ACCELERATOR PROGRAMME EVALUATION REPORT

1. Executive Summary

1.1. Accelerator science (i) enables advanced facilities that underpin fields as diverse as nuclear and particle physics, and physical and life sciences; and (ii) develops novel techniques that could revolutionise future research and lead to a wealth of applications.

1.2. Accelerator science within STFC is supported within the National Laboratories and by the Programmes Directorate (PD) programme. The PD programme funds accelerator R&D in universities via the UK's two accelerator institutes (the Cockcroft and John Adams Institutes), and by fixed contribution to the Accelerator Science and Technology Centre (ASTeC) National Laboratory.

1.3. This review has evaluated the STFC PD funded Accelerators Programme under three financial scenarios (flat cash, and ±10%). The review includes a consideration of the breadth and balance of the programme and its sustainability.

1.4. We find that the UK performs world class accelerator science and is a valued and sought-after international partner. UK scientists lead international collaborations and working groups, develop innovative techniques, produce high impact papers, and leverage international investment in projects. UK accelerator institutes and universities provide world-class training and skilled graduates that move into industry and the public sector,

1.5. This world-leading expertise provides a basis to successfully leverage support and lead work in future projects. For example, the UK's track record in cryomodules and targetry enabled the UK to successfully bid for BEIS funding and lead this work at Fermilab's Long Baseline Neutrino Facility (LBNF). We note that this investment dwarfs PD's total accelerator science budget, and that participation would not otherwise have been possible.

1.6. The programme has strong synergies with many scientific areas. Particle physics is directly underpinned by the frontier machines area. Novel accelerator research may also enable new particle physics experiments, but also high energy density science, ion acceleration and ultrafast imaging and creates compact facilities. Light source research enables physical and life sciences by imaging ultra-small structures and ultra-fast processes. Investment in these areas therefore benefits a much wider area. Conversely, a lack of investment hinders progress in all fields and any reduced funding for accelerator science should be considered in this context.

1.7. We find that the current level of funding is significantly sub-optimal and this has had a detrimental effect on programme breadth and balance. The cumulative effect of flat cash funding over a number of years has limited the number of development projects to the level of one project each for frontier machines, novel accelerators, and light sources, and accelerator applications has no development line at all. Limited funding has also limited student recruitment resulting in a lack of capability in certain fields of accelerator research. This situation presents risk for future programme sustainability, and limits ability to tension new opportunities if funding remains constrained.

1.8. To improve programme balance and mitigate against loss of opportunity in accelerator applications, we recommend that the new Technology and Accelerators Advisory Board and Accelerator Advisory Panel consider how best to support applications and maximise economic impact. We note the necessity to fund applications and technology across all technology readiness levels, and believe a gap exists within UKRI at the moment. We believe effort must be made to bridge this gap, which prevents delivery of industrial and medical applications.

1.9. We note that much of the breadth in the programme has been sustained by activities in the two accelerator institutes and ASTeC. All three have both distinct scientific strengths and complimentary research programmes; they underpin UK activities and are central to ensuring continued UK leadership and skills development. All are highly regarded by international partners and have been remarkably successful at leveraging external funding. We believe their role is vital. To ensure their sustainability we recommend that STFC explore routes to improve the consistency of their funding, taking care not to unfairly disadvantage any of them.

1.10. Given the community's reliance on external funding we believe that the UK must ensure that access to European funding is continued, or a replacement found, to maintain the breadth and balance of the programme. This is especially urgent for postgraduate training, where the accelerator institutes provide a vibrant and active programme of skills development necessary to sustain the programme, and the EUPRAXIA project where the UK is (currently) a leading partner.

1.11. Should funding reduce further, or if flat cash remains in place for a prolonged period, we find that the programme will be damaged irrevocably. It is likely that leadership can no longer be maintained in one or more significant areas. The UK will suffer reputational damage should a managed withdrawal from an existing project be necessary. In this scenario we recommend that a review take place, with full community consultation, to determine how best to sustain the accelerator science programme.

1.12. We regard an upturn of at least 10% as essential to reverse the damage already caused by flat cash funding. Funding the institutes at least at constant volume allows a restored work programme, protects breadth, and allows skills gaps to be repaired. Any additional uplift could be used for thematic or application-based funding calls to exploit the many opportunities the UK is positioned to lead. We urge STFC to uplift funding to ensure the future health of this exciting and important area.

Contents

1. Executive Summary 1
ACCELERATOR SCIENCE PROGRAMME EVALUATION REPORT 4
2. Introduction 4
3. Governance and previous reviews 5
SCIENCE PRIORITIES 6
4. Assessment 6
5. Frontier Machines 7
6. Novel Accelerators 9
7. Light Sources 12
8. Accelerator Science Applications 14
9. Breadth and balance of programme 15
10. Synergies 17
11. Societal and economic impact 18
12. Skills balance and pipeline 19
FUNDING OPPORTUNITIES AND SCENARIOS 22
13. New funding opportunities 22
14. Flat cash planning scenarios 24
15. Reduced (-10%) financial scenario 25
16. Increased (+10%) funding scenario 25
17. ASTeC funding 26
SUMMARY OF RECOMMENDATIONS 28
18. Summary and Recommendations 28
Appendix A: Recommendations from the 2017 Accelerator Strategy Review 30
Appendix B: Recommendations from the 2017 BoP Review 32
Appendix C: Ranking Scoresheet for Programme Evaluations 2018/19 33

ACCELERATOR SCIENCE PROGRAMME EVALUATION REPORT

2. Introduction

2.1. Accelerators underpin STFC's activities in Frontier Science and enable a wide range of physical and life sciences research at the National Laboratories. The accelerator science programme within STFC is sub-divided into five main themes: high energy physics accelerators; light sources; neutron sources; novel accelerator R&D; and accelerator development and applications.

2.2. Support for accelerator science comes from the National Laboratories and Programmes Directorate (PD). The PD programme touches on most areas and has traditionally had a greater emphasis on high energy physics and novel acceleration.

2.3. The accelerator programme evaluated in this review is the portion of accelerator science that sits within PD. The programme funds accelerator R&D in universities and National Laboratories via two accelerator institutes. The corresponding activities are connected and synergistic with, but distinct from, those run by the national laboratories themselves in support of the STFC facilities and by the Accelerator Science Technology Centre (ASTeC).

2.4. The two accelerator institutes, the Cockcroft Institute (ASTeC, Lancaster, Liverpool, Manchester, and Strathclyde universities); and the John Adams Institute (Imperial, Oxford, and Royal Holloway universities), have existed for over ten years. The institutes are typically funded by PD for a four-year period.

2.5. The PD resource budget for accelerator science is approximately £6.3M per annum. Of this, £1.2M supports research at ASTeC, £3.5M supports activities at the Cockcroft Institute (CI) and John Adams Institute (JAI) accelerator institutes, and the remaining £1.7M supports project grants. Besides this, there is £0.75M capital funding per annum. The financial forecast of the programme, in a flat cash scenario, is summarised below.

Table 1: Financial forecast of the Accelerator Programme

Accelerator Programme	**19/20**	**20/21**	**21/22**	**22/23**	**23/24**	**24/25**
ASTeC	1.2	1.2	1.2	1.2	1.2	1.2
Institute Grants	3.5	3.5	3.7	3.5	3.5	3.5
Accelerator Projects	2.5	2.5	2.2	2.5	2.5	2.5
Total (Capital + Resource)	**7.2**	**7.2**	**7.1**	**7.2**	**7.2**	**7.2**

2.6. The programme does not have oversight of the £1.2M ASTeC funding, as ASTeC falls within STFC National Laboratories. Accelerator institute funding is reviewed and awarded under the Consolidated Grant (CG) mechanism. Project grants are reviewed by the STFC Project Peer Review Panel (PPRP).

2.7. In addition to the two accelerator institutes, which as with the entirety of the PD programme have been funded at a flat cash level for a number of years, the programme currently supports five projects (AWAKE-I, HL-LHC-UK, LESS, PWFA-FEL, and MICE).

3. Governance and previous reviews

3.1. An Accelerator Strategy Board (ASB) was established in 2010 with the aim of providing STFC Executive Board with advice on all aspects of accelerator science and technology covering both the PD programme and National Laboratories. This body was responsible for producing an initial accelerator strategy roadmap.

3.2. The draft roadmap was used as a basis for a strategic review of the accelerator R&D programme that was completed in 2014 (“Review2014”), following the recommendation of the 2013 Programmatic Review. The findings and recommendations of Review2014 were used to define a framework for the peer review of the accelerator institutes and the programme’s projects in 2016.

3.3. Review2014 provided input into the STFC 2017 Accelerator Strategy Review (“Review2017”), which reviewed the wider context of accelerators beyond that of the PD programme.

3.4. Review2017 found the ongoing accelerator work within the UK to be broad and vibrant. In particular, accelerator development with novel applications was identified as important for supporting basic underlying research and development for facilities and applications in the future. The Panel confirmed that it supported the recommendations of the 2017 Accelerator Strategy Review, which are given in Appendix A.

3.5. In 2017, STFC published the Balance of Programmes (BoP) review which looked at the balance of funding between the Accelerator, Particle Physics, Particle-Astro, Astronomy, and Nuclear Physics (PPAN) research disciplines. The BoP made five recommendations for the PD Accelerator Programme, recommendations 17 – 21 (see Appendix B). In line with recommendations 17 and 19, STFC has removed indexation from ASTeC funding within the PD funding context, and funding for CI and JAI has been held at flat cash.

3.6. ASB held its last meeting in March 2019. It is being replaced by a new Technology and Accelerator Advisory Board (TAAB) which will report directly to STFC Council. A new Accelerator Advisory Panel (AccAP) will be established to provide advice to support the PD accelerator programme.

3.7. The Accelerator Programme Evaluation Panel (hereafter, ‘the Panel’) considered it important that AccAP provide a link from the community to STFC and TAAB. AccAP should provide regular updates to Science Board to ensure that it, and STFC, have visibility of the excellent work being undertaken. The panel felt it would be helpful if there was some continuity in membership from ASB to both TAAB and AccAP, and that a similar breadth of expertise should be included. The Terms of Reference and remit would be in line with those of equivalent panels in other PD science areas. To first order, AccAP would view only with the PD accelerator programme, and TAAB only the broader STFC accelerator strategy.

Recommendation 1: The Accelerator Advisory Panel should represent the views of the community and provide a strategic link between the community, STFC and TAAB

3.8. The Panel recommended that the new Accelerator Advisory Panel should be tasked with both developing, and engaging the community with, an accelerator roadmap that builds on the STFC 2017 Accelerator Strategy Review, UKRI infrastructure roadmap, and the European Particle Physics Strategy Update. This would provide a valuable guide to the PD accelerator programme and the community.

Recommendation 2: The Accelerator Advisory Panel should be tasked with both developing, and engaging the community with, a PD-focused accelerator roadmap

SCIENCE PRIORITIES

4. Assessment

4.1. The Panel considered each of the four accelerator science areas. Each area is described and evaluated and priorities are assigned, but the ordering of the science areas is not significant. The Panel considered the excellence of the accelerator science, rather than the scientific excellence it facilitates in related disciplines such as particle physics, when ranking projects.

4.2. The Panel invited current and future projects and the accelerator institutes to submit proforma to enable priorities to be assessed. The assessment criteria were based on that previously used in the PR2013, namely '**α**' rankings for projects and '**g**' rankings for science exploitation experiments. In addition, '**i**' ranking was introduced to cover evaluation of impact for the economy and society. The ranking definitions are listed in Appendix C. Projects submitted through the 2018 'Developing a World Class Research Programme' (also referred to as 'priority projects') exercise, were noted in discussion but not ranked.

4.3. An overview of the current and anticipated future PD-funded accelerator programme is shown in Table 2.

Table 2 Overview of the PD-funded accelerator programme

Activity	16/17	17/18	18/19	19/20	20/21	21/22	22/23	23/24	24/25
Accelerator Institute and ASTeC Funding									
CI and JAI		Current							
ASTeC (top-slice)				Current					
Particle Physics Frontier Machines Project Funding									
HL-LHC	HL-LHC-UK				HL-LHC-UK2 (incl. LESS)				
Novel Accelerators Project Funding									
AWAKE	AWAKE-I				AWAKE-II				
Light Sources Project Funding									
PWFA-FEL				Exploring PWFA-FEL at CLARA					
Accelerator Science Applications Project Funding									
None									

5. Frontier Machines

5.1. The area of frontier machines covers the development of current and future accelerators for the particle and nuclear physics communities. It is the accelerator science area with the strongest synergy to the PPAN programme, and strategic priorities closely follow those of the European Strategy for Particle Physics (ESPP), and the US Particle Physics Prioritisation Panel.

5.2. Current STFC-supported work in the area includes CERN's frontier proton facility, the high luminosity Large Hadron Collider (HL-LHC) upgrade, the conclusion of the Muon Ionisation Cooling Experiment (MICE) project, and (through the institutes) International Linear Collider (ILC) and Compact Linear Collider (CLiC) R&D towards future electron colliders. Institute funding also supports modest activities at FNAL and JPARC to support charged lepton flavour violation facilities. BEIS funding supports the LBNF DUNE neutrino facility project, with accelerator-based Target and Beam System, and Proton Improvement Plan-II (PIP-II) sub-projects.

5.3. HL-LHC is forecast to deliver data after 2025 and, in current planning, will deliver an annual integrated luminosity of 250 (50) fb^{-1} to the ATLAS and CMS (LHCb) experiments. The HL-LHC work in the UK is split into two phases. HL-LHC-UK Phase-1 grew from the EU HiLumi project and is funded until 2020. HL-LHC-UK Phase 2 is intended to continue the work from 2020 and is currently under review.

5.4. HL-LHC-UK Phase 1 focuses on four areas of UK strength: advanced collimators, crab cavities, beam instrumentation and cold-powering systems. These activities were chosen to maintain and expand UK leadership, building on UK simulation expertise and delivering critical hardware. The UK have co-led HL-LHC work packages and acted as Chair of the HL-LHC Collaboration Board for two terms. The project achieved the first crabbing of a proton beam in 2018; a major milestone which had substantive UK input.

5.5. The Panel noted the broad strength and high level of international competitiveness of this area in the UK. The Panel considered that the UK is viewed as a reliable and valued partner, a fact evidenced by leveraging a contribution of approximately 50% of the HL-LHC-UK Phase 1 project costs from CERN. Such contributions significantly increase the UK's impact on such projects. The Panel felt this emphasised the unique expertise in the UK that is critical to the success of large international collaborative projects.

5.6. The HL-LHC-UK Phase 2 project is due to be reviewed by PPRP in autumn 2019 at the same time as the AWAKE project (see Novel Accelerators). There is insufficient funding within a flat cash budget to fund both projects at the level requested. If this funding level continues the projects will be tensioned against one another and one, if not both, could receive an inadequate level of support.

5.7. HL-LHC-UK Phase 2 includes the LESS (Laser Engineered Surface Structure) sub-project in the proposal submitted to PPRP and considered by this evaluation. LESS is a proof of concept project to design and build a prototype automated machine for the laser treatment of the inner wall of vacuum chambers. The resulting engineered surface should lower the secondary electron yield surface resistance, and gas desorption, and therefore potentially mitigate the electron cloud problem that restricts the performance of high-power particle accelerators.

5.8. The Panel noted that the HL-LHC project is considered to be a high priority internationally, as identified by the European Strategy for Particle Physics (ESPP), and although largely a construction project, was clearly not a build-to-print endeavour for the UK. The science drivers for the project are a high priority and are likely to advance the subject, and the accelerator project itself has highly innovative components in respect of LESS and the gas-jet beam monitor work. The Panel noted that LESS, if successful, would be of benefit to many accelerator facilities and experiments around the world. The Panel further noted that although the HL-LHC-UK Phase 2 project has no direct link to industry, it is anticipated that strong links will develop in the future, and that the current active and successful public engagement activities would continue. The HL-LHC-UK Phase-2 (including LESS) project was scored as (**α4, i4**).

5.9. STFC previously supported UK involvement in the international MICE project, intended to demonstrate an essential technology for the design of a muon collider or neutrino factory. MICE began step-wise construction in 2005 on a dedicated muon beam from ISIS. Having encountered a number of issues it was decided to end data taking at Step IV (to study the material properties of the absorbers, to evaluate the MICE single-particle emittance measurement and to demonstrate reduction of normalised emittance through the absorber materials). MICE successfully completed data taking in December 2017 with first demonstration of ionisation cooling presented to IPAC 2018. It has now been decommissioned and is in the final stages of data analysis, which runs until mid-2020.

5.10. Both the CI and JAI have made significant contributions to the International Linear Collider (ILC) and Compact Linear Collider (CLiC) R&D over the past decade. Activities are complementary and high quality; both institutes have obtained a high degree of international visibility and become acknowledged centres of expertise. The UK supplies the current spokesperson of the CLIC accelerator collaboration. There is no funding line to support projects in this area.

5.11. The accelerator institutes also provide support to activities on g-2 and mu2e at FNAL and COMET at J-PARC, to support charged lepton flavour violation facilities where an excellent understanding of the beam is essential. UK personnel have key expertise and play critical roles in the accelerator science of these experiments. There is no funding line to support projects in this area.

5.12. An additional £30M funding has been received directly from BEIS to support the LBNF DUNE project. The UK will qualify and deliver cryomodules for the PIP-II (PIP-II, **α4, i4**) proton beamline at FNAL and produce the target system (Beam and Target System, **α3, i3**) necessary to generate neutrinos from the proton beam. Both are critical components for generating DUNE's neutrino beam. The Panel noted that the UK is world-leading in targetry work and that this work exploited experience gained with T2K. Additionally, the UK has a substantial international profile in cryomodule work, based on work for HL-LHC and ESS, and the PIP-II project offered substantive industrial impact through work with The Welding Institute (TWI). The UK also has leadership of the overall DUNE project by supplying two consecutive co-spokespersons.

5.13. Future activities are determined by the strategic direction of the particle physics community. The panel noted that a proposal for "CERN Future Collider projects" was submitted to the priority projects exercise, for R&D on the next generation of colliders in particle physics. As such, this represented a community future priority in this accelerator science area.

5.14. The Panel noted that the ESPP update will complete and report in 2020, and that future priorities will be set accordingly. It will therefore be necessary to review the balance of activities following the ESPP outcome. The community should be consulted as part of the review.

Recommendation 3: It is necessary to review, through community consultation, the balance of frontier machine projects following the European Strategy for Particle Physics update

6. Novel Accelerators

6.1. Novel accelerators are classed as those that: (i) develop new methods to accelerate charged particles to high energies over shorter distances than is possible using conventional techniques, or; (ii) produce particle beams with novel properties such as very short pulse duration. Both types of novel accelerators could enable new applications such as compact light sources or medical accelerators. Methods used in this area include plasma wakefield, dielectric and structured wakefield acceleration.

6.2. Plasma wakefield acceleration directs a short pulse of laser light, or a particle beam, into a plasma (an ionized gas). This driving pulse separates electrons and ions within the plasma to drive a trailing "plasma wave", within which are very intense electric fields ("plasma wakefields") that can be one thousand times larger than those within a conventional radio-frequency (RF) accelerator. Plasma wakefield accelerators could therefore be hundreds or thousands of times shorter than their conventional RF counterparts.

6.3. Dielectric Laser Acceleration (DLA) uses a dielectric structure to convert the large transverse electric fields of an intense optical or terahertz laser pulse into a longitudinal field suitable for accelerating particles. A variant approach is Direct Acceleration, in which the longitudinal field is produced by manipulating the polarisation of the drive pulse and focusing it or propagating it in a waveguide structure. Other microstructures are also being studied for high gradient acceleration such as Carbon nanotubes.

6.4. Structured wakefield acceleration (SWFA) uses a particle bunch to drive wakefields in a structure, for instance, a dielectric or a corrugated metallic tube. STFC do not currently fund work in this area.

6.5. The majority of current novel accelerator research within the UK focuses on laser and particle driven plasma wakefield acceleration. Laser driven wakefield research is supported by a variety of funding sources[1]. STFC supports the area through the accelerator institutes and indirectly through the Central Laser Facility at RAL; there is no project funding. STFC supports one project in particle driven plasma wakefield acceleration.

6.6. The UK groups have formed the Plasma Wakefield Accelerator Steering Committee (PWASC, http://pwasc.org.uk/) to represent the UK groups working in this area and to help coordinate their activities. Members of PWASC are drawn from UK research

[1] Non-STFC sources include other research councils (e.g. EPSRC), the European Union, and US funding agencies (e.g. DOE and US Air Force Office of Scientific Research)

groups, the Central Laser Facility, and the two Accelerator Institutes. PWASC recently published a UK roadmap for plasma wakefield accelerator research[2].

6.7. The UK has several internationally leading groups working on Laser Wakefield Accelerators (LWFAs). Much of the work on LWFAs has been undertaken at the Central Laser Facility (CLF) at RAL but, this is critically underpinned by work with smaller laser systems in universities. Additionally, the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) is a medium-scale facility at Strathclyde University used for research on LWFAs and their applications. SCAPA is run as a university facility with access fees.

6.8. UK groups have previously made major contributions to many areas of LWFA research, including: the first demonstration of the generation of narrow energy spread beams; pioneering demonstrations of acceleration to the GeV range; generation of incoherent X- and gamma-radiation, and its application to ultrafast imaging; the development of novel plasma channels; studies of novel methods for controlling electron injection via ionisation of dopant species; and characterisation of laser-accelerated electron bunches.

6.9. Leadership is evident from the high number of high-impact research papers authored by UK groups, the award of international prizes, strong involvement in international projects and invitations to serve on international bodies (e.g. ICFA Panel on Advanced and Novel Accelerators; the ALEGRO working group on the development of an Advanced International Linear Collider).

6.10. Much current LWFA work centres on the EuPRAXIA project, an EU-funded design study on a European plasma research accelerator with excellence in applications. The goal of the project is to produce a conceptual design report for the world’s first high energy plasma-based accelerator with industrial beam quality and user areas. UK groups constitute six of the 16 partners in EuPRAXIA, receive 21% of the total funding, and provide the Leader and/or Co-leader of three of the eight Work Packages supported by the EU Design Study. The present phase of EuPRAXIA will end in 2019.

6.11. The next phase of EuPRAXIA will be a 10-year, multi €100M programme to design and construct laser- and beam-driven plasma accelerator facilities generating high-quality multi-GeV electron beams. The resulting facility is likely to apply for inclusion in the ESFRI roadmap. UK groups are strongly involved with developing the EuPRAXIA proposal and it is anticipated that the UK will lead development of the application beamlines.

6.12. The panel noted that participation in the next phase of EuPRAXIA would benefit the UK enormously, from advances in accelerator science to the development of applications in science, medicine and industry. However, Brexit creates considerable uncertainty with respect to the mechanisms through which the UK could receive funding and the legal basis on which it could be a member of this project. The Panel felt that STFC and UKRI should support future membership of EuPRAXIA, and maintain a flexible approach to ensure the UK remains central to the project in any future Brexit scenario.

[2] PWASC recently published a UK roadmap for plasma wakefield accelerator research (available at https://arxiv.org/abs/1904.09205)

Recommendation 4: STFC and UKRI should strongly back UK membership of the EuPRAXIA project and should maintain a flexible approach to ensure the UK remains at the heart of this project in all future Brexit scenarios

6.13. The Panel noted that the UK also has a world-leading activity in laser acceleration of ions. This work is undertaken at high-power laser facilities, including the CLF, as well as in university laboratories. To date this work has largely been funded by EPSRC. For example the A-SAIL project is an EPSRC project to develop all-optical delivery of ion beams suitable for diagnosis and treatment of deep tumours. Whilst STFC is a partner in A-SAIL, the project itself, or ion acceleration more generally, are currently not funded directly by PD, despite an active UK community.

6.14. The recently announced Extreme Photonics Applications Centre (EPAC) in Oxfordshire will, in future, provide additional capability to explore industrial, medical, and security applications of laser driven accelerators. Built on the proof-of-principle tests done with LWFA-driven sources in Gemini, EPAC is expected to yield new tools and disruptive capabilities for the academic, industrial, medical and defence communities in the UK, and to help maintain the UK's international leadership in novel accelerator research.

6.15. UK groups are also involved in the AWAKE project (**α5, i3**), an accelerator R&D project based at CERN. It is a proof-of-principle experiment investigating acceleration of charged particles in plasma wakefields driven by a proton bunch. The Panel noted that it was not yet clear which of the many novel acceleration technologies being pursued in the wider community will create seminal changes in the field. Of the projects considered in this evaluation, the Panel felt that the AWAKE project was the most likely to achieve this, and that it had the potential to provide significant technological impact. It was noted that the project was highly innovative and likely to substantially advance the subject. Although the science drivers for conducting the project were not the highest priority, the Panel gave the AWAKE project **α5** for scientific excellence. The AWAKE-UK group comprises approximately 20% of the CERN AWAKE collaboration, and includes the Deputy Spokesperson. The UK has been key in providing the booster and pepper-pot diagnostic to enable measurement of the accelerated charged particles.

6.16. The AWAKE-UK project was initially awarded funding for two years in 2012, the financial constraints in place when it came in for review led to a bridging period before the current four year AWAKE-I award was put in place. The project has submitted a proposal for continued support (AWAKE-II) that will be reviewed in autumn of 2019 for funding from 01 April 2020. The Panel noted that AWAKE-II had also been submitted as a priority project.

6.17. Dielectric wakefield accelerator work and studies into DLA and CNT structures is carried out within university groups in collaboration with international partners in a number of different activities. The Panel noted that these activities were high quality and potentially leading. However, this leadership was in danger of being lost without a critical mass of effort in place. The Panel noted the success of the plasma wakefield community in focussing effort by forming a steering committee and developing a roadmap[3]. The Panel recommended that the dielectric wakefield and microstructures community consider a similar approach which would strengthen the case for investment.

[3] The Plasma Wakefield Accelerator Steering Committee (PWASC, http://pwasc.org.uk/), whose roadmap is available at https://arxiv.org/abs/1904.09205 ..

Recommendation 5: The dielectric wakefield and microstructures community should consider focussing effort and build critical mass to strengthen the case for investment.

6.18. The Panel noted that the UK has international leadership in several other novel accelerator areas: conceptual and experimental leadership (with the UCLA group) in the development of plasma photocathodes (the "Trojan Horse" method) for generating and trapping high-brightness bunches in plasma wakefields; the hybrid LWFA-PWFA concept; and PWFA-driven FELs. In this context, UK researchers led the E210 (Trojan Horse) and E203 (bunch diagnostics) experiments at SLAC FACET.

6.19. In this context the Panel also noted that, UKNOVA, a proposal submitted to the priority project exercise, proposed a coordinated research programme on novel acceleration techniques to enable plasma, dielectric and structured wakefield acceleration. The proposal includes upgrades to facilities at CLF, SCAPA, and CLARA, as well as development of targetry and diagnostics to enable high-repetition-rate ion acceleration.

7. Light Sources

7.1. Accelerator driven light sources facilitate advances in the physical and life sciences and deepen our understanding of the natural world. These key scientific instruments use accelerator technology to generate intense and ultrashort pulses of light, with wavelengths ranging from the infrared through ultraviolet to hard X-rays.

7.2. Over the past 40 years, significant progress in light sources has been driven by electron synchrotrons, such as the UK's Diamond Light Source, which provide high average brightness, high flux, and ultra-stable X-rays. The advent of 4th generation light sources (FELs), of which at least 13 are currently planned or in construction globally, will further enhance the beam brightness and transverse coherence of X-rays. FELs are advanced coherent light sources which allow imaging of ultra-small structures and ultrafast processes.

7.3. Most recently, novel schemes to drive FELs with electron beams generated by laser- and beam-driven plasma accelerators have been proposed, which could further improve delivered light parameters by several orders of magnitude and reduce overall size and cost. For example, driving FELs with LWFAs and PWFAs is one of the main goals of the EuPRAXIA project.

7.4. Sub-femtosecond coherent photon pulse generation is a highly desired capability, as attosecond X-ray radiation pulses would allow observation of, for example, electron dynamics within molecules and materials on their natural timescale, which would constitute a paradigm change. Such developments offer the potential to conduct ultrafast science at the timescales of chemical reactions.

7.5. STFC supports one project in the area. PWFA-FEL (**α4, i3**) is an exploratory study using simulations to develop the design and assess the performance of free electron lasers driven by electron-beam-driven plasma wakefield accelerators. The project provides the possibility of producing short and intense, high energy electron beams that are increasingly being considered as drivers for FELs in future compact systems. The project started in 2019.

7.6. The Panel considered PWFA-FEL to be highly innovative. The work builds on the expertise and groundwork of the UK collaboration, who, with SLAC, are conceptual leaders in the Trojan Horse scheme that led to the first experimental demonstration of plasma photocathode injection and acceleration. The impact of the project has been increased by leveraging in-kind contributions from SLAC and UCLA. Technological advances from the project could lead to future bids to schemes like the Industrial Strategy Challenge Fund. The Panel noted the potential for an SME spinoff in the UK and that although pathways to impact are not yet finalised a coherent commercialisation strategy exists.

7.7. Elsewhere in the programme, ASTeC has developed novel FEL concepts which are internationally leading. UK FEL expertise has influenced FEL facilities worldwide, such as the Linac Coherent Light Source at SLAC, by use of the Strathclyde FEL code Puffin.

7.8. The area also includes R&D for light source facility upgrades to maintain international competitiveness. UK institutes have collaborated on low-emittance lattice designs for a future DLS-II upgrade, and UK experts hold leading positions internationally, including as the Technical Director of SESAME.

7.9. The Panel was supportive of R&D related to the DLS-II upgrade continuing in order to build and develop upon the PD accelerator programme’s links to the National Laboratory accelerator activities, and felt the work provided a good example of strong synergy between the two.

7.10. The Panel noted that CLARA had been submitted to the priority projects exercise as a potential future project. CLARA was conceived as a facility based at STFC Daresbury Laboratory to pave the way for a state-of-the-art FEL facility for the UK. The 2017 Accelerator Strategic Review recommended that the development of CLARA be completed and its exploitation supported. Extensive preliminary work has been completed and steps taken to realise this ambition.

7.11. The Panel noted that the forthcoming UKRI Infrastructure Roadmap may not recommend support for a UK FEL, in which case CLARA may not be supported.

7.12. Although outside of the scope of this evaluation, the Panel believed that future development would be of significant value as it would benefit accelerator R&D and the wider scientific community. The Panel noted that an important distinction existed between the higher value assigned to a UK FEL by its general users, compared to a lower value assigned to a UK FEL in the context of the PD accelerator programme.

7.13. An external (to STFC) evaluation review of FELs is currently underway with the aim of developing a UK strategy. The Panel stressed that guidance on the future construction of a FEL would be helpful to both accelerator and scientific communities but appreciated that the outcome of the review is on a year’s timescale.

7.14. The Panel stressed the importance of accessing the newest UK and international facilities, so that accelerator test facility R&D projects could be carried out at the cutting edge of technology, and UK expertise further developed. The Panel recommended that STFC seek to secure access to UK and international facilities to allow UK leadership in the area to be maintained.

Recommendation 6: STFC should seek to secure access to both UK and international light source facilities from an accelerator R&D perspective, to maintain UK expertise and leadership in the area.

8. Accelerator Science Applications

8.1. Although there are almost 50,000 particle accelerators in the world, those that are used for research are relatively small in number. The vast majority find use within health, security, energy, manufacturing, and environment applications. This strong spin-out from earlier research indicates that R&D into particle accelerators has excellent potential to create impact on an academic, societal, and economic level.

8.2. R&D in the UK has focused on the design and optimisation of medical accelerators and beam delivery systems, the development of detectors for dose, profile and energy measurement, Monte Carlo studies into beam propagation and beam-cell interactions, and automated image analysis using machine learning techniques. These studies provide a solid basis for applications also in other areas and relevant contacts with clinical centres are in place.

8.3. UK groups are developing collaborations with industry to achieve impact from technologies developed for current research. For example, UK scientists have undertaken joint R&D with SMEs and clinical centres to produce advanced healthcare applications such as A.D.A.M. and Adaptix. UK groups have developed high gradient linear accelerators with national and international companies for cargo screening, proton therapy and imaging. UK scientists have designed and built compact accelerators to treat contaminated water, and developed novel compact light sources with superior beam quality for advanced imaging application or material testing.

8.4. A wide range of applications is expected to become available from the profile, intensity and emittance measurement techniques that are being developed within AWAKE-UK. A company, ‘D-Beam’, has been established by the University of Liverpool and accepted into the STFC−CERN Business Incubation Centre. The company specialises in the commercialisation of beam diagnostics solutions, and ensures all R&D outcomes from AWAKE-UK now have a direct route to market.

8.5. Within the medium term future, plasma accelerators offer the potential for applications in high penetration and high resolution imaging, behind-barrier imaging, and advanced phase-sensitive imaging. These three areas alone are envisaged to be of benefit to the advanced manufacturing, aerospace, automotive, nuclear waste, biomedical, and security sectors.

8.6. The recently announced EPAC provides several opportunities for synergies with other areas of interest to STFC, in particular, the development of novel imaging capabilities and their applications in areas ranging from medicine to national security. The Panel noted the applications of LWFAs to be explored in this new centre could enable an expanded UK role in the future EuPRAXIA programme.

8.7. The Panel noted that opportunities for applications increase as accelerator R&D develops, and the technologies available to spin-off become cheaper and more performant. However, there is no STFC funding line to support projects in applications at the moment.

8.8. Other STFC funding routes are insufficient (in funding level and timescale), to provide continuity in funding work moving between research and application. The lack of available funds within PD to support applications leads to loss of opportunity. The Panel felt that significant opportunity to capitalise on research was wasted, and that STFC should consider (perhaps through the newly established AccAP and TAAB) routes to survey opportunities and mitigate potential loss.

Recommendation 7: Both the Accelerator Advisory Panel and Technology and Accelerators Advisory Board should consider how best to support the Programmes Directorate theme of accelerator applications so that loss of opportunity is mitigated, and economic impact maximised.

8.9. Continuity remains a problem even if funding can be met by more than one research council. In the case of novel accelerators continuity is lost when the focus of work evolves from accelerators (when EPSRC might be considered the most appropriate funding council) to applications (when STFC might be more appropriate). The period between these two phases is critical, and current funding mechanisms do not appear to work well at supporting it.

Recommendation 8: Efforts should be made to maximise the use of cross council support. STFC should improve existing arrangements for cross-council support to ensure continuation of funding as research areas mature.

8.10. There may be a similar gap in support when work evolves from being undertaken largely within university groups to being developed within national laboratories. The Panel noted that it is anticipated that UKRI could help to bridge this funding gap in the future as greater emphasis is put on multidisciplinary research

8.11. The .Panel felt that a Technological Readiness Level (TRL) gap within UKRI exists at the moment, hindering access to support delivery of accelerator technology for industrial and medical applications, where the science often falls within the gaps of Research Councils, or due to the technology not being at the correct development stage to receive support.

Recommendation 9: Effort should be made to bridge the current TRL gap which prevents delivery of accelerator technology for industrial and medical applications. Ensuring a route to support projects across the TRLs is a necessity for success.

9. Breadth and balance of programme

9.1. PD funded research covers a range of activities ranging from research into novel techniques and methods, to applications of established technologies in the medical and security sectors.

9.2. The theme areas of frontier machines, novel accelerators and light sources are supported by one development project each. The Panel noted that this represented a reasonable spread of activities, given the small size of the accelerator budget. However, the Panel felt that the breadth is significantly sub-optimal. Only a subset of current activities can be supported, and there is insufficient funding available to support project funding for the fourth accelerators programme area of applications, to fully exploit potential opportunities.

9.3. Further breadth is offered through institute activities. Excluding ASTeC, a significant proportion of the accelerator budget is used to fund the CI and JAI to perform R&D in accelerator science and technology and training. The Panel noted that the institutes have distinct scientific strengths and complementary research programmes. Within CI, the largest area of work is novel accelerators, followed by colliders and light sources. At JAI, the largest area of work is within colliders, followed by novel accelerators, light sources, and neutron and muon beams. The accelerator institutes also play significant roles in funded projects, support applications development, and support Central Facilities (ISIS, DLS).

9.4. The Panel noted that both accelerator institutes are highly regarded by their international partners, evidenced by their ability to gain leadership roles and CERN-UK agreements for R&D in linear colliders, LHC upgrades, and future hadron colliders. The institutes are also very successful at leveraging additional funding against its STFC consolidated grant. This has increased the impact of their work and allowed a greater breadth of activities to be supported than would otherwise be possible.

9.5. Overall, the Panel felt that breadth has been maintained by prioritising accelerator institute funding, which supports a limited critical mass across a wide array of activities. The investment has also maintained the positive interconnections that exist between the accelerator institutes, National Laboratories, and universities. The Panel felt that as the institutes perform a vital role in maintaining much of the breadth of the programme, their funding should be protected. The Panel urged STFC to consider seeking additional funds if necessary to ensure this.

9.6. However, prioritising institute funding within a flat cash environment constrains the development line of the accelerator programme. This limits UK participation in international projects and reduces opportunities for UK leadership where strong potential for it exists.

9.7. The issue is compounded by high project costs that dominate the accelerator programme development budget. Investment can result in near-matched funding (e.g. for HL-LHC-UK through CERN contributions to projects), and effectively increase programme funding. However, in a constrained financial environment this presents a high barrier to entry, and so risks a reduction in future leveraged funding as well as reduced UK leadership.

9.8. The Panel noted that the cyclical nature of build-R&D-build alters the balance of the accelerator science programme with time, and that available finances were insufficient to fully support the cycle and mitigate against inadequate exploitation of value.

9.9. Previous investment across the programme in R&D had allowed the UK to enter into projects but, opportunities to continue through to build phases, and gain future leadership, are now at risk of being lost. For example, dielectric novel acceleration activity could have high impact and the UK has potential leadership in the area, but funds are not available to commit R&D activities to a build phase. Similarly, there are inadequate funds in the budget to support EuPRAXIA, within which the UK is a leading partner, on the timescale required.

9.10. **The Panel considered the current balance of the accelerator programme to be significantly sub-optimal, and that the current accelerator programme budget is already having a damaging impact on the sustainability of the programme.**

10. Synergies

10.1. The accelerator programme is cross-cutting and underpins STFC activities. It has synergies with many scientific areas, most notably particle physics which is underpinned by the frontier machines area. The Panel understood that there were also likely to be synergies with nuclear physics but the accelerator budget is insufficient to develop these.

10.2. Electron acceleration techniques and gradients developed by AWAKE may also enable new particle physics experiments, for example, those looking for dark photons, measuring strong-field QED, and investigating the fundamental structure of matter using electron–proton/ion collisions. More generally, AWAKE research has synergy with all areas of STFC science that require accelerators through its advancement of novel acceleration techniques and potential to create compact facilities – for example, FELs could be reduced in size by a factor of at least ten.

10.3. The broader field of novel accelerator research extends these scientific overlaps to include high energy density science, ion acceleration and ultrafast imaging. Proof-of-principle experiments to demonstrate the application of plasma accelerators to ultrafast X-ray imaging in medical and materials science have recently been undertaken, indicating scientific applications on a five year timescale.

10.4. Synergies between these scientific areas rise for several reasons: (i) the areas use the same (or similar) science facilities or computational methods; (ii) research groups often work in one or more areas; (iii) connections exist in the underlying science; or (iv) the work on novel accelerators seeks to provide new tools for these areas.

10.5. The Panel noted this implied that investment in novel accelerator research can benefit work in a much wider area. A new infrastructure for LWFA research would benefit work on ion acceleration, high energy density science, and high-field physics, for example, and co-location of high-power lasers and a conventional FEL could provide new capabilities in probing matter under extreme conditions. Conversely, a lack of investment in the area would hinder progress in all fields.

10.6. The accelerator programme also includes examples of close partnerships with industry to develop cutting-edge technologies and build UK capability, for example in the supply of superconducting magnets. The Panel noted that building up these contacts and areas of expertise maintains UK scientific and industrial competitiveness.

10.7. The Target and Beam System sub-project of LBNF DUNE will use remote manipulator technology developed for the JET facility at Culham and target expertise gained with T2K in Japan to meet the requirements of the LBNF facility. The expertise gained from this project will position the UK to lead future target work for new facilities or upgrades.

10.8. National Laboratories involvement (and expertise) in SRF technology enabled the delivery of all of the high-beta SRF cavities for the European Spallation Source in Lund, Sweden. Through partnership with CERN, the UK now provides the prototype two-cavity SRF cryomodule which will be used to validate crab cavity technologies to maximise HL-LHC luminosity.

10.9. In turn, this SRF cryomodule expertise enabled the UK to successfully bid for PIP-II cryomodules with Fermilab. The PIP-II work will develop skills in cryomodule production, which will enhance the UK position in future proposed colliders requiring crab cavities (FCC, CLiC, and ILC). PIP-II groups work with TWI to develop expertise within UK industry to enable contributions to large scale SRF technology-based accelerators.

10.10. HL-LHC includes other areas of synergy. Beam diagnostic and instrumentation techniques developed for HL-LHC are likely to benefit to future accelerator upgrades including those within the UK. Cold powering, that allows high currents to be passed through superconducting cables, was developed for HL-LHC Phase-1 and continues to be developed in Phase-2, developing technology that will benefit superconducting industry. LESS will also have potential industrial benefits.

10.11. Beam and plasma diagnostics solutions developed for AWAKE-UK should have significant impact on other short-pulse beams, such as FELs. Adaptive optics methods developed for parallel proton and electron beam imaging could be used in synchrotron radiation sources (imaging of stored and injected beam, HDR imaging), single-shot optical emittance measurements and phase space tomography in linear accelerators, as well as part of coronagraphs.

10.12. Although computing requirements are less than other STFC scientific areas, novel accelerator research makes extensive use of high-performance computing (HPC) to run numerically-intensive, particle-in-cell codes. Synergies therefore exist across STFC programmes in HPC facility provision, development and capabilities.

11. Societal and economic impact

11.1. Despite the small size of the community, UK accelerator science represents a rich opportunity to deliver both societal and economic impact. The accelerator institutes have an active public engagement programme. The postgraduate training element, which is provided by the institutes and university groups, provides skilled graduates that move into industry and the public sector, and is further described in section 12. Economic impact is expected to increase with the adoption of business cases as a precondition for increased awareness that comes with the adoption of UKRI funding.

11.2. Public Engagement plays an important role in inspiring the younger generation into STEM education, and accelerator science is a major attraction. The accelerators programme engages with the general public via its institutes at the local, national and international level.

11.3. The CI activities include the Schools Competition, the Work-Experience Programme and Masterclasses run for school students. The CI-Manchester ‘Tactile Collider’ for visually impaired audiences was recently recognised with the EPS HEP PP Outreach Prize. Eight workshops at Daresbury delivered by AWAKE involved 277 students and 22 teachers from local schools, and a ‘Physics of Star Wars’ event further aimed at introducing cutting-edge science to hundreds of secondary school children.

11.4. The JAI reaches 15,000 school-age pupils directly per annum, with ‘Accelerate!’ talks, e.g. at the Curiosity Carnival, and hosts the annual APPEAL A-level teachers masterclass and the Conference for Undergraduate Women in JAI-Oxford. JAI-RHUL has won SEPnet Public Engagement awards for many contributions to Science Festivals, HL-LHC-UK Big Bang talks, CERN’s Beamline4Schools, Girls into Physics, Soapbox Science, FameLab, and popular evening lecture series.

11.5. Both accelerator institutes contribute to newspaper articles, radio, TV and new media, such as JAI's 'Particle Accelerators for Humanity' Royal Institution videos which reached over 375,000 YouTube views, and a recent TEDx talk that has amassed over 1,544,000 views.

11.6. The Panel noted some success regarding industrial engagement within the LBNF DUNE project funded directly by BEIS. The accelerator programme's investment in R&D has given the community the ability to engage with industry at early stages, as evidenced within the PIP-II sub-project of LBNF DUNE. This engagement will now build new skills within UK industry in collaboration with Shakespeare Engineering, and support a wider capability programme for the UK through collaboration with TWI. Both are expected to yield enhanced economic impact.

11.7. BEIS funding required a business case that included economic and skills impact considerations, against which project success is assessed. The Panel noted that this ensures that applicants construct a proposal that establishes industrial engagement at the start of a project rather than on an ad hoc basis. Historically only projects above a certain level of funding have been required to provide a business case. However, business cases are expected to become more widespread under UKRI.

11.8. Given the success of LBNF-DUNE, STFC could consider adding elements of business case criteria (for example identification of success factors, monitoring and evaluation programmes) to project and/or institute funding to enhance likely economic impact. The Panel noted that community engagement could be increased if this approach were supported by the Accelerator Advisory Panel.

12. Skills balance and pipeline

12.1. The approximate size of the accelerator community supported through STFC project and institute grants in 2018 is shown in the table below. It was noted that the ratio of PDRAs to Academics was higher than in other programmes. However, the comparatively small size of the accelerator programme introduced risk in maintaining this research volume, as reductions in funding would have a proportionately large effect in the research activity that could be maintained. The size of the supported community has remained static over time due partly to the length of projects but also, as a consequence of flat cash.

Table 34 Size of the Programmes Directorate-funded Accelerator community[4]

Community	2018
Number of Academics supported	49
Average Academic FEC	9.4%
Academics – Total FTE per year	4.8
PDRA – Total FTE per year	54.6
Number of Studentships	6
Technician – Total FTE per year	2.1
Total Number of FTE per year	72.1

[4] The table does not include effort supported through the £1.2M contribution to ASTeC. These numbers should be used as an approximate guide and an approximate comparison against the Nuclear Physics, Particle Physics and Astronomy areas, which have Consolidated Grant lines that support their corresponding communities as a whole

12.2. Training the next generation of UK researchers is key to advancing its world-class accelerator programme, and sustaining the UK's position as a globally leading research and innovation nation. Enhancing the skills pipeline to provide strong career pathways will be essential if the accelerator programme is to succeed as a leading research and innovation hub. Both CI and JAI contribute significantly to the accelerators skills pipeline with both institutes providing comprehensive training programmes for PDRAs, technicians, PhDs and students. Technical apprenticeships at the national laboratories also feed into the wider accelerator programme's remit.

12.3. The Accelerator Institutes attract funding from a variety of non-STFC sources to create student cohorts much larger than indicated in Table 4, JAI is organised around three pillars, one of which is 'training the next generation of accelerator scientists and engineers', and has trained 72 PhD students since its inception in 2007. A unique aspect of the JAI is the academic training for PhD students which comprises approximately 100 hours of formal instruction delivered across two academic terms in the first year of the PhD programme, followed by two to three years of hands-on research. CI has trained approximately 150 PhD students since its inception in 2006, representing a well-established training programme involving lecture course modules, transferable skills training (project management and outreach), and engagement with industry. The CI also has an outstanding track record in leading large scale international training programmes in accelerator science connecting universities, research centres and industry from across Europe.

12.4. The accelerator institutes also play an important role in the transfer of knowledge by a vigorous programme of collaboration with industry (UK and non-UK). In this way, they each obtain external funding, finance training opportunities for students, obtain commercial license agreements, and provide a potential pathway to bring any new products to market.

12.5. The accelerator institutes collectively receive approximately seven STFC quota studentships per annum to cover all aspects of their research, so that only around two per annum will work on novel accelerators or industry applications. Since graduate students are the life blood of any research group, progress is inevitably slower than it could be. Many excellent students are attracted by the fields of novel accelerators and industry applications; however, limited funding means that the number of graduate students recruited remains a serious problem. Enhancing funding in these areas would benefit many areas of science in the future.

12.6. STFC National laboratories play an important role in training, which is underpinned by STFC's strategy to maintain the health of its world leading science and technology. It is widely recognised that there is a growing international demand for technical skills, such as mechanical, electrical and software engineers, and data scientists. Therefore, an increasingly important approach will be to grow much of the UK's own talent, strengthening the UK's skills base from apprentices to researchers, which can be achieved through the CI and JAI.

12.7. Recommendation five of the 2017 Accelerators Strategy Review highlighted the importance of maintaining the skills base through effective recruitment, retention and professional development of scientific and technical staff at all levels, and across all relevant disciplines. It has been hard to meet this goal within the flat cash environment and a lack of capability remains in certain fields of accelerator research. For example, in the UK there are currently very few researchers who understand the chemical processing required in cavity manufacture, and it is hoped that work with

TWI will enhance the UK's capability to take up a leading position in cavity production following the PIP-II project.

12.8. First destination data of PhD graduates from JAI shows that 62% of graduates took up a fellowship or PDRA position (38% of which were based in the UK), 24% a lectureship or (overseas) research institute staff position, and 12% went into the private sector. The high percentage of PhD graduates achieving a fellowship, staff or PDRA position highlights the high level of training undertaken at the JAI and CI. The Panel considered that additional second and third destination data would be a valuable indication of the level of impact that training in accelerator physics has within the UK and beyond. A destination survey over the last five years should be implemented and could be undertaken by the Accelerator Advisory Panel.

Recommendation 10: A destination survey over the last five years would provide valuable information and could be undertaken by the Accelerator Advisory Panel (AccAP). Such data would be a valuable indication of the level of impact training in accelerator physics has within the UK and beyond.

12.9. The Panel considered the level of direct funding available for university and industrial collaboration. PhD students allow strong links to be established with industry partners through joint projects that will be realized over 3-4 years. This represents an excellent opportunity to leverage industry funding which is not currently used. PDRAs can work closely with industry and build collaborations that enable technology transfer. The Panel noted that at present the level of funding available is not always attractive to industry and this can hinder industrial collaborations from forming. Increasing support for training and PDRAs could mitigate this and help to overcome the low levels of support often available for research addressing industrial challenges and the UK's Industrial Strategy.

12.10. A Centre for Doctoral Training (CDT) specific to accelerator research would help to ensure the next generation of doctoral level students are equipped to tackle research and innovation challenges across the accelerator science landscape. CDTs with industrial partners could lead to innovation in areas of (SC) RF, machine learning, sensors and diagnostics, as well as the capability of collaborative research both nationally and internationally. A CDT based on the Accelerators for Security, Healthcare and Environmental Applications (ASHE) initiative could provide the industrial engagement foundations upon which the accelerator community could build in order to attract and/or compete for further funding to deliver impact in this area. Training at JAI and CI is considered to be world leading, and a CDT in accelerator science would further enhance the relatively small yet excellent training undertaken within the community, and potentially leverage funding from industrial partners.

12.11. Another area where a CDT would be extremely beneficial, and should be considered, is in novel accelerating techniques. This would combine efforts at the accelerator institutes, other universities and the national labs, as well as bridge between STFC and EPSRC funded research, thus meeting UKRI strategic priorities. Such a CDT would provide an excellent opportunity for an interdisciplinary, cross-sector training programme that would help advance knowledge and technologies in one of the most dynamic research areas in accelerator science and technology.

12.12. The 2014 Accelerator Review identified how a number of institutes and facilities have experts working in many science areas, such as diagnostics for neutron sources and RF development. However, there appeared to be little communication between these groups. The Panel considered that the level of collaboration was still sub-optimal. A skill base or pooled effort, such as a CDT, where effort can be used across projects would be a potential solution to enable cross-institute collaboration.

12.13. The possibility of establishing a Centre for Doctoral Training in accelerator science should be explored should new funding opportunities become available. Focus areas should be either industry applications or novel acceleration techniques as identified priorities. Such a CDT will help to ensure the next generation of doctoral level students are equipped to tackle research and innovation challenges across the accelerator science landscape, as well as aiding industrial and cross-institute collaboration.

12.14. The Panel noted that the gender balance of the Co-Is and PIs currently supported was poor. There is currently no female PI supported by STFC through the institutes or project grants, and of the 72 Co-Is supported, only seven are female. The Panel noted that the gender balance for early career researchers was better.

12.15. From gender data submitted by CI and JAI, the gender balance for non-STFC-funded posts was significantly better than those supported by STFC; 13% of PDRAs funded by STFC were female, whereas 44% of PDRAs funded through other means were female. The Panel was of the opinion that the UKRI Terms and Conditions relating to student eligibility restricted the pool of applicants more than posts supported by other means. The Panel noted that to improve gender balance for future generations, positive and visible role models, both male and female, are required to encourage young students into STEM education.

Recommendation 11: Equality, Diversity and Inclusion characteristics of the PD-funded accelerator programme should strive to align with the long-term goals of UK Research and Innovation.

12.16. The accelerator programme has not received an Ernest Rutherford Fellow since the creation of this scheme, despite several applications from this area. It appeared that candidates had been turned away due to not aligning with the call and concerns had been raised by ASB, recognising that the guidelines of the scheme did not acknowledge that accelerator science is one of the areas of research supported by STFC. As a consequence, the guidelines are in the process of being updated. The ASB welcomed these changes at the time, and the Panel felt that in addition it would be helpful if accelerator science could be represented in the scheme’s sub-panel membership structure to help bring about the step change needed.

Recommendation 12: Fellowships enable early career researchers with clear leadership potential to establish a strong, independent research programme. Further steps to open up The Ernest Rutherford Fellowship scheme to accelerator researchers should be taken.

FUNDING OPPORTUNITIES AND SCENARIOS

13. New funding opportunities

13.1. The creation of UKRI in April 2018 has coincided with overall Government funding for research and innovation seeing a significant uplift as a proportion of GDP into the 2020s. At present, new investment is being made through a number of new directed mode funds, with STFC [and other Research Councils’] allocations currently being held to flat-cash. The creation of these schemes requires a different approach to future planning.

13.2. It was considered that access to UKRI directed funds could reduce pressures within the constrained accelerator programme. In particular, support for just one of the four priority projects would not only help to relieve such pressures, but would also create significant scientific impact as well as UK leadership.

13.3. The Panel agreed that while these new UKRI funding modes present a significant opportunity to the programme, they are not a replacement for core funding which underpins the programme. Gaining support through the directed funds is not guaranteed, and there would also be increased competition. A reliance on such funds could create uncertainty in the programme and hinder long-term planning.

13.4. Accelerator research activities have received further support of £1.1M from other STFC funding streams since 2014. This additional support has been acquired through the PRD scheme (£520k, 2014-2016), the 2017 Global Challenges Research Fund (GCRF) Foundation Award (£80k) and the 2018 Capital and Opportunities Calls (£500k). It was noted that significant additional support may have also been obtained from other sources, such as EPSRC fellowships, outside the remit of this Panel. These injections of support allow for small R&D activities which, although valued, do not allow for the strategic planning of a sustainable future programme.

13.5. Both accelerator institutes are in receipt of additional non-STFC funding, and to put this into perspective, JAI has been able to leverage almost 100% of STFC's investment from other sources, such as Horizon 2020, CERN and EPSRC over the last five years. These extra funds strengthen the breadth of the programme and enable UK leadership that would not be possible otherwise. However, the funds are often project based and do not allow for sustainable programme planning.

13.6. The 2017 Global Challenge Research Fund (GCRF) was supported through STFC's GCRF allocation (Foundation Award). The aim of the activity was to support projects to access the untapped potential of STFC's community to contribute to addressing challenges in developing countries. Up to £4M over two years was made available for the call. In total, 35 proposals were received, of which three were related to the accelerators programme. One of the accelerator proposals was successful (£78k) within the small project (under £100K, 12 months or less) category.

13.7. In 2019, STFC held a joint workshop with CERN and the International Cancer Expert Corps (ICEC) in Botswana to take a step forward to address the shortage of cancer care in global regions where distinct health inequalities exist. This was a follow-up workshop to ones held at CERN in October 2017, and the UK in March 2019, and is part of an ongoing series of workshops. As a result of these workshops, five small projects were supported through GCRF (~£75k each), to address the issues confronting developing countries in providing radiation therapy treatment (RTT) for palliative care and treatment of cancer in parts of the world where 70% of people do not have access to treatment.

13.8. The Panel noted that some novel accelerator activities will have societal impact indirectly. For example, development of novel accelerators could result in using accelerators for radiation hardness testing. This can then prevent the need for developing countries to use radioactive sources which carries proliferation dangers. The benefit of such developments can often be difficult to portray, especially when the societal benefit isn't the priority of the research. Greater thought is required from the accelerator community as to how such possible benefits can be emphasised and utilised as a tool to obtaining funds to address global challenges.

13.9. The training that is undertaken within the accelerator community is considered to be world leading, evidenced by the large number of graduates who obtain work overseas and within the private sector. Consideration should be given as to how the excellent training undertaken at the institutes can be rolled out to developing countries where there is long term advantage of training such personnel, achieving skills to tackle those cross-cutting issues. The skills developed in cutting-edge technologies associated with accelerators will help to sustain knowledge-based economies in developing countries; creating economic and societal impact.

European Grant Income

13.10. From 2014 to 2017, Particle Physics, Astronomy and Nuclear Physics received over €213M from European grants. 15% of CI's total research grant funding and 22% of JAI's is from the EU. The CI has a unique track record in attracting European funding from MSCA. Since 2008, grants totalling more than £20M were coordinated by the CI and this has provided funding for training around 100 early stage researchers at institutions across Europe. It has also allowed the organisation of dozens of international workshops and schools for the international community.

13.11. Post-2020, the UK must ensure that either access to this funding is maintained or that the funding is replaced in full to maintain the breadth and balance of the programme.

Recommendation 13: The UK must ensure that either access to European funding is maintained or that the funding is replaced in full to maintain the breadth and balance of the current programme. The AccAP should monitor impact of the changes.

14. Flat cash planning scenarios

14.1. The accelerator programme has been held at flat cash since 2011. The ASTeC element remained at constant volume until BOP1, which recommended changing this to flat cash to stop development lines eroding further. During this time institute funding remained at flat cash.

14.2. Much of the accelerator budget is already committed over the next five years. Some (limited) development funding opens up from 2022, but large scale project funding (e.g. of the scale of HL-LHC-UK), will only be possible after 2025. It is therefore not possible to change the balance of the budget to increase the share for institute funding, or development funding, without reneging on existing commitments or reducing already committed grants.

14.3. The Panel noted that reducing development funding would not only negatively impact the future programme but also risk reputational damage to the UK, especially for those international projects where the UK is relied upon to meet its commitments.

14.4. Although the Panel regarded constant volume funding to be the minimum to keep the accelerator institutes sustainable, it is impossible to meet this in a flat cash scenario, given the financial constraints posed by committed development funds. The Panel therefore recommends that to maintain breadth and balance as far as possible, the accelerator institutes should also be funded at flat cash.

Recommendation 14: In a flat cash funding scenario, the current balance between accelerator institutes and development projects should be retained.

14.5. The Panel considered that continuing flat cash funding risks the sustainability of the accelerator and wider-PPAN programme.

15. Reduced (-10%) financial scenario

15.1. In a -10% scenario (~£700k), the Panel agreed that the programme and UK accelerator science community would be damaged irrevocably. The Panel considered that the programme would not be able to maintain leadership in one or more significant areas, and the community would not be able to capitalise on previous investments, reducing return on investment, and value for money still further.

15.2. If the accelerator institute funding is held at flat cash, reductions must be made to development projects. Funding reductions to either the HL-LHC-UK2 or AWAKE-II projects would need to be applied post-award (April 2020 onwards), and could result in a managed withdrawal from one or both projects. In addition, ongoing commitment to the current PWFA-FEL project may need to be reduced. Any route that is taken in a -10% scenario would unavoidably result in reputational damage, damage to international collaborations, and loss of leadership for the UK.

15.3. Maintaining the committed level of development project funding requires reducing institute support. Reducing support at this level would risk losing one of the two institutes and, given the complementarity of the institutes, leadership in one or more science areas which would place severe strain on the community.

15.4. The Panel noted that either choice would result in the need to make a severe down-selection in the number of established accelerator activities and research themes. Such a down-selection would risk the loss of some internationally renowned and world-leading UK research groups. An associated risk is that key technology areas of high-brightness electron sources, high-power hadron sources, superconducting RF, and high-power lasers, which are all extremely competitive, may lose leading UK expertise if not supported. These risks threaten the ability of the field to attract and educate young talent in science and technology for the UK employment market.

15.5. The Panel considered that in a reduced funding scenario, or a scenario where flat cash funding continues into the early 2020s, (i.e. when funding headroom in the PD accelerator programme *begins* to open up), it is imperative that a full review be carried out to determine the least damaging option. The review would need to seek community consultation and involvement.

Recommendation 15: In a reduced or prolonged flat cash funding scenario a review must be carried out with full community consultation and involvement, to determine how best to sustain the accelerator science programme.

16. Increased (+10%) funding scenario

16.1. The +10% financial scenario maintains the current volume of activity in the area. The panel noted that, given the sub-optimal breadth and balance of the current programme, even this scenario is insufficient to ensure programme sustainability and health.

16.2. The Panel considered that an uplift in support for the accelerator institutes is essential to reverse the damage caused by years of flat cash funding. An uplift would allow a restored work programme, protecting programme breadth, and existing skills gaps to be repaired. The key technology areas of high-brightness electron sources, high-power hadron sources, superconducting RF and high-power lasers in particular require additional support to maintain the UK's leadership position in these areas. The Panel noted that restoring income to the institutes also provided increased opportunity to leverage funds from other sources, which would further ease funding pressures. The Panel recommended that institutes be funded at least at constant volume.

16.3. An uplift could also allow some headroom to open in the development lines which could be used to augment existing projects. However, the Panel felt that greater value would be obtained by investing in new opportunities. In particular, this could introduce opportunities for directed funding calls, i.e. a mechanism to strategically direct thematic project-type funding, for example, in regard to applications.

Recommendation 16: In an uplifted funding scenario, STFC should explore mechanisms for thematic project funding calls and fund accelerator institutes at least at constant volume.

17. ASTeC funding

17.1. At present, £1.2M (equivalent to ~20%) is allocated from the PD accelerator budget to the National Laboratories budget to support ASTeC. The contribution originally supported the ASTeC test facilities: the ALICE (Accelerators and Lasers In Combined Experiments) project, which has now finished as well as enabling skills retention within ASTeC. The funding has continued and, together with National Laboratories funding[5], supports ASTeC to develop accelerator test facilities, technological infrastructures, and a broad range of accelerator and engineering capability. At the moment the £1.2M primarily funds work on CLARA, supporting its exploitation and development to enable under-pinning support to CI, and to a lesser extent, JAI, activities. Additionally the funding continues to support the critical retention of staff expertise needed for the CLARA and other ASTeC programmes.

17.2. Unlike accelerator institute funding, ASTeC funding is not peer reviewed by PD, however, oversight is provided by STFC National Laboratories Directorate Departmental processes where objectives, finances, staffing plans, project management and risks are all reported and tracked on a regular basis. It is noted that ASTeC provides excellent support to the PD-funded accelerator institute activities and participates in PD funded development projects, but these activities are not allocated funds specifically from the PD contribution to the ASTeC budget.

17.3. The Panel noted ASTeC's extensive collaboration with CI and recognised ASTeC to be a centre of excellence of international importance. The rationale behind the ongoing split in ASTeC support between PD and National Laboratories was felt to be less clear due to the completion of ALICE and, given the inconsistent treatment with other elements of the programme, harder to justify. The Panel believed that it was

[5] The ASTeC core allocation in 18/19 was £7.43M, which includes the £1.2M PD contribution and an £800K uplift from BEIS.

important that ASTeC be maintained at the current level of funding, but that it would be more appropriate for support to be met in full by the National Laboratories.

17.4. Full ASTeC support should not be achieved by moving £1.2M from PD to the National Laboratories budget. Should the National Laboratories support ASTeC in full, the £1.2M should be retained within PD. It is the Panel's view that the funds should remain within the PD accelerator programme specifically.

17.5. The Panel had previously noted that a 10% uplift was insufficient to ensure programme sustainability and health. The £1.2M would also allow additional support for the key technology areas of high-brightness electron sources, high-power hadron sources, superconducting RF and high-power lasers, to maintain UK leadership, and allow funding for a project in applications to prevent the loss of this area.

17.6. The Panel also noted a future risk to the UK as R&D projects (particularly in frontier machines) become more international and expensive. Within a flat cash budget the programme cannot be balanced; either support is decreased across the other science themes, potentially leading to further losses besides applications, or a rapid erosion of the UK's capability to compete and have impact within international collaborations across all four PD accelerator science themes will ensue. This risk can be mitigated, and the future health of the programme protected, by retaining the £1.2M.

17.7. If it is not possible for the National Laboratories to fully support ASTeC, the Panel felt it was important that ASTeC funding be awarded on a consistent basis with funding for the accelerator institutes. ASTeC could be supported to enter the accelerator institute review round either by itself, or in consortium with the CI, to enable peer review and tensioning. It is noted that ASTeC and the institutes have separate remits so would need to be assessed in an appropriate manner.

17.8. The Panel noted that unifying the funding approach could pose a number of risks to the accelerator institutes and ASTeC. Potential risks arise from: inappropriate comparison and treatment of R&D and academic effort within the accelerator institutes compared to operational effort within ASTeC; the contrasting manner in which the three organisations have been funded, staffed, and governed (for example, ASTeC hosts world-leading accelerator infrastructure that the accelerator institutes do not); ASTeC's potential need for guidance and support to avoid being unfairly disadvantaged in a new funding environment.

17.9. These risks would need to be mitigated with appropriate guidance for any accelerator grant review containing ASTeC. The Panel noted that care would need to be taken to protect the accelerator institutes and ASTeC from any disproportionate negative impacts that could potentially lead to a reduction in their respective capabilities, or ultimately, their demise, when unifying the funding approach.

17.10. The Panel concluded that at least two approaches were possible to improve the consistency of funding treatment in the programme, and that this in turn could protect programme health and sustainability:

1. ASTeC support should be maintained at the current level but met in full by the National Laboratories budget. The £1.2M currently assigned to ASTeC should remain in the PD accelerator science programme.
2. If ASTeC remains part-funded within PD, then it should be supported to enter the Accelerator Institute grant review round with the accelerator institutes to enable peer review and tensioning, with appropriate guidance provided.

17.11. The Panel recommended that STFC explore these approaches with all parties, with the aim of ensuring an outcome of most benefit to the area and the sustainability and health of UK accelerator science in general.

Recommendation 17: STFC should explore the funding approaches suggested by the Panel with all relevant parties, with the aim of ensuring an outcome of most benefit to the area and the sustainability and health of UK accelerator science in general.

SUMMARY OF RECOMMENDATIONS

18. Summary and Recommendations

18.1. This evaluation has considered the PD funded accelerator science programme. It has examined current research and future opportunities, and the impact on the programme of different financial scenarios.

18.2. The Panel has made a number of recommendations concerning how best to sustain the health, breadth and balance of the area, and how to position the UK to exploit future opportunities.

Recommendation 1: The Accelerator Advisory Panel should represent the views of the community and provide a strategic between the community, STFC and TAAB

Recommendation 2: The Accelerator Advisory Panel should be tasked with both developing, and engaging the community with, a PD-focused accelerator roadmap

Recommendation 3: It is necessary to review, through community consultation, the balance of frontier machine projects following the European Strategy for Particle Physics update

Recommendation 4: STFC and UKRI should strongly back UK membership of the EuPRAXIA project and should maintain a flexible approach to ensure the UK remains at the heart of this project in all future Brexit scenarios

Recommendation 5: The dielectric wakefield and microstructures community should consider focussing effort and build critical mass to strengthen the case for investment.

Recommendation 6: STFC should seek to secure access to both UK and international light source facilities from an accelerator R&D perspective, to maintain UK expertise and leadership in the area.

Recommendation 7: Both the Accelerator Advisory Panel and Technology and Accelerators Advisory Board should consider how best to support the Programmes Directorate theme of accelerator applications so that loss of opportunity is mitigated, and economic impact maximised.

Recommendation 8: Efforts should be made to maximise the use of cross council support. STFC should improve existing arrangements for cross-council support to ensure continuation of funding as research areas mature.

Recommendation 9: Effort should be made to bridge the current TRL gap which prevents delivery of accelerator technology for industrial and medical applications. Ensuring a route to support projects across the TRLs is a necessity for success.

Recommendation 10: A destination survey over the last five years would provide valuable information and could be undertaken by the Accelerator Advisory Panel (AccAP). Such data would be a valuable indication of the level of impact training in accelerator physics has within the UK and beyond.

Recommendation 11: Equality, Diversity and Inclusion characteristics of the PD-funded accelerator programme should strive to align with the long-term goals of UK Research and Innovation.

Recommendation 12: Fellowships enable early career researchers with clear leadership potential to establish a strong, independent research programme. Further steps to open up The Ernest Rutherford Fellowship scheme to accelerator researchers should be taken. The AccAP should monitor impact of the changes.

Recommendation 13: The UK must ensure that either access to European funding is maintained or that the funding is replaced in full to maintain the breadth and balance of the current programme.

Recommendation 14: In a flat cash funding scenario, the current balance between accelerator institutes and development projects should be retained.

Recommendation 15: In a reduced or prolonged flat cash funding scenario a review must be carried out with full community consultation and involvement, to determine how best to sustain the accelerator science programme.

Recommendation 16: In an uplifted funding scenario, STFC should explore mechanisms for thematic project funding calls and fund accelerator institutes at least at constant volume.

Recommendation 17: STFC should explore the funding approaches suggested by the Panel with all relevant parties, with the aim of ensuring an outcome of most benefit to the area and the sustainability and health of UK accelerator science in general.

Appendix A: Recommendations from the 2017 Accelerator Strategy Review

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

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.

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.

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.

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.

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

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.

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.

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.

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

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

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

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.

Appendix B: Recommendations from the 2017 BoP Review

Recommendation 17: We recommend that indexation be removed from ASTeC funding, in order to reduce pressure on the rest of the Accelerator programme.

Recommendation 18: We recommend an R&D strategy is developed in collaboration with the accelerator institutes and ASTeC to support the aspirations of the FEL Strategic review.

Recommendation 19: We recommend that flat cash funding continue for the Cockcroft Institute and the John Adams Institute with all elements of the programme including ASTeC subject to appropriate external peer review.

Recommendation 20: We recommend that the funding level for future accelerator projects be reviewed at the time of the next European Strategy Update: specifically future high energy facilities HL-LHC, HE-LHC and FCC for hadron colliders and ILC and CLIC for lepton colliders.

Recommendation 21: If a funding opportunity within STFC programmes arises, we recommend that the funding levels for highly speculative future accelerator technologies including beam and laser plasma wakefield acceleration (for example the AWAKE experiment at CERN and the experimental programme at CLF) should be reviewed.

Appendix C: Ranking Scoresheet for Programme Evaluations 2018/19

During the 2017/18 Programme Evaluations, projects/experiments/facilities within each discipline will be ranked. The ranking criteria will cover scientific excellence, exploitation within grants, and impact/industrial engagement. The exercise will look at all funded projects/experiments/facilities and ensure each is considered at whatever its stage of the exploitation cycle.

The panels will consider the merits or otherwise of supporting areas currently receiving STFC investment. This will include consideration of international engagement and subscriptions.

The ranking criteria will be largely based on that previously used by STFC, namely **α** rankings for projects/experiments and “g” rankings for science exploitation themes within grants as used in the last Programmatic Review. In addition a new “i” ranking will be introduced to cover evaluation of impact for the economy and society.

The Panel will be asked to consider the strategic value of the projects/experiments/ facilities that submitted proforma and how highly aligned they are to the mission of STFC. Consideration should also be given to the international standing and the potential for leadership of the area under review. Additional value, such as synergies within the STFC frontier science disciplines (Particle Physics, Astronomy, Nuclear Physics, Particle Astrophysics, Computing, Accelerators) programme should also be taken into account.
The Panel will be asked to score each of the projects/experiments/facilities on the following criteria and submitted 2 days before the meeting.

The Panel member should complete section 1 and 4 below for each proforma. A marking should be given for either section 2 or 3 dependent on which is most appropriate.

The below wording is generic for the six evaluations and may be slightly modified to suit the specific requirements of the individual reviews.

What is the life cycle stage of the Project/Experiment/Facility?
Early / Developing / Mature

Scientific Excellence of Project/Proposal

α5 - Highly innovative and very likely to result in seminal changes in knowledge.
α4 - Likely to substantially advance the subject.
α3 - Likely to make an important contribution to the subject.
α2 - Competent, worthy science.
α1 - Interesting science but outcomes considered doubtful.
β - Poor quality, flawed or unlikely to deliver meaningful or interesting results.

Exploitation
Projects in the science exploitation phase are funded via grant panels. Three categories are defined, intended as strategic guidance to the peer review carried out by grant panels. Please consider the value of exploitation when the area under evaluation reaches maturity.

g3 - A project with high strategic importance in the STFC programme, which has received substantial investment. We would expect to see it adequately funded via grants after peer review
g2 - A project with high potential for excellent science which should be considered via peer review
g1 - A project which is not well matched to the STFC programme, we would be surprised if it were to receive funding via the grants panel.

Impact and Engagement

Please consider if there is important impact within industry and/or wider society that STFC should be looking to exploit and that will otherwise not happen elsewhere.

i5 - Very exciting impact already under IP management or a close working partnership or exchange with non-academic partners is already in place.
i4 - Very exciting opportunities proposed, with some first connections made.
i3 - Interesting opportunities suggested but needs significant further work.
i2 - Little opportunity, although some could evolve in near future.
i1 - Little opportunity and unlikely to develop significantly in near future.
i0 - No apparent opportunities at all.