz acceleration:

- Technology-choice point for dielectric wakefield or THz for future facility research and development focus based on energy efficiency of structures and of terahertz sources.
- Development of collinear staging schemes.
- Develop novel DWA structures for high transformer ratios
- Lead beginning conceptual design study of 1-4 GeV light source facility based on DWA or THz technology
- Complete design and testing of structures for DLA.

Applications and technology:

- Develop beamlines for dedicated applications such as FEL research on SCAPA (Strathclyde), medical applications and hadron-therapy on TARANIS (QUB) / SCAPA (Strathclyde) or biomedical imaging in the Centre for the Clinical Application of Particles CCAP (ICL).
- Investigate commercialisation/industrialisation of accelerators based on plasmas and dielectrics that can be used for imaging, space radiation testing and RHA, material testing and security, radiobiology, and further industrial uses.
- Develop diagnostics for characterising ultra-bright attosecond beams.
- Continued development of targetry for XFEL and HEP applications exceeding metre lengths with high fidelity
- Develop and measure ultrabright γ-beams up to the GeV level with 10 PW-class lasers
- Contribute to preliminary outline design studies of future TeV range e+e- collider that are expected to begin in early 2020's.

iii. 10-20 years

LWFA, PWFA, hybrid LWFA→PWFA, Dielectric electron and laser-driven and THz acceleration:

For all of the novel schemes based on electron acceleration the end goals are similar and can potentially be realised on a 20 year times scale:

- Conceptual, and technical design phase of a novel accelerator based light source facility, selecting the best technology available
- Build phase of a light source user facility (15-20 years).
- Contribute to, and in at least one significant area lead, on international conceptual design phase of multi-TeV colliders based on novel accelerator technologies.
- Build phase of an economical fixed target high-

energy physics experiment (15-20 years) to address a number of the big science questions, such as the nature of dark matter, unifying the fundamental forces, understanding the fundamental structure of matter, search for new symmetries, etc…

- In addition, the AWAKE experiment at CERN can be developed to produce an e-p collider which can probe many of these questions too.
- Development, in cooperation with industry, of commercial accelerators based on novel accelerator technology e.g. ultra-compact radiation sources and micro electron accelerator for endoscopic medical applications.

Laser proton-ion acceleration:

- Ion energies driven by lasers will exceed GeV per nucleon, either directly or by coupling to RF beamlines.
- Laser generated ion (and other particle) beams to be routinely used for dosimetry studies, and also for radiation susceptibility especially for radiobiological effectiveness.
- Clinical trials of laser generated ion beams to be performed, especially for treatment by exotic nuclei such as for carbon therapy.
- Laser generated ion beams to be tested for industrial applications such as accelerator driven fission and fast-ignition fusion.
- Laser generated neutron sources to reach peak brightness comparable to conventional accelerator systems.

1b. Please comment on the current UK position of each accelerator science and technology activity in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and capacity be exploited**

LWFA: LWFA is the most active novel acceleration field worldwide, as is also the case in the UK (laser driven particle acceleration has been studied in the CLF, for example, since the late 1980's). UK groups are involved in various national and international projects, such as ALPHA-X, Lab in a Bubble, EuPRAXIA, Laserlab Europe, ELI, BNL ATF-II, SINBAD etc. In a number of areas, including plasma targetry and laser guiding, injection and high brightness beam production, and high efficiency laser drivers, the UK possesses undisputed world leaders. For example, UK expertise is critical in these areas for the EuPRAXIA design and development, and in developing a number of the ELI beamlines. These developments offer exciting new opportunities, but with the limited level of funding for plasma accelerator research in the UK, it is difficult to commit strongly to these projects beyond the basic level. Also, as of yet, there is no firm commitment from the UK to support access for UK researchers to these pan-European or US-based facilities. This lack of commitment, compounded by political uncertainty, clearly diminishes UK leadership in international projects and collaboration.

As has been pointed out for a number of years now32 (also see e.g. STFC Accelerator Review Report 20142), other countries (notably Germany, France, China, US) invest far more into LWFA than the UK. For example, in Germany there are now >10 laser systems at the 100 TW to PW level at various labs used for plasma acceleration, funded including beamtime costs and programmatic R&D. Despite these limitations, UK groups have a world-leading standing in this field, with notable achievements including the first demonstration of the transport of narrow energy spread beams in a LWFA1 and the development of capillary waveguides for acceleration to GeV level . The UK has also led in development of applications of LWFA, including FEL development, betatron imaging, and production of secondary beams of radiation (positrons, gamma). However, in recent years, a lack of timely upgrades to facilities has severely limited the rate of development. This lack of access is particularly acute on the Gemini Facility at the CLF, built in 2007. As a facility that directs a majority of its time for LWFA development and its applications, Gemini is probably one of the most mature tools for LWFA research in the world. However, the fact it only has one target area, so that a great deal of laser operation time is wasted whilst new experiments are being installed. That and the fact that there has been no major enhancement in laser parameters in 10 years, now endangers Gemini's preeminent position.

At Strathclyde, SCAPA has been erected as a collaborative university-based research centre which can complement activities and highest laser power research at CLF.

PWFA and hybrid LWFA→PWFA: Electron-driven PWFA is new in the UK and as an experimental field. Indeed, due to the lack of suitable electron beam drivers, the only mature PWFA program so far is in the US. This is primarily due to the FACET facility at SLAC with its high beam quality and energies, which has resulted in pioneering R&D. The US continues to invest in PWFA research with developments at SLAC FACET-II and BNL ATF-II, but will soon be joined by European large facilities at DESY, CERN and at INFN. The UK combines intellectual leadership & IP in this highly promising field such as the E210: Trojan Horse R&D programme at SLAC FACET, which despite being highly regarded has yet to receive any UK research council funding. However, where possible UK groups will seek to engage in these international projects.

A major development for work in this field in the UK is the development of the CLARA facility at Daresbury Laboratory. As well as combining a photocathode-quality bunched relativistic electron beam with a multi-TW laser system, CLARA will feature (in principle) 24/7 accessibility of the experimental area. This is in contrast to operations such as SLAC FACET-II or DESY FLASHForward, where experimental access is limited to the order of few hours per week in consideration of FEL users. PWFA R&D at CLARA is possible at various positions along the CLARA beamline and also is planned in the optional PARS station. PWFA research on CLARA, especially high-brightness novel plasma photocathodes/Trojan Horse promises to enhance CLARA's primary mission of developing novel FEL capabilities, and diagnostics e.g. via spatiotemporal synchronization. Complementary PWFA R&D capabilities via will be possible via hybrid LWFA→PWFA at SCAPA.

AWAKE-UK is comprised of four institutes (CI-Lanc, CI-Liv, CI-Man, UCL) receiving STFC project-grant funding. The institutes themselves have also provided significant resources and support. It is the largest group in AWAKE after CERN and MPI Munich. The effort is mainly focussed on electron acceleration, with the UK providing the initial accelerating structure, electron beam diagnostics and the electron energy spectrometer. This will lead to the measurement of the accelerated electron energy, which is a key indicator of the success of AWAKE. Unfortunately, none of the "plasma" aspects, e.g. plasma source and diagnostics, were funded in the AWAKE-UK bid, with only more conventional accelerator aspects approved. These systems, in particular the discharge plasma source and plasma diagnostics, would have been extra leading contributions from the UK and are missed opportunities. An attractive aspect of the AWAKE-UK group was its breadth in expertise, which unfortunately due to the limited funding, was not fully exploited. Although the AWAKE-UK grant will allow the groups to make significant contributions, the investment compared to e.g. MPI is low.Plasma wakefield accelerator R&D funding via the accelerator institutes CI/JAI is very useful as a small baseline, however dedicated project funding is required to reach critical mass.

Laser proton-ion acceleration: The generation of energetic ion beams with lasers is actively being pursued around the world with major programs in Germany, France, China, Japan, Korea and the US. Many of these programs are driven by the potential use of these sources for clinical applications. This has also been one of the main drivers for its study in the UK, through developments such as the ASAIL consortium (QUB, CI-Strath, JAI-ICL, STFC-CLF) and the Centre for Clinical Applications of Particles (CCAP - ICL, JIA-Ox, ICR).

The UK plays a world-leading role in this area, with many of the leading breakthroughs in the field having taken place in the UK, many associated with developments at the CLF, such as the first measurement of tens of MeV protons and the development of radiation-pressure acceleration schemes[24]. Hence as in LWFA research, the health of this field is tied to the constant upgrade of laser facilities, which once world-leading, are now being leapfrogged by persistent investment in other countries. Whilst several university-based developments are presently in progress, which would impact the field especially in terms of applications (such as the 350 TW SCAPA laser, TARANIS at QUB, and CCAP at ICL), the most pressing need for this field is long desired upgrades to the Gemini and Vulcan lasers at the CLF.

Ion and proton acceleration also forms an important facet of the experimental program of international facilities such as ELI and the BNL ATF-II CO_2 laser, and again the UK involvement in these developments would be welcome, though it is tied to political decisions. However, for the UK to have meaningful involvement in such international projects, the availability of leading edge technology in national facilities remains the priority to maintain the vitality of the field.

Dielectric and THz acceleration: US, Germany, UK and Switzerland (PSI) engage in these novel accelerator topics. The field is led by the US and Germany. UK has not investigated greatly in this area and is mostly supported by ASTeC and CI core resources (in the DATA programme). Energy gradients up to the 1 GV/m scale have been observed, and net energy gains up to few hundreds of MeV, using the SLAC 20 GeV linac in electron-beam-driven dielectric wakefield acceleration, and in laser-driven dielectrics gains on the sub-MeV scale have been reported. The UK has a unique mix of skills (Cockcroft) and facilities (VELA/CLARA) that will allow the UK to have a competitive edge against international competition, while collaboration does also exist with international groups such as PSI or RadiaBeam Technologies. The exploitation of VELA/CLARA as a test bed is a key for the development of dielectric wakefield acceleration in the UK[25]. Lancaster, Strathclyde and others have experience in mm-wave, THz sources and accelerating structures, high frequency travelling wave tubes and are active in the development of metamaterial, dielectric waveguide, and double corrugated metallic waveguide accelerating structures, and have both simulation and measurement capabilities with a mm-wave measurement lab with a high frequency VNA. The ASTeC/Manchester/Lancaster collaboration in is internationally competitive or leading in demonstrations for length-scalable terahertz acceleration.

Internationally, CLEAR/CERN are at a very good stage of development to contribute and lead as international test-beds over the next 5+ years. This international resource should be exploited next to CLARA. There are also links to US-based research groups and facilities.

2a. What enabling accelerator technologies/capabilities (including computing, vacuum, RF, lasers etc.) are necessary to pursue each accelerator activity?

The matrix below maps an overview on accelerator technologies and capabilities required for each Novel Accelerator activity (in strongly condensed form):

Accelerator Science & Technology Activities			Enabling Technologies																			
			Diagnostics	Computing / HPC / Big data	High Power Laser Technology	Energy-efficient pump laser technology	High current, high rep-rate LINAC technology	Linacscompression techniques & photocathodes	Beam transport and manipulation instrumentation	Ultrafast Electronics e.g for Timing & Synchronisation	SC / permanent / miniature magnets	Plasma sources and structures	High-resolution x-ray cameras	Plasma-based optics and beam dumps	Large area chip technology	Vacuum technology	High repetition rate targetry	Skills / retention / training	Undulators	FEL expertise	Interlocks and control	Automation/feedback loops
Science	Laser-driven plasma	Beam quality & energy improvement	x	x	x					x	x	x				x	x	x				x
		Control & stability & transport	x	x		x			x	x	x	x		x		x		x			x	x
		electron/proton/ion applications	x	x	x	x			x	x	x	x	x	x	x	x	x	x			x	x
		Photon beam applications	x	x	x	x				x	x	x	x	x	x	x	x	x	x	x	x	x
		HEP applications	x	x	x				x	x	x	x				x		x			x	x
	Particle-beam driven	Beam quality & energy improvement	x	x			x	x	x	x	x					x					x	x
		Control & stability & transport	x	x					x	x	x					x					x	x
		electron beam applications	x	x			x	x	x	x	x					x		x	x		x	x
		Photon beam applications	x	x			x	x	x	x	x		x		x			x	x		x	x
		HEP applications	x	x			x	x	x	x	x		x		x			x	x		x	x
	Dielectric and THz	Beam quality & energy improvement	x	x		x				x								x			x	x
		Control & stability & transport	x	x		x				x								x			x	x
		DLA-based light sources	x	x						x		x						x	x		x	x
		THz transverse deflector										x										
		HEP applications										x										
Technology	HPL & linacs	HPL facility upgrades	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x		x	x
		CLARA test facility upgrade																				
		University HPL upgrades	x	x		x			x	x	x	x				x	x	x	x		x	x
	Driver tech	Laser power & rep rate upgrades	x		x	x				x						x		x			x	x
		mid-to far IR lasers	x		x	x				x						x		x			x	x
		High-kA linac R&D, photocathodes	x			x	x	x	x	x	x					x	x	x			x	x

Since all Novel Accelerator schemes are based on laser or particle beam drivers, continuing advances in this field require constant improvements in driver beam quality (enhanced capability), and improved access to these facilities (enhanced capacity) for sustained R&D programmes.

For LWFA, hybrid LWFA→PWFA and laser ion/proton acceleration: the laser beam drivers that push electron energies to the 10 GeV level and ion energies beyond 250 MeV/nucleon will be provided by the next generation of PW-scale lasers. This type of accelerator would be directly applicable to major long-term goals of the field, including driving light source and high-energy physics applications. It is clear that to remain competitive with the worldwide effort in this field, major upgrades to the laser facilities at the Central Laser Facility are imperative. An immediate goal would be enhancement of the energy of the Gemini laser, which despite not having a major upgrade in ten years, is still one of the main workhorses for advances in this field. A higher energy driver (either in Gemini or the 20 PW Vulcan upgrade) would deliver the laser performance required to support this work over the timescale of this roadmap. Gemini remains competitive in the field because of the steadily accumulated expertise of operating lasers for wakefield acceleration experiments. However, a major roadblock to these studies is that Gemini only offers a single target area, such that permanent installations are impossible. A dedicated extra target area for wakefield research is an immediate aim, and a possible new building with a number of dedicated target areas would be invaluable in the longer-term.

LWFA and hybrid schemes produce bright sources of secondary radiation and energetic particles that have a multitude of applications ranging from medicine to security. Although proof-of-principle tests for several of these applications have been successfully conducted using state-of-the-art PW-class lasers including Gemini, their applicability for real-world scenarios is currently limited by the repetition rate of the laser driver. It is therefore imperative to develop laser technologies that would allow PW-class lasers at high repetition rates. CLF is a pioneer in this area; upgrading the Gemini beamlines with the DPSSL technology developed by CLF (DiPOLE) is critical for exploiting Gemini's capabilities for these applications. Also important is high repetition rate laser technology and e.g. plasma optics for improving contrast (laser-solid) and staging (LWFA).

The lack of capacity is severe and has motivated the development of 10's to multi-100 TW at university centres such as Taranis at QUB, Cerberus at IC, the ASL at Oxford, and the 5-10 Hz, 40 & 350 TW SCAPA lasers at Strathclyde that complement the research done at CLF. These secondary beamlines, though lacking in many of the intangible benefits of working at the Rutherford-Lab such as its engineering and technical support, are vital for maintaining a healthy program in Novel Accelerator work, e.g. since they allow dedicated fixed goal experiments and programmatic R&D, unlike CLF where there is typically a 5-week turnaround of experiments. This is particularly necessary for application-based research, or the setting up of fixed beam lines, such as the undulator station on SCAPA, or the biomedical beamline on TARANIS. STFC, via the Accelerator Institutes, has recently invested in capital upgrades for these projects, such as the Cockcroft beamline on SCAPA, the ASL laser in Oxford and the compressor chamber on Cerberus. These investments are welcome and would be required in the future, to maintain the effectiveness of these resources.

For **PWFA**, VELA/CLARA promises to provide the world-class electron beam driver facility in the UK comparable to what the high-power lasers at the CLF provide for laser beam drivers. Even at low energy, a beamline with a high degree of control on the electron beam properties, and collocated with a laser source, could deliver a profound advance in PWFA in much the same way that the original 10 TW Astra laser provided1. The existing co-location of the TW laser is an invaluable advantage and achieving a similar infrastructure required many substantial efforts e.g. at SLAC FACET in recent years. Likewise, the accessibility of CLARA puts its potential for PWFA research at the worldwide forefront. Ideally, the upgrade of CLARA to 250 MeV energy and advanced bunch compression would allow wakefield acceleration experiments that would be very relevant to an eventual driver for an XFEL. Hence for PWFA, the exploitation and upgrade of CLARA on an aggressive timescale is seen as a high priority. No STFC project funding for e-beam driven PWFA could be allocated yet, which is in discrepancy to the potential which can harnessed at CLARA and the worldwide importance of e-PWFA. It is therefore imperative that future funding will allow campaigns and ideally setting up of dedicated stations or beamlines to support the programmatic PWFA R&D which is required to deliver the programme.

It is clear that the advancements in the LWFA/PWFA fields will require next-generation facilities and in some cases, the R&D advancements would lead to new facilities themselves. In order to continue leadership in this area, we envisage that the UK would require a 100-PW-class laser, along with a 100-Hz, PW-class laser facility driving applications, and an energy-extended CLARA-like facility, or both combined as is currently studied within EuPRAXIA.

For **e-beam driven dielectric wakefield acceleration**, VELA/CLARA is likewise the key for delivering world-class research. As for PWFA, already intermediate energies are highly useful. Some ASTeC/CI/STFC funding has already been invested into dielectric wakefield acceleration, and a steady ramp-up in support is required to maintain the speed of progress in the field. In particular, a research station dedicated to dielectric wakefield acceleration, similar to AWA at ANL, would be highly desirable.

Due to the overlap as regards requirements of PWFA and DWA and the unique research opportunity for this at CLARA, a combined Advanced Accelerator Research Area at CLARA would be advantageous, similar to that created at SLAC FACET, where PWFA and dielectric acceleration work has taken place cooperatively.

HPC access, modelling and simulations is a large and crucial part of all Novel Accelerator R&D, e.g. for particle-in-cell simulations. CLF provides a limited access to HPC facilities (SCARF) for users, and many universities have their own HPC initiatives which offer paid or in some cases, limited scope for free access to HPC. However, these opportunities are not universal, and a standalone, low-threshold access path for Novel Acceleration simulation work needs to be established in the UK. Similarly, the codes used run from commercial ones (many groups use VORPAL/VSim as developed by Tech-X) down to open-source or self-developed codes. The UK community is particularly fortunate to be able to draw on the use of the EPOCH simulation code for laser/beam/plasma simulations. EPOCH was developed, via an EPSRC code, on the basis of being free to use for academic users. The EPOCH developers also run instruction schools (funded by the CLF), which are useful for learning about HPC in general, not just EPOCH. Unfortunately, EPSRC grants are time limited which means that though now a mature code, EPOCH support is funded on an ad-hoc basis. Direct funding of an EPOCH developer (either partially or fully) to support Novel Accelerator work, would allow faster resolution of bugs/problems and dedicate developer effort towards problems encountered by Novel Accelerator researchers.

Diagnostic/plasma structure/target development is critical in order to exploit the advancements made in the laser drivers. Development of high frame-rate diagnostics and plasma targets capable of operating at high repetition rates (several Hz to kHz) would be necessary for advancement in all areas of novel acceleration. In particular, for imaging applications of LWFA-based photon sources, development of high-resolution, large area x-ray cameras would be highly beneficial.

Training: The facilities and centres such as CLF, CLARA, SCAPA need well-trained staff to deliver operational excellence. The staff who work on topics related to Novel Accelerator work are typically of the highest quality, and usually particularly motivated by the area of research. An increasing number of the scientists working for STFC are PhD's trained in relevant areas. However, there are a few areas (such as RF engineers) where finding the required expertise is difficult. However, the national facilities allow both on the job training and also more formal training routes, such as cosponsored PhD programs (a number have been with the Accelerator Institutes).

The lifeblood of Novel Accelerator research is PhD students and PDRAs within the research groups. STFC has recently formalised a direct allocation of PhD students in accelerator science for both the CI and JAI. Of these, many prospective students find the idea of working in Novel Accelerator research highly desirable, and this is an increasingly popular route into accelerator physics in general. Both institutes provide a structured training programme for new PhD students (with some cross-institute coordination), which includes aspects of Novel Accelerator research in their syllabuses. There has also been a Doctoral Training network organised between QUB and Strathclyde organising postgraduate student recruitment and training on topics related to Novel Accelerator work.

There is never a shortage of high quality applicants for projects in these fields, and never a shortage of projects for them to undertake. This can be witnessed by the numerous international PhD prizes won by graduates from UK universities, and the high level of posts that they occupy post-PhD. A coordinated doctoral training network for work in this area, could easily provide projects and students to give the field a major impetus.

2b. Please comment on the current UK position of each enabling technology/capability in the international context?

- **Please indicate activities towards support of international projects and facilities.**
- **Is the UK world leading or lagging?**
- **Should international capability and/or capacity be exploited?**

Lasers: In terms of high power laser development, the UK, particularly with relevance to advances at the CLF, are world leading. The CLF has pioneered diode-pumped solid-state laser (DPSSL) pumping of high intensity lasers that promise orders of magnitude improvement in efficiency and repetition-rate and would truly deliver on the promise of making wakefield driven plasma accelerators comparable in these terms with standard (warm) conventional accelerators. A 100J 10 Hz DPSSL-based driver, called DIPOLE, has been developed at the CLF and would be the basis of a major upgrade to the Gemini laser which has been proposed.

Work at the CLF was also a major instigator of optical-parametric chirped-pulse-amplification (OPCPA) which offers a route to fast amplification of extremely short pulse laser pulses to very high energy. OPCPA is now used in the front end of many large-scale laser facilities that could not previously offer short pulse performance due to their limited bandwidth, such as the Vulcan laser at CLF. Plans exist that would make the final amplifier of Vulcan OPCPA, that would allow unprecedented energies to be amplified in a short pulse. This would produce a peak power of Vulcan20 PW, making it a world leading driver for wakefield and ion acceleration studies.

The UK (particularly through JAI-Ox) has also been at the forefront of ideas to use multiple pulse to drive a laser wakefield (MP-LWFA) which would allow a number of more compact lasers, such as fibre laser or thin-disk lasers to be used to drive a laser wakefield accelerator. These emerging laser technologies also offer high efficiency and very high repetition rates, such that a GeV kHz accelerator based on MP-LWFA has been envisaged.

The UK is also actively investigating mid-IR laser development (particularly ICL) which can have advantages for LWFA and also for some ion acceleration schemes.

World-leading research is also delivered in plasma-based laser amplification[26] such as Raman amplification[27], which is a potentially disruptive way for unprecedented next-generation laser beam capabilities.

Despite the significant intellectual lead that the UK plays in many of these developments, and the quite mature state of many of these upgrade plans, the planned upgrades have not yet been delivered due primarily to the lack of UK science funding. As has been noted, these upgrades are vital to advances in the field of novel accelerators.

Particle drivers/linacs: Clearly the lack of a suitable particle beam driver for Novel Acceleration work has been a major deficiency in this area (same in other parts in the world besides the US which is why PWFA experimental state-of-the-art lags behind its potential). This has been rectified with the commissioning of CLARA. Though comparably low in energy, the high quality of the CLARA beam and its short pulse length make it a unique driver for potentially driving high density PWFA possibly even up to TV/m-scale fields. Also, its colocation with a high power laser, enable the ability to investigate a number of demanding schemes for PWFA optimisation. These unique abilities make CLARA highly competitive with other centres for PWFA research. CLARA is world-leading, and compared to other upcoming PWFA facilities worldwide, following the disruptive success of SLAC FACET, little effort is required to harness CLARA's great potential for PWFA, and DWA. The upcoming SLAC FACET-II or INFN SPARC or DESY FLASHForward facilities, where UK scientists are heavily involved and need national support to be able to fulfil their leadership roles further, will not be detrimental to the potential impact of CLARA for PWFA research, as they will be heavily oversubscribed and operate in different parameter regimes. A co-existence and exploitation of national and international capabilities and capacities is required in this comparably unexplored field.

In terms of proton beam drivers, which could offer unprecedented energy gain per stage, the facilities offered for wakefield studies at CERN are unique. Clearly CERN is world leading, but the AWAKE experiment as a whole is an enabling technology for future high energy physics applications. AWAKE could be developed to investigate fixed-target experiments with a high-energy electron beam to search for e.g. dark photons and a high-energy electron–proton collider, either LHeC-like (with a ~60 GeV electron beam colliding with LHC proton bunches) or TeV-scale electrons colliding with LHC proton bunches. The UK is world-leading in ideas for application of the AWAKE scheme to particle physics experiments. The development of novel electron bunch diagnostics for the initial, unaccelerated electrons, can have applications to other accelerators, novel or conventional. Here, the UK is also world-leading, although the funding for this aspect of AWAKE-UK is not large. The development of a long discharge plasma source is a world-leading UK activity which was not funded in the AWAKE-UK grant. This R&D is continued via Institute resources. As this could develop into the effective accelerating structure, its impact could be very high.

RF: Sources are required for THz and linacs which drive PWFA or dielectric wakefield acceleration experiments.

HPC, modelling, simulation: All Novel Acceleration activities rely heavily on HPC, especially on particle-in-cell-simulations e.g. EPOCH, VSim, WARP, Osiris etc. Many ground breaking ideas are tested in simulation-only, but still lead to high impact publication. Large UK HPC clusters, such as STFC Hartree and ARCHER, are suitable for terascale simulations. However, significant costs apply for these UK clusters (~1p per core hour for Hartree). By comparison internationally, multi-million core hours are available for free at HPC clusters in, for example, Germany, US or even Saudi-Arabia. These international capabilities are therefore used where possible even for core STFC accelerator research. The UK is a member of PRACE which can provides an access route, although groups in PRACE Hosting Countries have privileged access routes. Sometimes UK groups participate in such HPC grant collaborations, but are therefore then inevitably junior partners. There is also DiRAC as STFC’s HPC system, but in total, in terms of effort-to-access/performance ratio, UK HPC capacities for (Novel) Accelerator research are not world leading, and potentially reduced future eligibility for European cluster access (Brexit?) could further compromise the competitiveness of UK groups.

Targetry: UK groups have also made major contributions to the targetry required for plasma acceleration experiments. From capillary discharges that can act as waveguides for laser drivers, or high uniformity long scale length media for particle drivers, to versatile gas targetry that allows novel injection schemes, enhanced beam quality such as final acceleration, and allows staging to be contemplated, to shaped gas or ultrathin foils or cryogenic hydrogen targets that can be used for ion acceleration and to the highly optimised dielectric structures required for DLA/DWA. These developments have occurred on a number of fronts at a number of institutes and almost all of the groups working in novel accelerator schemes have world leading expertise in some area of targetry development which is often the vital cog of the accelerator scheme in question.

Diagnostics: due to their unique properties, Novel Accelerators also require unique properties to be able to fully diagnose their operation. Whether it is measuring beam pulse lengths on the femtosecond scale, or measuring the density variations in a relativistically moving plasma wave, the diagnostics required for novel accelerator schemes are also exceptional. However, many of these diagnostic developments can also be potentially translated to conventional accelerators, such as for some advanced feedback and synchronisation applications.

3. Map the necessary enabling technologies/ capabilities required for activities within this theme against accelerator activities within the other accelerator themes.

Key enabling technologies (Novel Accelerators)			Industrial, Medical, Defence and Security Applications													Light Sources			
	Neutron Sources (e.g. Ion sources, integrable optics)	**Frontier and Nuclear Physics Machines** (e.g. CLIC)	keV electron beams	MeV electron beams	Ion beams	X-ray radiotherapy	Particle therapy	VHEE	Radioisotope production	X-ray imaging	Nuclear security	ADSR	Transmutation	Nuclear / material testing	Water/sludge treatment	CLARA	UK-XFEL	DLS-II	EuPRAXIA
Diagnostics	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Computing / HPC / Big data		x				x	x	x		x	x					x	x	x	x
High Power Laser technology			?	?	?	?	?	?	?	?	?		?	?		x	x		x
Energy-efficient pump lasers			?	?	?	?	?	?	?	?	?		?	?					
High current, high rep-rate linacs		x	x	x		x	x	x	x	x	x		x	x	x	x	x	x	x
Linac bunching & photocathodes		x	x	x		x	x	x	x	x	x		x	x		x	x		x
Beam transport & manipulation instr.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ultrafast electronics e.g. for timing		x				x	x	x		x						x	x		x
SC /permanent / miniature magnets	x	x	x	x	x	x	x	x	x	x	x	?	?	?	?	x	x	x	x
Plasma sources and structures			?	?	?	?	?	?	?	?	?		?	?					x
High-resolution x-ray cameras						x	x	x		x	x					x	x	x	x
Plasma-based optics and beam dumps																			x
Large area chip technology	?	x				x	x	x		x				x		x	x	x	x
Vacuum technology	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
High repetition rate targetry		x	?	?	?	?	?	?	?	?	?		?	?		x	x		x
Skills / retention / training	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Undulators																x	x		x
FEL expertise																x	x		x
Interlocks & control	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Automation/feedback loops		x				x	x	x		x	x			x		x	x		x

Mapping to neutron sources:

- Laser driven ion sources could be used as a driver for compact, portable high brightness neutron sources, which could be used for:
  - o diagnostic development
  - o field applications (and thus potentially grow the number of neutron users)
  - o Vice versa – neutron sources can be used to optimize diagnostics for next generation fusion / laser initiated fission experiments

Mapping to frontier / nuclear physics:

- LWFA drivers (but also DLA) may be compact sources of high energy electrons, which could be useful for:
  - o collider detector development / testing
  - o accelerator beamline diagnostic testing
  - o assessment of fixed target experiments
  - o synchronising with scattering laser to provide high quality gamma source for
- nuclear physics applications
- development of gamma-gamma collider
  - o producing pre-accelerated positron beams for collider applications
- Electron beam driven wakefield could be used as
  - o an energy multiplier or a brightness enhancer to extend the discovery reach of next generation linear colliders

  - a bright photoinjector for high brightness beams
- Proton driven wakefield can be used
  - as a source of electrons only for fixed target experiments
  - coupled to the proton beam to produce an ep collider
- Laser driven ion accelerators could be used for:
  - versatile source of exotic accelerated ionic species, i.e. one whose composition can be easily changed
  - high brightness injectors for storage rings and linacs

Mapping to light source:

- LWFA can be used for:
  - a medium to high (100 MeV-5 GeV) energy ultrafast test beam for insertion devices
  - a cheap source of bright x-rays and gamma rays for synchrotron applications
  - a synchronised source of high-harmonics which can be used for high stability FEL seeding
  - a synchronised source of high intensity laser light for inverse Compton scattering production of hard photons.
- PWFA can be used for:
  - an energy and brightness multiplier that can extend the range of existing FEL facilities
  - a high brightness photoinjector for extreme brightness FEL

Mapping to Industrial, Medical, Defence and Security:

- LWFA and DLA could produce extremely compact sources of keV electrons for:
  - x-ray generation
  - material inspection
- LWFA, DLA could produce extremely compact sources of MeV electrons for:
  - nuclear activation
  - radiolysis (pump-probe experiments)
  - ultrafast electron diffraction
- Laser generated ion and electron beams could be used for:
  - radioisotope production
  - radiography
  - radiation and space hardening testing
- Laser generated ion beams can be used for:
  - nuclear physics
  - ignition of fusion reactions
  - initiation of fission reactions
  - generating neutrons
  - materials testing – especially radioactive material detection
  - nuclear security
  - (transmutation – unlikely)
- LWFA and PWFA driven betatron radiation could be used for
  - high quality radiography, including phase-contrast imaging
  - 3D imaging
  - in-vivo imaging
  - ultrafast diffraction
  - ultrafast absorption spectroscopy
- LWFA and DLA driven bremsstrahlung sources could be used for
  - low quality or dense material imaging
  - water/sludge treatment etc.
  - generation of positron beams

4a. What skills, experience and leadership is necessary to achieve each accelerator science and technology activity?

Novel Accelerators require cross-disciplinary training and skills, and even spanning the Research Councils, especially in case of laser-plasma accelerators.
The Accelerator Institutes with their university backbones provide excellent training and education programmes, including leadership of several EU International Training Networks (ITN's), an EPSRC Centre for Doctoral Training (CDT) on Applications of Next Generation Accelerators, seed Centres for

Doctoral Training with international emphasis or on big data. These training and education capabilities and capacities lead to very high employability for its students. The infrastructure and ability to offer training is strong, and the subject area of Novel Accelerator is known to be highly attractive for students.

However, Novel Acceleration is a worldwide growth field and there is huge demand for well-educated and trained technical, engineering and scientific personnel. For example, laser and RF engineers are required to ensure highest performance of research-enabling facilities and beamlines such as at CLF, CLARA or at the universities (e.g. SCAPA). Well-trained staff, sufficiently resourced, are required to ensure excellence in operations, which in turn is required to deliver world-class research. There is a huge need for RF engineers e.g. at CLARA. Such staff should ideally have experience of how operations are dealt with at other linac or laser facilities internationally. Exchange programs of staff e.g. with other European or US facilities or universities would be useful to stay abreast of the latest technology and techniques, to develop leadership and to foster international collaboration.

World-class research also requires academic staff and also a sufficient amount of well-trained PhD and PDRA scientists to carry through programmatic or campaign-based accelerator R&D. The education and training programs and infrastructure which is present at universities, accelerator institutes and facilities is well-suited to provide a sufficient number of PhD and PDRA. However, there are far too few PhD positions available e.g. through the Accelerator Institutes, while the quality of applicants for these positions are of very high quality and the positions attract the brightest students. Even small increases in number of PhD and PDRA positions would lead to huge benefits. Targeted CDT's in the Novel Accelerator area would be very useful. International experience is very important also for PhD's. Extended stays abroad or with international partner institutes are already part of many PhD programmes, mainly since collaboration with UK groups is highly sought due to their standing in the field. But a formal mechanism for such an exchange program would be welcome. Finally, as Novel Accelerator R&D has cross-council merit, options to have cross-council (e.g. STFC/EPSRC) RCUK/UKRI CDTs in the future would be desirable. A higher flexibility, for example, to allow tailored individual PhD studentships would also be helpful.

4b. Please comment on the current UK position regarding the necessary skills, experience, leadership and capacity in the international context.

The skills, experience and leadership capabilities in the Novel Accelerator field in the UK are world-leading. Not only are there experts in the many numerous otherwise dispersed fields which are required for mastering Novel Accelerator research (e.g. such as Optics and beam physics), but through the Accelerator Institutes, and the community consortia (such as PWASC and ASAIL) there is an increasing ability from these experts to meet and discuss synergies and propose novel directions. The wide range of expertise can then be passed down to new students, through the taught courses on accelerator physics, and also into the general Novel Accelerator community.

The strong intellectual and innovative leadership as regards novel concepts is reflected by the positions of leadership of UK investigators in international Novel Accelerator activities such as at SLAC (e.g. UK PI's of E203, E210, E216), CERN AWAKE, DESY, BNL ATF or within ELI. This leadership has been achieved despite limited funding routes to engage at these international research centres, in particular to those in the US. Clear, and increased funding options for those international activities are required in order to be able to maintain or even extend these roles in the future. Currently, even PPRP-approved projects such as AWAKE suffer because current funding levels means that only very limited engagement is possible.

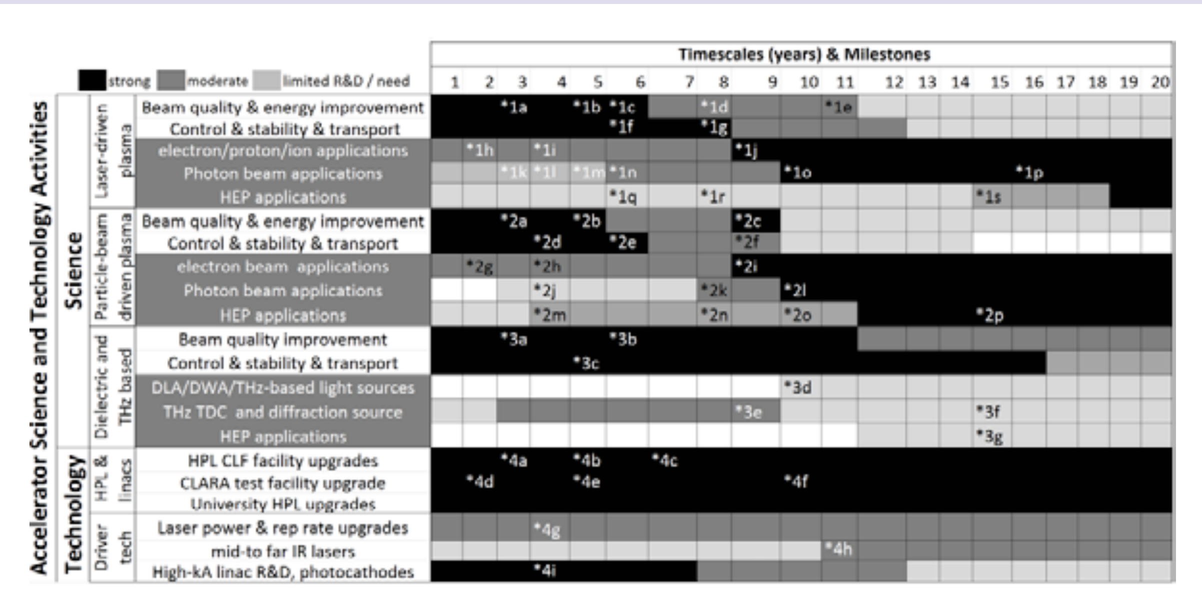
In context of what is mentioned in section 4a regarding PhD training, such activities could be coupled efficiently to the goals of providing an international experience as part e.g. of a PhD programme: the researcher stays at a facility abroad as part of an international research activity, benefitting from the training experience whilst contributing to the project R&D.

5. What are the milestones, timescales and indicative costs for pursuing each accelerator science and technology activity?

Novel Accelerators worldwide are currently in an innovation, discovery and exploration phase, with first applications already being applied. The field continues to be extremely dynamic, and transformative discoveries are being made at a constant rate. Examples of such discoveries include the ability of laser-plasma-accelerators to generate monoenergetic beams[1,22], the potential of generating μC charges of energetic ions with laser beams[23], the potential for plasma-based FELs as demonstrated by the coupling of LWFA with a beam transport lines and undulators[28,29,30] or the recent innovation of plasma photocathodes[15,31]. As is often commented, the UK is not always particularly good at benefiting from its own creativity. Though there is a long list of these breakthrough advances we could point to, being able to produce dependable accelerators based on these breakthroughs will require a doubling of effort, especially in view of international competition[2].

The improvement of quality, stability and controllability are all areas which might not be as publishable as the major advances highlighted above, but are still of primary importance for the development of the field. While first applications have been delivered with existing beam parameters, the most exacting applications such as high-brightness x-ray photon sources will require substantial improvements in beam stability and quality in terms of emittance, energy spread and shot-to-shot jitter. This focus on reliability holds for all areas of Novel Accelerators, albeit on different timescales. This is reflected by the Gantt chart below, which indicates milestones for "beam improvement" and "secondaries, photon beams and applications" for laser-driven plasma in particular LWFA, PWFA and dielectrics and THz. LWFA and PWFA both now routinely produce multi-GeV scale beams and are already used for light sources from VUV to gamma-ray range and are comparably mature, while dielectric and THz-based accelerators show promising acceleration gradients but need further R&D to reach comparable maturity, which is also reflected in the Gantt chart.

Next to these science activities and goals, there are technology goals which are broken down into "Access to HPL & linacs" and "Driver technology". CLF and VELA/CLARA are the main STFC-supported facilities for laser-driven and electron-beam driven novel acceleration. These systems need further development and upgrade. These upgrades encompass the setting-up of dedicated beamlines on the laser facilities to recognise the importance of accelerator research to their program. Ideally these beamlines would be developed in conjunction with the Accelerator Research area of STFC to highlight their importance to the future of this field. Likewise, university-based HPL systems will need continuous support to complement and prepare experiments at these facilities, though no milestones are detailed for these due to the large number of smaller upgrades required to maintain these resources.



Science Milestones:

MS *1a: Improve injection schemes, and expand parameter accessible parameter range to attosecond durations, current to >20 kA at multi-pC charges, emittance e by factor of 3, energy spread ΔE/E by factor of 3, brightness by factor of 6.

MS *1b: Improve emittance & energy spread by factor of 3, brightness by factor of 6 (at the same time).

MS *1c: >100 MeV by pulse train, kHz-repetition rate capable

MS *1d: 10 GeV single stage, 3 GeV + 3 GeV staged

MS *1e: 4 GeV + 4 GeV staging, FEL quality

MS *1f: Reduction of shot-to-shot jitter of charge, energy, energy spread by factor of 5

MS *1g: Beam quality preservation: emittance loss to sub-μmrad level (single stage). Staging: Δε~ μmrad level, 50% charge

MS *1h: Electron beam for material testing such as RHA

MS *1i: Electron/proton/ion beam radiography
MS *1j: Electron/proton/ion beam radiobiology / therapy

MS *1k: User-ready betatron radiation imaging
MS *1l: User-ready synchrotron undulator radiation down to XUV imaging

MS *1m: User-ready inverse Compton Scattering imaging

MS *1n: Experimental LWFA-driven FEL towards soft x-raysMS *1o: Experimental LWFA-driven FEL towards hard x-rays

MS *1p: User-ready LWFA-driven FEL in hard x-ray regime

MS *1q: Start of exploiting e-beam/photon beams for nuclear physics, radiation reaction, lab astrophysics, e-/e+ physics

MS *1r: LWFA-driven/assisted e-/e+ or γγ-collider feasibility study MS *1s: LWFA-driven/assisted e-/e+ or γγ-collider design study

MS *2a: Demonstration of energy doubling and in-plasma injection schemes

MS *2b: Demonstration of ultralow emittance and unprecedented 5D/6D-brightness

MS *2c: Routinely production of tunable ultrahigh 5D/6D-brightness beams and multi-bunches

MS *2d: Experimentally evidenced S2E concept for beam quality preservation during extraction & staging (e.g. nm-scale emittance)

MS *2e: Experimental demonstration of beam quality preservation during extraction / capture / conditioning for applications

MS *2f: Controlled beam quality preservation during extraction / capture / conditioning for applications

MS *2g: Use of head/tail acceleration to reproduce space radiation and testing for UK space community

MS *2h: Use of head/tail acceleration for broadband radiobiology / therapy R&D

MS *2i: Exploitation of ultralow emittance beam radiography & diffraction

MS *2j: First measurement of PWFA-driven betatron
MS *2k: First experimental undulator radiation

MS *2l: First FEL signatures in soft x-ray, working towards hard x-ray

MS *2m: AWAKE energy gain demonstration

MS *2n: AWAKE HEP exploitation CDR

MS *2o: PWFA-driven/assisted e-/e+ or gg-collider feasibility study

MS *2p: PWFA-driven/assisted e-/e+ or gg-collider design study

MS *3a: Establish CLARA as test facility for dielectrics with international collaboration

MS *3b: Demonstration of acceleration/deflection at similar gradients to rf and multi-MeV acceleration

MS *3c: Staged acceleration with quality preservation

MS *3d: Conceptual DLA light source phase

MS *3e: Demonstration of dielectric/THz transverse deflector

MS *3f: Staged acceleration in a compact linac for electron diffraction

MS *3g: Conceptual design considerations towards dielectrics based HEP/collider machines

Technology and infrastructure milestones:

MS *4a: CLF additional Gemini target areas

MS *4b: CLF Gemini energy upgrade

MS *4c: CLF Vulcan upgrade

MS *4d: Full exploitation of CLARA test facility capabilities

MS *4e: Full exploitation of CLARA test facility capabilities and dedicated research stations incl. FEL at 250 MeV

MS *4f: CLARA + upgrade

MS *4g: Conceptual kHz-scale rep. rate plasma acceleration demonstrated and explored

MS *4h: High-power mid- to far IR beamline established in the UK

MS *4i: Multi-tens of kA ultrashort photoguns at multi-100 Hz to kHz developed and implemented

Larger projects such as CLARA, CERN AWAKE, SLAC FACET and DESY have project or facility-specific milestones, these are detailed in the project collaborations and not given here in detail.

As regards indicative costs, we repeat here that for too long the area has not received substantial funding2. This has worsened since 2014, with other countries increasingly taking a lead in many areas. For example, countries such as the US and Germany invest many tens of millions of USD/EUR into Novel Accelerator R&D at various facilities such as SLAC, LBNL, DESY and many other Helmholtz centres. In addition, e.g. Helmholtz drives forward even larger national programmes at the 40M€ scale which add to local, already large local projects compared to UK investments. Furthermore, the European EuPRAXIA project for plasma acceleration is aiming at a ~150M€ scale facility, and countries such as France, Italy, and Germany are aiming to host this facility with substantial national funding contributions.

It is believed that major reason for the difficulty to release substantial funding for Novel Accelerators in the UK is found in its diversity: many approaches and initiatives within the Novel Accelerator theme make it difficult to secure and distribute major funding allocations. STFC's Executive Board has recognized the need for a coordinated approach in the area[32].

Fortunately, the Novel Accelerator community has made good progress to organize themselves in a bottom-up approach. For example, the pan-UK Plasma Wakefield Accelerator Steering Committee (PWASC) is productive in identifying overlaps and synergies across the facilities, accelerator institutes and universities in the LWFA/PWFA area, which constitute the large majority of the UK Novel Accelerator area. National funding structures in other nations such as Germany or on a European basis (e.g. EuPRAXIA or LEAPS, the League of European Accelerator-based Photon Sources), take a similar approach of establishing a central body which then distributes funding to the individual players within the larger area, to the collaborative benefit.

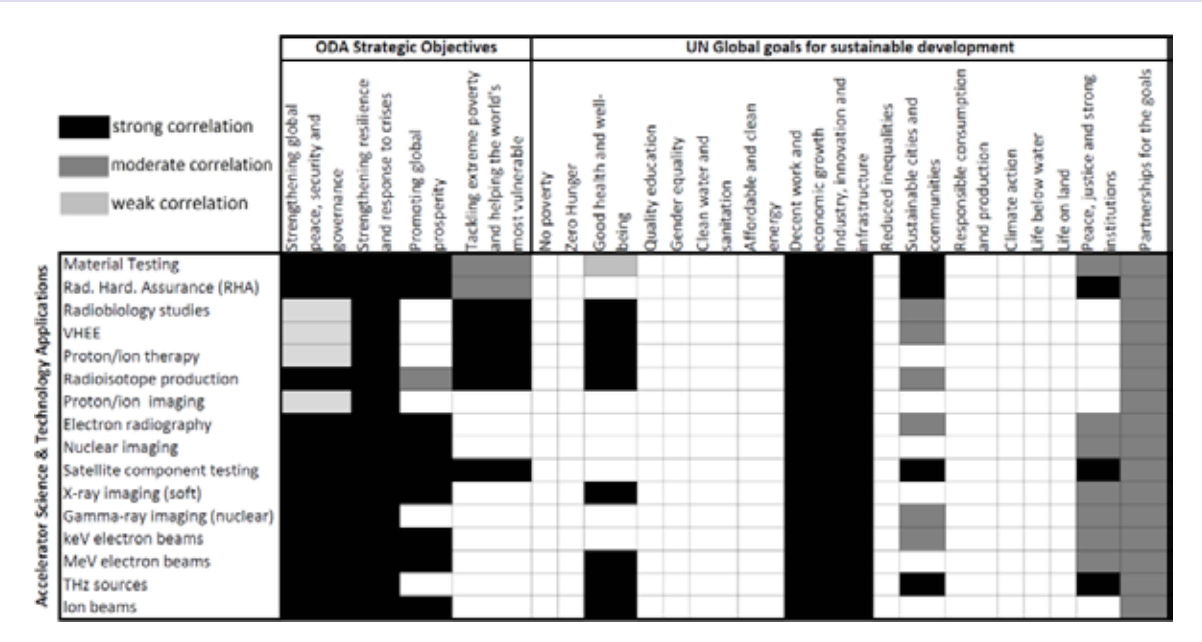
It is estimated that a funding volume of £40-50M would be required, front-loaded but distributable over ~5 years, in order to capitalise on the still strong intellectual leadership position of the UK in the Novel Accelerator area to boost the UK efficiently to a level where it can maintain and consolidate its worldwide leadership position. The PWASC and the Accelerator Institutes would be efficient bodies to manage this investment of a proposed "Novel Accelerator Action Plan", and to allow the UK to develop and harness the great potential which is offered by Novel Accelerators, and synergies within, such as detailed e.g. in section 1-4 and 6 of this roadmap.

6a. Map each accelerator science and technology activity and enabling technology/capability against potential impacts to:

i. ODA Strategic Objectives[1,2]

1 ODA Strategic Objectives: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/478834/ODA_strategy_final_web_0905.pdf
2 UN Global Goals: http://www.globalgoals.org/

A shared feature of Novel Accelerators is their compactness and the ability to put them to use even when a larger accelerator infrastructure is missing. This is highly useful for providing solutions for challenges faced by both non-industrialised, developing countries (GCRF) as well as for industries in developed nations like the UK (ISCF). Novel Accelerator R&D allows ODA countries to skip conventional accelerator technology and to directly engage in the growth field of novel accelerator research. Simulations, e.g. of plasma accelerators with particle-in-cell-codes developed by



UK academics or used at Daresbury in collaboration with industry, are an even more immediate, low-threshold path for ODA countries to contribute to world-class research with relevance e.g. to healthcare or security[33].

It is well-known that particle accelerator applications[34,35], (EuCARD2) and infrastructures[36] (OECD) have huge socio-economic benefits. It is estimated that the socio-economic impact of compact novel accelerators and e.g. "table-top" applications will be equal or larger than that of large infrastructures.

Furthermore, the very nature of plasma accelerators in particular, which deal with lasers, beams and plasmas, has substantial cross-council remit (e.g. relevant to EPSRC) and thus is an ideal candidate e.g. for cross-council remit and RCUK/UKRI projects.

The matrix below maps important ODA-relevant Novel Accelerator applications against ODA strategic objectives and UN Global Goals.

Important Novel Accelerator-relevant ODA topics are healthcare e.g. via plasma-based x-ray imaging or particle therapy. For example, x-ray imaging techniques have been developed at synchrotrons which enable earlier diagnosis of life-threatening diseases, such as cancer and cardiovascular disease. Despite the enormous promise of these methods, limited access to synchrotron facilities means that they are only available to a few hundred people per year. Compact, laser-plasma betatron radiation or undulator sources could make earlier diagnosis routinely available, and could transform treatment planning, delivery, and monitoring.

It should be noted that the impact of some novel accelerator activities on society and well-being is often indirect, nonetheless very important and possibly more sustainable when compared to other, more classical ODA activities. For example, promoting or enabling the ability of an ODA country to engage in space exploration by fostering capabilities to do radiation hardness assurance (RHA) of satellite components, indirectly can have large benefits to well-being, peace and security: Earth observation satellites e.g. allow to monitor borders and migrant movements, and to monitor agricultural changes. The use of Novel Accelerators to do RHA at the same time prevents the need for developing countries to use e.g. radioactive sources, which bear substantial proliferation dangers (terrorism). These "hidden benefits" are indirect but substantial, however their indirect nature makes it potentially difficult for the classical ODA community to correctly assess the benefits of such proposals.
In the past year, the plasma accelerator community had already submitted two bids based on plasma accelerators: one on their biomedical applications

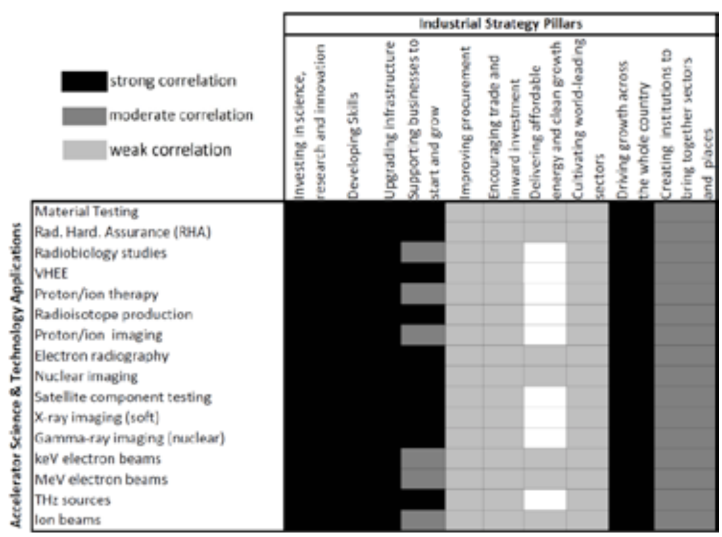
with Brazil, China, India, Kazakhstan and Serbia and another on security, RHA and space applications with Turkey, Egypt and Jordan. There is a strong interest in the partner countries in engaging with the UK on these projects to address some of the perennial challenges they face. There is also a secondary, long-term advantage via training of their skilled personnel in the cutting-edge technologies associated with novel accelerators that would help sustain knowledge-based economies in some of these countries.

ii. Industrial Strategy Pillars[3]

3 Industrial Strategy Pillars: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/611705/building-our-industrial-strategy-green-paper.pdf

Industrial applications are a known strength of compact Novel Accelerators[33,34,35]. The flexibility of Novel Accelerators and the ability to produce electron, proton, ion and photon beams, combined with their capability to be realised in "table-top", even portable setups, makes them ideal instruments for industrial exploitation and transformative applications. As a result, many of the Novel Accelerator activities & applications meet most of the 10 Industrial Strategy Pillars[37], and in any case the first Pillar Investing in Science, Research and Innovation. For example, Developing Skills is met by interdisciplinary (lasers, beams, plasmas, high-end electronics) Novel Accelerator science & engineering training e.g. at the accelerator institutes and universities; Upgrading Infrastructure is a central need which is shared by the Novel Accelerator community, see e.g. the expressed need for CLF, CLARA and university centre accelerator infrastructure upgrades, which also enable international leadership and partnership as well as 'local' engagement and access by industry to radiation sources; and the technology and innovation centres and incubators e.g. at Daresbury, at Harwell or at universities are directly responding to Supporting businesses to start and grow. The pillar Improving procurement is also met, for example by the need of highly specialized, high performance electronics, nano-fabricated structures or laser products for accelerator applications, and the commercialization opportunities which result and can put companies in a lead position before wider technology demand and need for mass production sets in. Driving growth across the whole country is promoted by access into application-heavy distributed accelerator infrastructures e.g. for Harwell (e.g. CALA) or Glasgow (SCAPA) or other universities for high-power laser systems, or at Daresbury as a key linac-based accelerator test facility (VELA/CLARA). The expansion of these test facilities and centres, research programmes and industry links fosters growth in industrial development and has very high return on investment[36]. Likewise, the distributed accelerator infrastructure approach is an ideal fit to Creating the right institutions to bring together sectors and places, e.g. through institutional links between national laboratories and facilities, universities and industry.

The table below maps selected Novel Accelerator applications to the 10 Industrial Strategy Pillars.



iii. Other industrial applications and spin-out opportunities

Most of the industrial applications have direct or indirect benefit or relevance to ODA and/or ISCF. This sections is here used to comment on spin-out opportunities and industrial applications. The US DOE SBIR model is a success story which e.g. has promoted growth of various spin-out companies such as RadiaBeam Technologies, which is a strong player in Novel Accelerator R&D and strongly supported e.g. the UK-led E210 collaboration at SLAC. The Innovate UK SBRI is a similar instrument, in principle, however it seems that the fundamental import of accelerators as enabling and underlying instruments of research and industry is not yet picked up by this UK instrument, in contrast to the US version. It would be highly beneficial to the economic impact and industrial exploitation of Novel Accelerators if the Innovate SBRI would offer to engage in accelerator-engaged projects.

Another notable instrument for industrial exploitation are incubators, e.g. in the UK or at CERN, which was recently used to spin-out the Liverpool-led D-Beam Ltd. which engages in novel accelerator diagnostics. The promotion of further accelerator-related spin-outs would be highly desirable and useful to harness the industrial potential Novel Accelerator and light sources in the UK.

There is also large potential for significant additional opportunities coming from collaboration with NPL, which is co-managed by the University of Strathclyde, and Surrey.

6b. How could STFC support the development of the potential impacts identified?

STFC could take a coordinating role, acting as a bridge between the academic institutions and the primary beneficiaries of the impacts identified for novel accelerators (ODA countries, industries etc.). It would also be desirable to have a cross-council partnership with EPSRC in assessing and prioritising these proposals as a large number of ODA-related applications of novel accelerators are low TRL but nonetheless fundamentally important instruments for generating sustainable socio-economic benefits in future[33,34,35,36]. Assessing them with the same yardsticks used for the traditional ODA-relevant activities would naturally put novel-accelerator-based proposals at a disadvantage.

As pointed out in section 6a iii), it would be useful if the field would be represented stronger within the SBRI calls and similar opportunities, incubators and the like, and that the need for fundamental accelerator activities in the ISCF is brought across. Currently, the threshold for generating spin-out companies is still rather high and any further knowledge transfer and seed activities which can help spin-outs get off the ground, and promote collaboration with industry, would be highly beneficial. Novel Accelerators are an ideal area for such industrial exploitation.

As pointed out in section 4a and b, Centres for Doctoral Training in the Novel Accelerator area would be highly useful to educate and train young scientists, which are urgently needed. There is high demand, by excellent candidates.

A further important mechanism are fellowships. There are a number of STFC fellowships, but even excellent candidates from the accelerator/Novel Accelerator area do not seem to be very successful in these calls hitherto. Mechanisms should be found to increase the probability of Novel Accelerator fellow candidates to succeed within existing schemes, or a more targeted Accelerator/Novel Accelerator fellowship should be established.

7a. In a reduced funding environment, which accelerator activities would you prioritise within this theme?

- **What is the minimum activity level required to keep skills alive within this theme over the next 15-20 years?**
- **What are the wider impacts of maintaining skills within this theme?**

It has been recognized for many years now that “There is some evidence that the UK laser plasma wakefield accelerator community is losing leadership due to relatively modest investment in this area compared with international competitors in the US and Europe”[2]. This unsatisfactory situation has been further aggravated in recent years, because the field is growing rapidly and others are increasing their investments[32]. Accelerator experts[2] and STFC Executive Board have suggested establishing organisational structures for a coordinated approach[32], which makes sense because of the diversity of the Novel Accelerator field, and have recognized that there are important commercial opportunities which will emerge over the next years[32] and that there is need to invest in UK facilities[32]. The community has organised itself and there are now coordinating structures in place in the UK such as the Plasma Wakefield Accelerator Steering Committee (PWASC), which involves the STFC facilities at Daresbury and Harwell, representatives of the Accelerator Institutes and the ASB, and the universities. At the same time, the already manifesting and increasing commercialization opportunities in the field fit well the increased emphasis the UK puts on industrialization of scientific research.

The compactness and versatility of Novel Accelerators also makes it highly interesting for ODA activities e.g. in context of the GCRF and for industrial collaboration e.g. in context of the ISCF. The diversity of the field – in terms of the range of required skills, the underpinning science, as well as regards the range of applications – makes Novel Accelerators well suited to cross-council or joint RCUK/UKRI funding.

The above considerations and the scientific activities and needs discussed in previous sections suggest that major investments are necessary in order to allow the UK players to maintain or re-establish world leadership in this growth field. These could be delivered efficiently and are expected to have high ROI e.g. via industrial exploitation and therefore would be also economically worthwhile. The most urgent investments include

- RAL CLF upgrades
- CLARA test facility exploitation and upgrade
- University laser operation, exploitation and upgrades
- Support of programmatic R&D projects at UK facilities & universities
- Support of R&D at international facilities and projects such as EuPRAXIA, SLAC FACET, CERN AWAKE

There is a strong case for delivering this investment not via a multitude of small projects, but in form of a larger, coordinated "Novel Accelerator Action Plan" with a volume of £40-50M over the next 5 years. A potential route to afford such a considerable investment which may put the UK on par with competing countries could be realised via cross-council and cross-fund engagement, including BEIS, or e.g. as a UKRI flagship.

The investment could be efficiently delivered and overseen by involving the above mentioned cross-UK structures as part of a "Distributed Novel Accelerator Infrastructure", which would then ensure to harness the synergies and additional value and impact which comes from realising applications and industrial exploitation.

This investment would be benefit across the different accelerator activities. For example, LWFA would be pursued at CLF and university laser centres, PWFA and dielectric-based acceleration at CLARA, and would be synergistic with the "Light Source" and the "Industrial, Medical, Defence and Security Applications" theme. The enabled research in the "Novel Accelerator" theme would then also be able to stimulate the "Frontier Machines and Nuclear Physics Machines" and the "Neutron Sources" theme.

7b. In an environment of increased funding, what additional activities, enabling technologies/ capabilities - or enhancements to activities, enabling technologies/capabilities already specified - would it be desirable to pursue?

- **What aspirations exist for investment into nascent areas of research?**
- **How could current, planned or proposed activities be enhanced?**

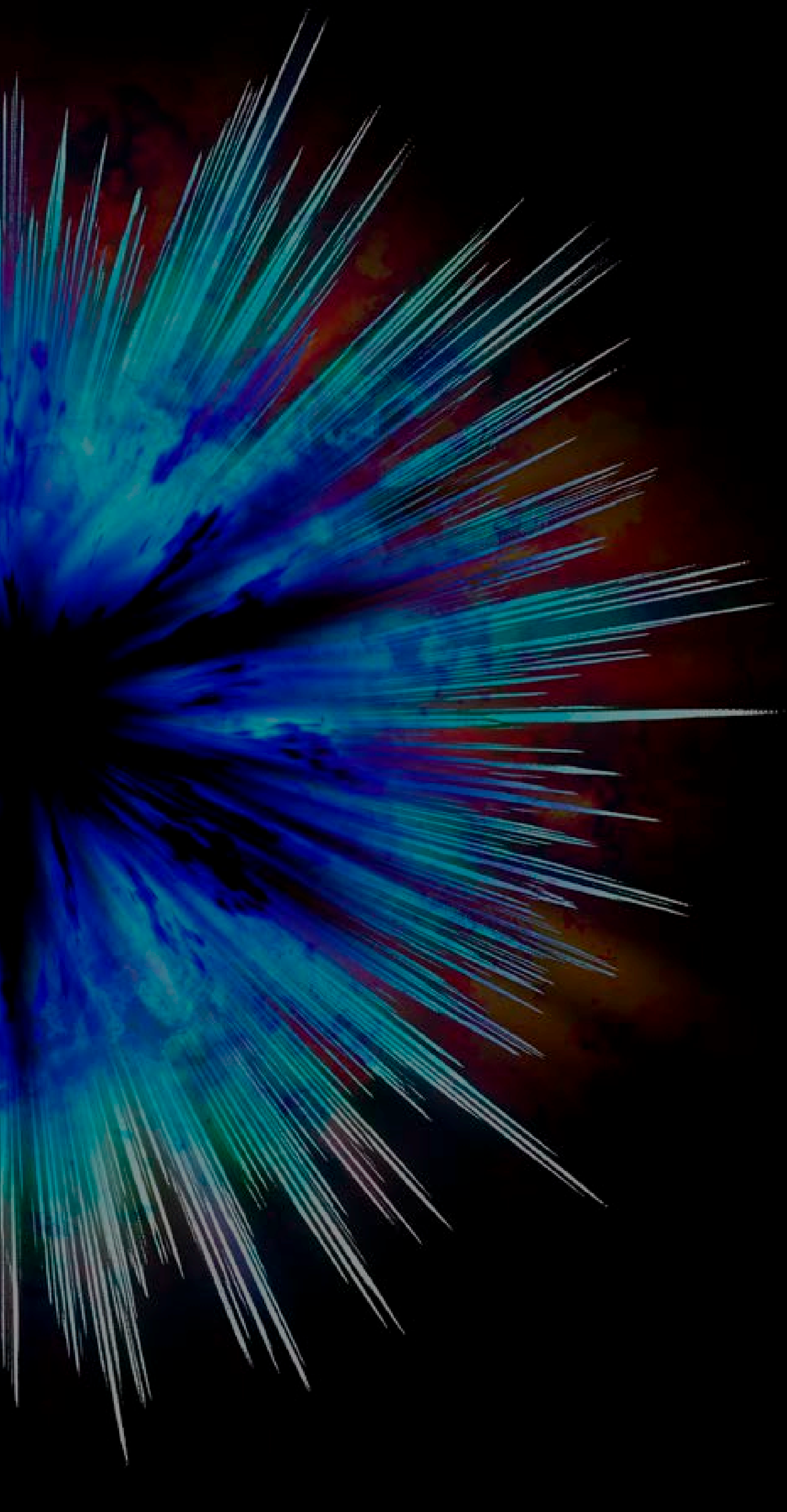
In an increased funding scenario, or in the event of windfall funding opportunities, the UK should bid to host EuPRAXIA – the "Compact European Plasma Accelerator With Superior Beam Quality". EuPRAXIA is a H2020 design study which could put such a facility on the ESFRI roadmap (the only other ongoing ESFRI accelerator design study is EuroCirCol). ESFRI is currently chaired by the previous STFC CEO, and has already put large infrastructures on the roadmap such as the ESS, ELI, European X-FEL, FAIR and HL-LHC. EuPRAXIA aims at plasma-based FEL as well as HEP applications. The UK is a strong beneficiary of EuPRAXIA (receiving 21% of total funding) and comprises 6 of 19 partners (Strathclyde, Liverpool, Manchester, IC, STFC, Manchester, Oxford) and has intellectual leadership on in key areas: for example, with the ALPHA-X programme the UK has one of the first plasma-accelerator based FEL research programmes and unrivalled systematic undulator beamline radiation generation progress worldwide, and UK-researchers have produced milestones in these advancements of LWFA-driven FEL's[28,29,30]. In addition, plasma photocathodes/Trojan Horse technology[15,16,31] which is led by UK researchers is a unique path to realize the "superior beam quality" which EuPRAXIA needs. Bidding for EuPRAXIA requires strong national support (such as the "Novel Accelerator Action Plan") and this could be provided by the UK in such a funding scenario. The UK does not currently host an accelerator European infrastructure and this could be a unique way to stay abreast of the developments in a post-Brexit era, and would also allow significant further funding options and photon science developments e.g. via LEAPS.

A further option which would be enabled by an increased funding scenario would be to maintain or increase international funding subscriptions to international facilities such as CERN or ELI.

A third option would be to intensify the efforts towards Novel Accelerator-based HEP colliders, which is currently most actively pursued by US DoE3, whereas the UK is currently focused on nearer-term applications and already demanding mid-term applications such as competitive plasma-based light sources.

References

1 Nature 431 "Dream Beam" issue, 535-538, Mangles et al. (2004)
2 STFC Accelerator Review Panel Report (2014)
3 US DoE Advanced Accelerator Development Strategy Report (2016)
4 Towards a Proposal for an Advanced Linear Collider: Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop ANAR at CERN (2017)
5 STFC Impact Report (2016)
6 B Hidding et al, Sci. Reports 7, 42354 (2017)
7 MP Tooley et al., Phys. Rev. Letters 119, 044801 (2017)
8 FY Li et al., Phys. Rev. Letters 110, 135002 (2013)
9 S Kneip et al., Nature Physics 6, 980-983 (2010)
10 S Cippiccia et al., Nature Physics 7, 867-871 (2011)
11 B Ersfeld et al., New J. Physics 16, 093025 (2014)
12 A Jochmann et al., Phys. Rev. Letters 111, 114803 (2013)
13 V Moskvin et al., Medical Phys. 39, 3813 (2012); A Subiel et al., Phys.Med.Bio. 59, 5811 (2014)
14 AWAKE collaboration, R Assmann et al., Plasma Phys. Control. Fusion 56, 084013 (2014)
15 B Hidding et al, Phys. Rev. Letters 108, 035001, (2012)
16 GG Manahan, FA Habib et al., Nature Comm. 8, 15705 (2017); UK patent 1617173.8 (2016)
17 B Hidding et al, Phys. Rev. Letters 104, 195002, (2010)
18 TP Rowlands-Rees et al., Phys. Rev. Letters 100, 105005 (2008)
19 AJ Gonsalves et al., Phys. Rev. Letters 98, 025002 (2007)
20 A Caldwell and M Wing, Eur. Phys. J. C 76, 463 (2016)
21 G Sarri et al, Nature Comm. 6, 6747 (2015)
22 WP Leemans et al., Nature Physics 2, 696-699 (2006)
23 E Clark et al., Phys. Rev. Letters 84, 670 (2000)
24 APL Robinson et al., New J. Phys. 10, 013021 (2008)
25 Nature Communications, Walsh et al. (2017)
26 LL Yu et al, Nature Communications 7, 11893 (2016)
27 RMGM Trines et al., Nature Phys. 7, 87–92 (2011); G Vieux et al., Sci. Rep. 7, 2399 (2017)
28 HP Schlenvoigt et al., Nature Physics 4, 130-133 (2008)
29 M Fuchs et al., Nature Physics 5, 826-829 (2009)
30 MP Anania et al., Appl. Phys. Letters 105, 264102 (2014)
31 N Bourgeois et al., Phys. Rev. Letters 111, 155004 (2013)
32 STFC Executive Board Annex A to this Review
33 Smaller, affordable particle accelerators for security, STFC
34 EUCARD2, Applications of Particle Accelerators in Europe
35 TIARA Report, http://www.accelerators-for-society.org/
36 OECD: The impact of large research infrastructures (2010)
37 Building our Industrial Strategy Green Paper (2017)



Establishments at Boulby Underground Science Facility, Cleveland; Chilbolton Observatory, Hampshire; Daresbury Laboratory, Cheshire; Polaris House (STFC headquarters), Swindon; Rutherford Appleton Laboratory, Oxfordshire; UK Astronomy Technology Centre, Edinburgh.

Science & Technology Facilities Council