Science Board: Response to BIS Open Consultation "Science and Research: proposals for long-term capital investment"

Introduction

1 What is your name?

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3 What is your organisation?

Organisation:
Response on behalf of STFC's Science Board with input from STFC's Advisory Panels

4 KEY QUESTION: What balance should we strike between meeting capital requirements at the individual research project and institution level, relative to the need for large-scale investments at national and international levels? (1000 words maximum)

Answer to question 1:
It is vital that UK scientists and engineers have access to state-of-the-art research facilities at departmental, regional, national and international levels. In order to achieve this, investment in large national and international facilities needs to be carefully tensioned with investment at regional and departmental levels so that all science disciplines can function at an internationally excellent level.

For national and international facilities, there must be a balance between investment in new facilities that give access to exciting new techniques, and a programme of upgrades to existing facilities. Such upgrades are vital to provide continuous improvement in their capabilities (new and better measurements), capacity and efficiency (faster measurements), and cost-effectiveness (lower cost operations), while operating at an internationally excellent level in order to fully exploit the capital investment that they have already received.

All researchers, and in particular those using large facilities or developing high profile overseas projects, need access to local and regional infrastructure to develop their underpinning science and measurement methods to the point where they can fully exploit the beamtime/instrument time that they are awarded. Even for large scale international facilities, the development and planning often occurs from the "bottom-up"', with initial facility development work being carried out at the institutional level.

The balance between institution/local-level and national/international-level investment varies amongst different science areas. It is therefore necessary to develop a strategic science roadmap for each science area so that there is an appropriate balance between the various scales of capital investment to ensure the health of individual research disciplines.

Such science strategies must also include any necessary e-infrastructure. Wherever e-infrastructure is an integral part of a facility or research project, it should be considered in parallel and with the same level of priority: if this does not happen, it may put at risk the effectiveness and efficiency with which the facility or project will be exploited. Large international projects usually involve e-infrastructure, which operates at local project level, national level and often forms part of an international aggregate.

Science that is supported by STFC in the fields of particle physics, astronomy and nuclear physics is critically dependent on access to major international facilities. Large international projects are always developed over a number of years, and require a research and development phase followed by an extended construction phase. It is vital that the UK maintains a reputation as a reliable international partner, which means that long-term stability in funding streams for large-scale international investments is essential.

Whether at local or international levels, any decisions on capital funding must be taken with a clear view of whether it will be possible to provide resources to operate facilities and run projects as effectively and efficiently as possible, a problem that has been described as the "batteries not included" syndrome.

The balance between capital requirements at the individual research project and institution level relative to the need for large-scale investments at national and international levels is explored in the Capital Budget Scenarios in the Consultation Document. Scenario 3 proposes levels of Research Council project-level and HE capital investment that are similar to or lower than current levels, which are currently inadequate to provide the infrastructure for the purposes described above. However, based on our experience of the STFC programme, we estimate that Scenario 1 does not provide sufficient capital to support the priority projects described in our submission. The optimum balance therefore lies between these two, and should be determined according to the approach described above, noting that the balance between capital requirements at the individual research project and institution level relative to the need for large-scale investments at national and international levels will vary between fields.

5 How can we maximise collaboration, equipment sharing, and access to industry to ensure we make the most of this investment? (1000 words maximum)

Answer to question 2:
STFC science is inherently collaborative, whether at international or national levels, for example through participation in international organisations such as

CERN, ESO, ILL, ESRF and ESS, and through the wide user base of national facilities such as ISIS, Diamond and CLF. The underpinning e-infrastructure is also operated in a co-operative manner, for example GridPP, the national collaboration of UK particle physics groups for LHC computing, forms part of the larger worldwide LHC Computing Grid (wLCG). Tier-2 computing resources are held at individual collaborating universities and laboratories but use is shared by all LHC physicists across the UK and worldwide.

At regional and local levels there is much good practice already, for example in particle physics major items of lab equipment (for instance wire bonders and probe stations) held at specific institutions support work carried out across the UK, which benefits particle physics projects through equipment being utilised by a wider pool of researchers for more time in a more efficient manner. In astronomy, UK participation in the Low Frequency Array (LOFAR) was possible because of a strategic alliance between STFC and UK universities across the country, but especially the South-east Physics Network (SEPnet) who helped construct a LOFAR array in Hampshire.

Pools of smaller equipment items that can be loaned for evaluation and for shorter duration experiments are very useful. A good example is the EPSRC Laser Loan Pool hosted by the Central Laser Facility at RAL. At the wider European level, a good example is the European Gamma-Ray Spectroscopy Pool.

There is currently considerable pressure on both Research Council and University funding streams so there is increasing interest in the development of regional centres for sharing mid-range facilities. This is a valuable opportunity for developing further collaborative research amongst academics in different institutions and with industry, as well as providing vital cost sharing with industry, charities and other funders. Such infrastructure is only cost-effective where there is sustainable resource to run the facilities in an efficient manner. Furthermore, access models, incentives and metrics need to be very carefully developed so that these are used in a co-operative way rather than as an opportunity for individual Universities to further their own interests at the expense of other users. It is also crucial that equipment available for wider use is well publicised so that researchers in both industry and academia are aware of what is available.

Diamond, ISIS, and CLF have industrial users who pay for beamtime for proprietary measurements using mature techniques. Underpinning this, there is also a rich culture of less formal collaborations between academic and industrial groups in carrying out more fundamental research and technique development that is crucial for the evolution of future industrially-important measurements. This needs to be recognised in the funding model for operating large facilities, which currently tends to focus on the needs of Research Council grant-holders.

The Collaborative R&D scheme at ISIS, in which an industrial partner can decide after the experiment if the results are to be published in the open literature or kept confidential, offers an effective method to develop engagement with industry by providing a low risk route for use of large facilities to access new experimental methods. Extending such mechanisms to other facilities could be invaluable for giving further access to industry to enhance their research and development activities by exploiting cutting-edge research techniques. The Harwell Campus and the Research Complex at Harwell are very well placed to contribute to developing industrial engagement through their proximity to major STFC facilities, as is the Daresbury Science and Innovation Campus: for example, VELA has already been used for industrial research.

Modest investment in science and technology leadership in ESA L and M missions can also help leverage far greater investment in the UK. For example, Astrium UK in 2012 was awarded a contract for €300M for the construction of the ESA M1 Solar Orbiter after investment of just a few tens millions into the academic science and technology sectors. The same is true of ESA M2 mission Euclid, which has led to investment of tens of millions of pounds into UK detector company e2v making them world-leaders in this technology.

6 What factors should we consider when determining the research capital requirement of the higher education estate? (1000 words maximum)

Answer to question 3:
Capital equipment in the HE estate needs to support excellent science as well as training the next generation of scientists and engineers and offering opportunities for engagement with industrial partners. This requires stable funding streams with adequate funds for operation and maintenance of equipment in an efficient and sustainable manner

Excellent science in Universities is supported not only by the Research Councils, but also by industry, charities, the EU, and Universities themselves as well as independently-funded students. Evaluation of capital needs requires input from all stakeholders, which should also include professional bodies to ensure the health of disciplines.

University-based science is carried out with equipment that is based locally, regionally, nationally and internationally, but in all cases, substantial underpinning and preparatory research and training is likely to be carried out within Universities. Capital investment in large facilities needs to be carried out with due consideration of the equipment that is required in Universities to ensure that there is adequate infrastructure to underpin large facility science.

Universities are under increasing pressure to provide matched funding for equipment, as well as the infrastructure costs associated with new equipment, which often requires, for example, better vibrational stability or environmental control. Following very serious erosion of capital funding for both Research Councils and Universities in recent years coupled with the loss of SRIF, UK University infrastructure is falling behind that of our international competitors and is reaching an unsustainable point.

Future involvement in new international projects requires maintenance of expertise and infrastructure in Universities to sustain the UK's position as a partner of choice in high profile international collaborations such as the LHC, E-ELT, and SKA, and in future world-class space missions. As part of this, it is vital that we are seen as a reliable partner: underfunding resulting in only minor roles or withdrawal from commitments is extremely damaging. Maintaining infrastructure and developing skills and technology in the inherently interdisciplinary environment found in Universities is very beneficial for developing industrial impact and spin-out companies: for example, silicon pixels and scintillator detectors are used in medical imaging and dosimetry, Grid computing has been used to model spread of pandemic flu; low mass electrical connections and cooling systems from particle physics trackers have potential for use in aviation industry.

Support for e-infrastructure is essential for Universities: local facilities provide for flexibility, development and in some cases the full resource needed for a project, complementing the national and international provision. Further consideration should also be given to the infrastructure requirements for data preservation, curation, and open access.

7 Should - subject to state aids and other considerations - science and research capital be extended to Research and Technology Organisations and Independent Research Organisations when there are wider benefits for doing so? (1000 words maximum)

Answer to question 4:
Full exploitation by UK researchers of any capital investment requires a guarantee of open access to facilities over the long term in a sustainable manner. This is most readily achieved through Universities, and Research Council Institutes and laboratories. In principle, science capital could be extended to RTOs and IROs, but this should only be done if they offer unique capabilities essential to UK research that are not otherwise available to UK researchers outside the RTOs and IROs, and that it is possible to ensure that there will be long-term open access to the research community in a sustainable manner.

8 KEY QUESTION: What should be the UK's priorities for large scale capital investments in the national interest, including where appropriate collaborating in international projects? (1000 words maximum)

Answer to question 2:
The UK's priorities in particle physics are closely aligned with our international partners in Europe (https://cds.cern.ch/record/1551933) and the US (http://usparticlephysics.org/p5/). Upgrades to ATLAS and CMS at the LHC will explore new territory Beyond the Standard Model (BSM) of particle physics following discovery of the Higgs boson, particularly by searching for dark matter particles. LHCb upgrades will search for BSM physics through its effects on decays of B-meson particles. The UK has high-level leadership in all three experiments. The UK CERN subscription and UK capital investment are critical. The technology has wider applications, e.g. pixel detectors in medical imaging, low-mass welding in aerospace and grid computing in Big Data, as well as immense impact in public engagement, particularly relating to the discovery of the Higgs boson. Further studies of the Higgs boson and BSM physics will be possible at the ILC under consideration in Japan. UK scientists already lead several areas of this project.

Long baseline neutrino experiments in Japan (T2HK) and the US (LBNE) are a very high priority for further understanding of matter/anti-matter asymmetry. The UK already has a sizeable community of neutrino physicists, including field-leaders. A number of smaller scale experiments also have the potential to deliver Nobel-prize winning breakthroughs including searches for neutrinoless double-beta decay processes (SuperNEMO and SNO+), anomalous properties of the muon (g-2 experiment) and dark matter particles (LUX-ZEPLIN). In the area of dark matter searches, a low background counting facility at the Boulby Mine in Yorkshire is a key requirement.

The highest profile astrophysics/space activities are SKA, E-ELT, LSST and continuing membership of ESO (E-ELT, ALMA, VLT). Investment in the SKA headquarters and Data Centre is essential, as is a Data Centre for LSST. Consideration should be given to a National Astronomy Data Centre, together with computing infrastructure for theory and science exploitation.

Involvement in ESA missions remains a major priority, requiring infrastructure in Universities and laboratories to prepare for large missions e.g. ATHENA, LISA well in advance of final decisions and launch. Technology readiness is key to UK leadership, and such infrastructure is also vital for small-to-medium-sized projects such as new instruments on smaller ESO telescopes, in addition to large projects such as E-ELT, VLT and SKA.

There is strong support for enhancement of the national space programme to include bilateral space science missions with other national space agencies e.g. USA, Japan, China, and India with commercial and scientific spin-offs. The recent Global Collaborative Space Programme does not meet this need as it is targeted at projects for international development.

The search for gravitational waves requires world-wide coordinated effort: many UK university groups are heavily involved in the science and technical development of Advanced-LIGO in the US and India, and the next-generation ground-based gravitational wave facility, the Einstein Telescope. The gamma-ray observatory CTA is a top priority of the astro-particle community.

The small but highly effective Nuclear Physics community currently has only one project underway: NuSTAR (incorporating AGATA) at FAIR. Maintaining the strength and diversity of this community is a major priority: three projects are currently under peer review: JLAB (US), and the ALICE upgrade and ISOL-SRS at ISOLDE, both at CERN. Capital investment in these major projects is vital to allow this community to retain its position as an international "partner of choice" owing to the UK's considerable expertise in innovative detector systems and instrumentation as well as providing valuable underpinning knowledge and training for the nuclear industry.

The UK research community needs access to world class neutron, synchrotron and laser facilities. In all areas, the need for investment in new facilities needs to be tensioned with ongoing investment in existing beamlines, for example developing automated sample handling, novel sample environments, faster and more sensitive detectors, and data acquisition, storage and processing to ensure that there is continuous improvement to maximise the efficiency and exploitation of the facilities.

The recent investment in ESS is very welcome, and fits well with the long-term strategy of developing a high-power short-pulse facility at ISIS. The top priority for neutrons in the next few years is the upgrade to ISIS-TS1, a highly cost-effective investment giving an increase in performance of a factor 2-5 across TS1 instruments. Even with ESS, there will be significant loss of neutron capacity in Europe over the next decade, and ISIS can mitigate this, leading to opportunities for partnership and inward investment. Support for the ILL Endurance programme is essential for capability and capacity now, and to give Europe options in the 2020s.

The top priorities for synchrotrons are ongoing investment in beamlines and infrastructure for Diamond, and lattice upgrades both for ESRF and then Diamond. ESRF Upgrade Phase II includes a new lattice storage ring with horizontal emittance reduced by a factor 30, and providing synchrotron radiation beams of unprecedented quality in terms of coherence and brightness, especially at hard X-ray energies. A similar upgrade to Diamond is planned for the 2020s, building on the experience at ESRF.

Vulcan 20:20 is the top priority for lasers: it will enable the exploration of fundamental physics with intense fields, for example the effects of QED in high energy density physics, and underpin a cost-effective route for a future 200 PW upgrade. Novel source development via additional target stations on the CLF's Gemini Facility, and incorporating CLF's proprietary DiPOLE laser technology would underpin the targeted development of a potential "5th generation" light source, and provide a dedicated area for new science and industrial applications.

E-infrastructure is integral to data management and exploitation. Investment is vital for UK e-infrastructure including HPC(DiRAC,ARCHER), HTC (GridPP for LHC, Advanced LIGO and others), data centres (astronomy), facilities computing (e.g. MANTID at ISIS), and networking.

Developing the Harwell Campus as a major science hub and initiatives on imaging, energy, materials and laser applications are welcome. A student village will greatly enhance student training by providing inexpensive accommodation for extended stays.

Investment in accelerators will benefit upgrades (Diamond, ISIS), future facilities (UK-XFEL) and international projects, e.g. LHC, as well as developing accelerators for medical, security, and industrial applications.

9 What should the criteria for prioritising projects look like? (1000 words maximum)

Answer to question 6:
The process of prioritising projects should be carried out by peer review against an overall science strategy made up of roadmaps in individual areas to ensure that the whole science and technology "ecosystem" develops in a balanced and sustainable manner. The strategy should take into account the international context, the health of key science and engineering disciplines, including development of the skills base, needs and opportunities for economic and societal benefit, and underpinning technological advances that will lead to future progress in science and industry. It is vital that there is space for investigator-led "blue-skies" science that can lead to transformative advances in fields, as well as support and encouragement for interdisciplinary collaborations.

The key criteria for prioritising projects in the context of an established science strategy roadmap should be based on scientific excellence, economic and societal impact, UK leadership, and synergies with other activities in the science base. Of these, scientific excellence is critical: no project should be funded if this is not firmly established.
When carrying out a process of prioritisation, it is vital to consider the resource requirements to ensure that they will be sufficient for full exploitation of the project or facility in a sustainable manner. Under-resourcing of expensive facilities is very wasteful.

UK leadership is a very significant factor since our ability to continue to engage in high profile international projects, and to host future projects, depends on our reputation on the world stage for scientific and technological excellence.

The opportunity to leverage funding from other sources, particularly industry and international partners, is very important. This not only offers value for money, but also helps to enrich projects through engagement with a range of partners and stakeholders with different ideas and needs.

Consideration of project risk is important. A healthy portfolio will include some projects that have high risk and correspondingly high benefits. However, the consequences of "failure" and the risk mitigation that is built into a project must be taken into account very carefully. The project portfolio should have an appropriate range of scales and risks.

As part of the evaluation of a project, it is important to take into account timeliness: committing early to a project can offer great opportunities to influence its development, but committing before the benefits are clear and subsequently withdrawing can be very damaging to the UK's reputation as a reliable partner in large projects.

Projects which offer more than incremental advances may have long development timescales, so a long lead-time before possible economic or industrial impact should not in itself be a barrier to investment.

10 Are there new potential high priority projects which are not identified in this document? (1000 word maximum)

Answer to question 7:
International developments in free electron lasers (FELs) are opening up exciting opportunities in areas such as structure determination of very large proteins, direct detection of high speed chemical reactions and properties of matter under extreme conditions. It is vital that the UK builds a community to exploit these opportunities, with a pathway towards construction of a UK-XFEL in the 2020s. The UK is already investing in user consortia at the EU-XFEL, and the next stage is becoming a partner in the construction of EU-XFEL, exploring the applications that will be of greatest benefit to UK science and industry. At the same time, investment in the accelerator test-bed CLARA would develop R&D capabilities for construction of the UK-XFEL. Desirable parameters such as repetition rate, maximum photon energy and operation mode can be refined as more is known about the performance of international machines currently under construction and the key research interests of the UK user community develop.

AWAKE at CERN aims to demonstrate proton-driven plasma wakefield acceleration – a possible candidate for a future (>2040) very high energy collider facility. The proposed technique might be able to accelerate electrons from 10 GeV to 600 GeV in only 600 m, which would represent a revolutionary improvement in accelerating gradient. It would enable a compact high energy electron-positron collider for fundamental particle physics to be realised and is related to other developments in wakefield acceleration driven by laser beams which could deliver table-top accelerators for medical and other applications.

The international Muon Ionisation Cooling Experiment (MICE) which is under development at RAL will provide the proof-of-principle of ionisation cooling, a technique which could enable construction of a neutrino factory facility for detailed study of neutrino properties, or a high energy muon collider for studying the Higgs boson and searching for new physics.

Neutrinoless double-beta decay searches with the SuperNEMO and SNO+ experiments could reveal important fundamental details about the nature of the neutrino including whether it is its own anti-particle, unlike other known elementary fermions.

Direct searches for dark matter particles are one of the highest priorities in physics today. Evidence for a signal would revolutionise our understanding of the formation and current structure of the universe. The UK participates in the world-leading LUX experiment in the US and has the opportunity to make a significant impact in the follow-on LUX-ZEPLIN experiment currently under development.

The Boulby Underground Laboratory is vital to underpin dark matter searches. It provides material screening at world-class sensitivity levels, acts as a training ground for highly skilled scientists, and hosts dark matter work in the UK funded by international partners.

The E-ELT has assured funding for early instruments, but it is vital that instrument upgrades are continually being developed, to keep the telescope at the forefront. With six instruments initially planned, additional capital in 2018-20 is highly desirable so the UK can participate in a third instrument, with returns in telescope time and industrial participation.

Capital support will be required for the recently selected ESA L2 mission Athena (2028) and will consolidate UK science leadership and help position UK industry. In addition funding will be needed for future ESA missions, not yet fully determined, including L3 (a low frequency gravitational wave experiment, probably LISA) and the medium M4 & M5 missions.

Capital investment is required to develop the ability for the UK to lead international space missions as well as to be minor partners in the missions of other major European nations and, for example in new bilateral space missions e.g. WFIRST (NASA), SVOM (China).

The recent BICEP-2 measurements have highlighted the scientific importance of exploring the physics of the early Universe through study of polarisation of the Cosmic Microwave Background (CMB). The interpretation of the recent results is still under debate, and the Planck polarisation results, to come out later this year, are eagerly awaited. If a detection is confirmed, it is likely that further experimental projects (ground based and/or spaceborne) will be proposed with the objective of making major advances in fundamental physics using the CMB as a probe of the early Universe. The UK has a strong track record and a strong community (both theoretical and experimental) in this area, and could be well-placed to take a leading role in such experiments.

In nuclear physics there are two potential high priority projects that are not identified in the document: EURISOL and the Electron-Ion Collider. These are discussed in detail in the response to the question on major international projects.

The ALICE test facility at Daresbury has successfully demonstrated key technologies for future accelerator facilities, and has exceeded the original goals by showing potential as a source of intense infrared and terahertz radiation. For example, experiments recently carried out using the IR FEL include the high-resolution imaging of tissue samples using a Scanning Near-field Optical Microscope for improving the understanding and diagnosis of different types of cancer. Funding for hardware upgrades would allow conversion of ALICE into an IR FEL and terahertz user facility, capitalising on the existing investment. An IR FEL user facility would complement an X-ray FEL test facility (CLARA) and the future development of the UK-XFEL.

Development of a proton source covering a range of energies up to 150 MeV would address presently unmet needs of a number of user communities in the UK. Applications would include radiotherapy research, production of radiopharmaceuticals (where there is an ongoing threat to UK supply), and irradiation studies for the nuclear industry. A suitable facility (ProTec) could be based on a high current cyclotron feeding multiple research stations, one of which would comprise a linear accelerator for boosting the proton energy to 150 MeV.

11 Should we maintain a proportion of unallocated capital funding to respond to emerging priorities in the second half of this decade? (1000 word maximum)

Answer to question 8:
It is important to strike a balance between the benefits of stability conferred by long-term commitments to key projects with the ability to adapt to new opportunities in a changing landscape in an agile manner, reacting to new discoveries or the development of transformational technologies. The proportion of unallocated capital should certainly be greater towards 2020. It is also important to note that the need for longer-term commitments varies between fields. For example early commitment to some large particle physics, astrophysics and space projects gives a great benefit in terms of UK leadership, but the ability to react to new and surprising discoveries through a competitive bidding process is very important.

UK astronomy and would benefit from a capital line for small projects, to help restore and maintain breadth in the programme. This could accommodate, for example, PI instruments for observatories or scientific balloon programmes (which often act as pathfinders for future facility instruments).

Early investment in the modest but potentially greatly beneficial upgrade to TS1 at ISIS would lead to increased productivity much sooner and over a longer period, and encourage much larger inward investment from European partners for a more substantial upgrade in the longer term. Failure to invest early in the Endurance Programme of the ILL may result in missing the window of opportunity to maintain world leading capability in the 2020s and lead to premature loss of international competitiveness and hence threaten early closure of this facility.

12 Are the major international projects identified in the consultation the right priorities for this scale of investment at the international level? Are there other opportunities for UK involvement in major global collaborations? (1000 words maximum)

Answer to question 9:
At the Large Hadron Collider, upgrades to both the experiments (ATLAS, CMS and LHCb) and the LHC machine are of the highest priority for global particle physics. They will enable the landscape of new physics revealed by the discovery of the Higgs boson to be explored in detail and open up new possibilities for searches for physics beyond the standard model of particle physics, including searches for the production of dark matter particles, extra dimensions of space and particles predicted by new theories such as supersymmetry. The UK has high-level leadership in all three experiments, as well as in the machine itself, and the investment also supports UK membership of CERN. The technology has wider applications, e.g. silicon pixel detectors in medical imaging, low mass welding in aerospace and grid computing in Big Data, as well as immense impact in public engagement, particularly relating to the discovery of the Higgs boson.

It is vital that the UK remains at the cutting edge of international particle physics: if Japan decides to build the International Linear Collider (ILC) to exploit the science landscape opened up by discovery of the Higgs boson, it is essential that the UK participates with substantial capital investment in the 2020s. UK scientists already lead several key areas of ILC R&D, and modest investment in the interim will maintain UK leadership.

Long baseline neutrino experiments (LBNE, T2HK) offer the prospect of measuring an asymmetry in the properties of matter and anti-matter particles which could explain why the universe is predominantly composed of matter today. These experiments are currently under development with high priority in Japan and the US.

The UK already has a very high profile in this area, with many of the world leaders. The UK has strong opportunity to build on this position with investment in the capital phase of these experiments over the next decade.

The large future international ground-based astronomy projects in which the UK can play a major role are correctly identified, including SKA, E-ELT and LSST, as is support for theory through the DiRAC HPC facility. Flexibility to invest in smaller-scale projects is also vital to maintain a dynamic and healthy community.

Capital support will be required for the preparations for future ESA L and M class missions, as well as to develop the UK's ability to lead international space missions as well as to be minor partners in the missions of other major European nations and, for example in new bilateral space missions e.g. WFIRST (NASA), SVOM (China).

The Cherenkov Telescope Array (CTA) is a key instrument for global particle astrophysics and features on the ASPERA, ASTRONET and ESFRI roadmaps. It is a 27 nation effort involving over 1000 scientists to build a global observatory for the highest energy photons. IT will provide a census of particle acceleration in the universe, explore the role of high energy particles in feedback processes, probe extreme environments from close to black holes to cosmic voids, and search for dark matter and quantum gravity effects. The complementary nature of the CTA dark matter search to direct detection and LHC searches was recognised by the US P5 report and several roadmaps.

During the next decade, two new international nuclear physics facilities are likely to move towards the construction phases. EURISOL is the next generation accelerator system for radioactive ion beams based on online isotope separation, which will provide significant increases in luminosity to study exotic nuclear structure and reactions, particularly in systems relevant for astrophysical processes. In the hadron physics area, there will likely be a move towards an Electron-Ion Collider (EIC) where electrons will be used to probe the gluon and quark content of nucleons at high energies and luminosity. Plans for both facilities will condense in the next few years, in particular the locations: France or CERN might host EURISOL and EIC may be at JLAB or Brookhaven in the USA. In order to maintain a strong UK lead in science programmes for these new facilities, capital will be needed towards the latter part of the current period in order to being design and construction of relevant state-of-the-art detectors and equipment. In addition to these new projects an upgrade of the equipment currently being constructed for NuSTAR will also be of high priority.

XFELs can generate X-ray pulses of a hundred thousand times shorter duration than those from a synchrotron whilst being a billion times brighter. The EU-XFEL will become operational in 2017 and will be a world-leading international facility as it is the first high rep-rate hard X-ray FEL surpassing all existing machines in performance. Full collaboration in the construction of EU-XFEL is important to broaden access, develop the UK community, and give UK science a strategic voice in this rapidly evolving field.