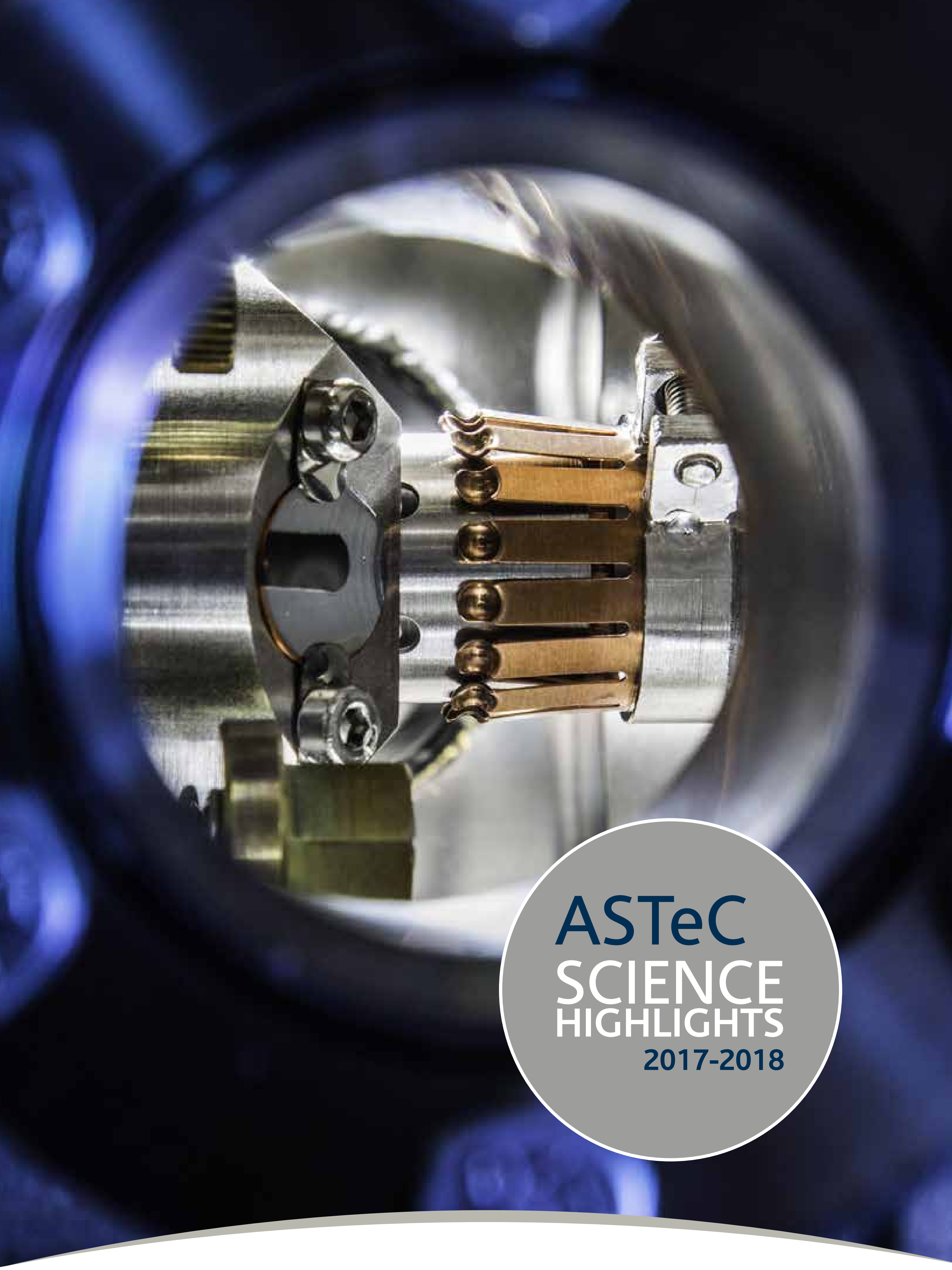

ASTeC SCIENCE HIGHLIGHTS 2017-2018

Science & Technology Facilities Council

UK Research and Innovation

Science Highlights
2017 - 2018

This report covers the work accomplished by the Accelerator Science & Technology Centre (ASTeC) for the financial year 2017 - 2018

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Director's foreword

I would like to take the opportunity to present some of the key highlights of ASTeC's research endeavours during 2017-2018. This year we have continued to deliver a world-class programme of research and development in the field of particle accelerators on behalf of STFC. Our mission is to "make a brighter future through advanced accelerators". A major goal for our research is to provide UK engineers and scientists with the accelerator infrastructure that they need to keep them at the forefront of global research and innovation.

Over the period covered by this report ASTeC has continued to be an important partner in many accelerator projects both in the UK and abroad. This year represents the first in which we present significant results from the UK XFEL project, which involves the preparatory research for making the decision on the likely next large-scale project for the UK. This project involves a wide collaboration between ASTeC and other major accelerator laboratories in the UK including the Cockcroft Institute, Diamond Light Source and the John Adams Institute. Additionally, the department continues to develop CLARA, a prototype of one possible design for the UK XFEL, which is a test bed for many of the key technologies required for the UK to develop a world-leading facility. ASTeC also continues its many important collaborations around the world, including CERN and the ESS in Lund, Sweden where it is delivering ground breaking technologies to enhance machine performance and hence increase the capability for science discovery.

As ever, none of the work reported would be possible without the exceptional contribution of our highly skilled workforce which remains ASTeC's greatest asset. Members of the department have a wide range of skills across the science, engineering and project management areas. Many are world leaders in their respective technology areas, using their experience across multiple projects both locally and internationally. They are committed to maintaining their skills both through the varied training opportunities provided by the department and participation in conferences and workshops with their peers from all parts of the world. These interactions, both at conferences and project collaboration meetings help to keep UK accelerator science and technology at the forefront of global efforts to drive forward this exciting field.

The development of next generation free electron lasers remains the highest priority for ASTeC and this is particularly highlighted by the kick-off of the UK XFEL preparatory phase. At this stage ASTeC members and their collaborators are exploring a wide range of options for what a future UK facility might look like. Researchers are investigating various options to arrive at a proposed design which blends the appropriate amount of risk with more established technologies to deliver a world-leading machine. Perhaps the most important aspect of ASTeC’s FEL programme is the CLARA accelerator being built in the Electron Hall at Daresbury, where we plan to test some of the more advanced technologies and FEL schemes that may deliver world-leading capability. This work on UK XFEL and CLARA is part of a world-wide effort to drive forward FEL design and is therefore complementary to other collaborative international projects in which ASTeC is engaged, including EU projects such as the CompactLight and EuPRAXIA design studies.

International collaborations remain an extremely important part of ASTeC’s research portfolio. The ARIES programme is an integrating activity of the EU’s Horizon 2020 programme which aims to bring together various laboratories in the study of many of the critical technologies needed for next generation accelerators. ASTeC is involved in two important aspects of this project, transnational access, where collaborators from across Europe can obtain access to accelerator infrastructure and test facilities and a more targeted project on the development of superconducting thin film materials for RF cavities. The AMICI project, another European programme, is a direct attempt to bring together national laboratories with the industrial supply chain that is so important in delivering large scale accelerator projects. Through a series of meetings and workshops the project aims to develop closer collaboration to reduce the cost barrier to industrial involvement and hence enhance innovation in this area. The EuroCirCol collaboration is yet another area where ASTeC is exploiting its expertise in thin films technologies, this time for the future circular collider project; the development of low secondary electron yield coatings which are suitable for the cryogenic beam vacuum system has been identified as a key technology area.

One particular field where ASTeC has developed expertise over many years is in superconducting technologies. An example of this is the development of a superconducting undulator magnet which we are carrying out in close collaboration with our colleagues in the Technology Department at the Rutherford Appleton Laboratory. It is because of our experience in this area that we are contributing to the European Spallation Source project in Lund, Sweden by establishing a cryogenic testing capability which will be used to qualify the high beta cavities required. Additionally, we have an extensive programme of research into superconducting thin films much of which is collaborative with our many international partners.

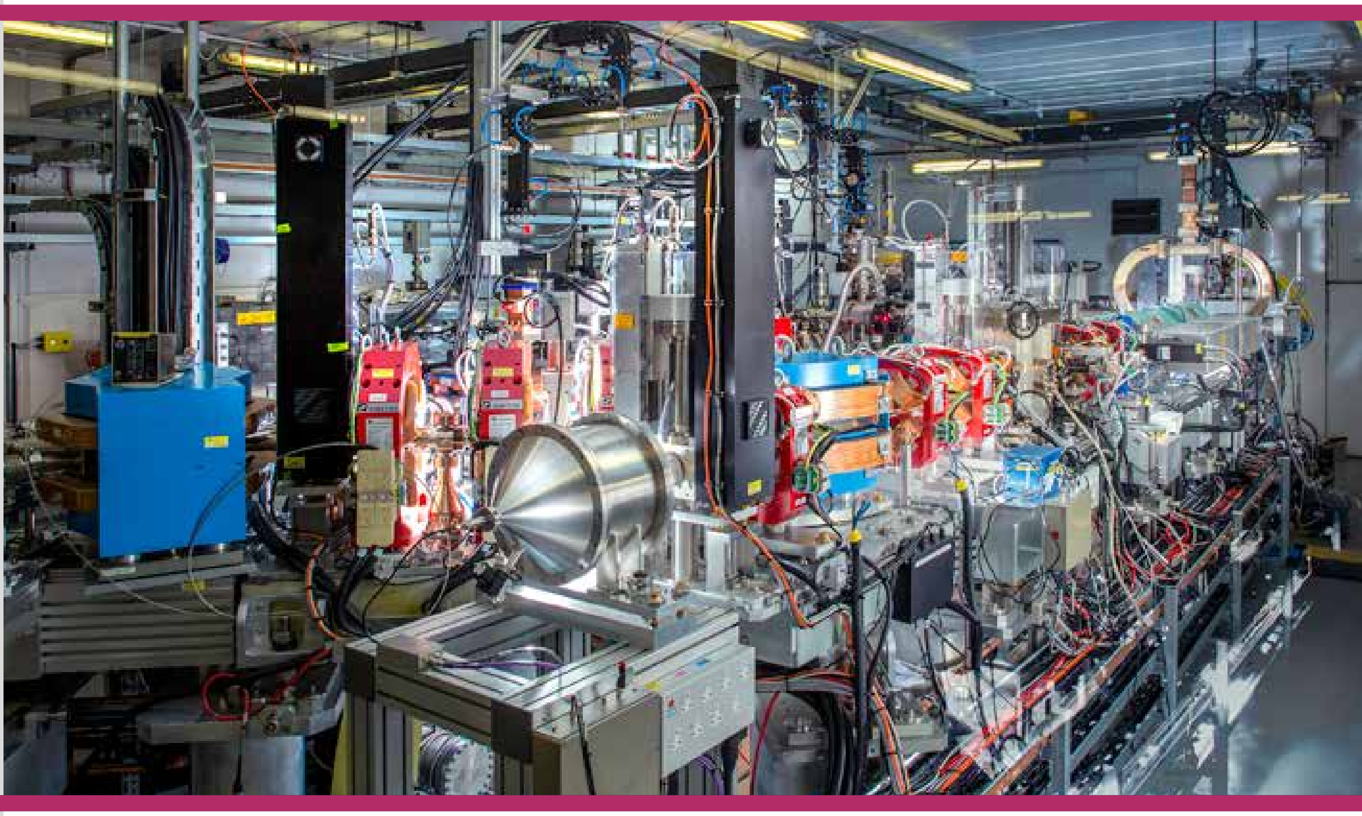
Over the years there has been an increasing awareness of the very high energy requirements needed to run particle accelerators. Here we cover some of the approaches that we are taking to try to minimise the environmental impact of large scale science facilities such as these. One of the options being considered for the new UK XFEL is a multi-pass energy recovery linac which has the advantages of having a reduced physical footprint, using a reduced number of expensive accelerating modules and recovery of much of the energy from the spent beam before dumping which additionally reduces the radiation protection requirements. Another technology developed at ASTeC that is now being commercialised is the design and construction of permanent magnets for accelerator applications; these effectively save energy by not requiring the very high electric currents that are typically drawn by electromagnets. Finally, at the Daresbury Laboratory site we are investigating the possibility of using ground water cooling for our accelerator plant another approach which could yield substantial savings in our energy bills.

To finish I would like to take the opportunity to thank all those who have assisted us with our research efforts this year including our partners both internationally and within the UK. I would particularly like to highlight the close working relationship we have with the university researchers and students within the Cockcroft Institute here at Daresbury and the fabulous support we get from the Technology Department at the laboratory. Without these partners we would not be able to make such a significant contribution to the advancement of accelerator science and technology or achieve many of the highlights presented here.

Professor Susan Smith

ASTeC Director & Head of Daresbury Laboratory

Free Electron Lasers for Science Discovery



Free electron lasers (FELs) are incredibly intense sources of pulsed electromagnetic radiation driven by relativistic electron bunches. These light sources have the power to transform research across a range of disciplines, taking developments in the physics, materials and life sciences into new territory. This is due to the numerous advantageous properties of FEL light compared to existing light sources. FELs can generate radiation across a wide range of wavelengths, spanning the infrared to the X-ray spectral region. The duration of pulses generated by a FEL can be less than a femtosecond; shorter than the time required for a chemical bond to break. The peak brightness far exceeds existing X-ray synchrotron sources by several orders of magnitude, meaning a vast amount of data from a sample interacting with the radiation can be acquired in a short period. Finally, FELs have excellent spatial coherence, meaning advanced X-ray imaging techniques can be employed to characterise systems smaller than a micrometre with unprecedented spatial resolution.

In 2016 the STFC outlined the case for the development of a UK-based X-ray FEL (UK XFEL) facility to ensure national academia and industry maintains an edge over their competitors in research and innovation. ASTeC is underpinning this case through the construction and commissioning of the Compact Linear Accelerator for Research and Applications (CLARA); a FEL test facility designed to evaluate state-of-the-art FEL concepts and technology. CLARA is a vital stepping stone to a UK XFEL and will help ensure such a machine is both world-leading and cost-effective. In the sections below, we highlight the work of ASTeC scientists leading the UK XFEL preparative research phase and the development of world-first concepts on CLARA, which will ultimately inform a funding decision on a possible new facility in the 2020s.

ASTeC FEL scientists are also recognised internationally for their expertise and provide input and leadership to many significant multi-national accelerator developments. In the sections below, the ASTeC contributions to two such leading projects – CompactLight and EuPRAXIA – are discussed.

UK XFEL

The 2016 STFC FEL strategic review recognised the revolutionary potential of X-ray Free Electron Lasers (XFELs) for science and industry internationally. In order for the UK to stay competitive, a recommendation was made to join the European XFEL, based in Hamburg. This was enacted and the UK formally joined in March 2018. In the longer term it was foreseen that the UK would need its own XFEL to meet the anticipated demand and to have a source matched to the needs of UK researchers. To this end ASTeC has led the development of a UK wide R&D programme which formally started in April 2017. CLARA is the major part of this effort, being a dedicated FEL test facility aimed at developing technologies and techniques to improve the radiation output of FELs. In addition to this experimental work at longer wavelengths, ASTeC is exploring options for what a final full-scale UK-XFEL facility might look like.

As a starting point, ASTeC has initiated consultation with UK academia and industry, in particular the UK users of the two longest established hard X-ray XFELs; LCLS in USA and SACLA in Japan, in order to establish the requirements and aspirations of this pioneering user community. Based upon these discussions ASTeC is formulating options to best address the identified needs and to ensure that, should the UK decide to build a national facility, it would have world leading and unique capabilities and so give UK researchers and industry a competitive edge.

The R&D programme covers most of the key FEL sub-systems as well as theoretical studies on the development of new ways of creating higher quality light from FELs. One aspect which XFEL users have highlighted is the synchronisation between the FEL output pulse and a high power laser; this combination of two powerful light sources is key to many experiments. Users need to control the time of arrival at the sample to the femtosecond level because they want to study extraordinarily fast atomic processes that determine how matter behaves. ASTeC staff have spent significant effort in understanding the fundamental performance of the accelerating system which largely sets the arrival time of the electrons and so the FEL pulse. By studying the hardware performance on CLARA, we will be able to identify which sub-systems determine the overall synchronisation and so put our efforts into improving these. Our measurements show that the CLARA hardware is exceptionally stable but that improvements are still required to meet the challenge set by our potential UK XFEL users.

A second aspect of our work is in the improvement of FEL output performance. ASTeC staff are studying how pulses of light shorter than currently available elsewhere can be generated by manipulating the electron bunch using magnets and lasers. A second area of study is looking at how the pulses from the FEL can be made to be more repeatable shot to shot. UK users of XFELs have highlighted this as an area that, if improved upon, could lead to making some experiments viable that are not currently possible. ASTeC staff are investigating how some relatively simple changes to the FEL layout could increase the stability.

Two other areas of XFEL R&D that ASTeC is leading are in potential recirculation and energy recovery schemes (see page 18) and in the development of superconducting undulators for FELS (see page 13). Both of these areas could potentially have a positive impact on the costs required to build and operate a future XFEL.

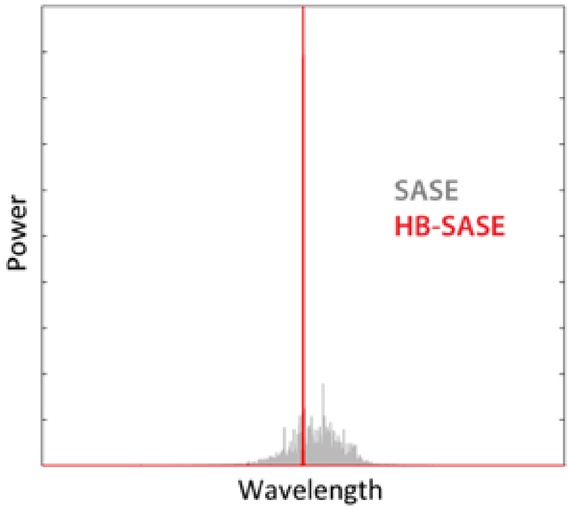
CLARA – a test platform for ground-breaking concepts

A FEL relies on a means of amplifying light (gain) and positive feedback to increase that amplitude to very high levels. An electron bunch travelling with relativistic energies is passed through a magnetic undulator consisting of a series of alternating magnetic dipoles. The magnetic forces cause the electron bunch to oscillate in a direction perpendicular to the undulator and emit synchrotron radiation. The key technological challenge to FELs is generating positive feedback between the emitted radiation and the driving electron bunch. This principally determines the intensity (along with other properties) of the radiation emitted and therefore ultimately how the light can be used in scientific experiments. For infrared and visible FELs feedback is generated by placing the undulator in an optical cavity consisting of a pair of mirrors, which forces the radiation to make multiple passes of the undulator and interact with multiple electron bunches. At X-ray frequencies however, there are no appropriate mirror materials; instead a single long undulator is used and the random emission from the start of the undulator is ultimately amplified to high power by the end of the undulator. This process is called Self-Amplified Spontaneous Emission (SASE).

While commonly used, SASE has the disadvantage that the output radiation is essentially amplified noise; it has very poor temporal coherence, comprising of many random spikes, and each output pulse is different. To get around this problem a technique called seeding can be used: a longer wavelength, temporally coherent seed pulse generated by a laser is injected into the start of the FEL. This ultimately generates an intense pulse of radiation at a higher harmonic of the seed. Unfortunately, this process cannot be used for X-ray FELs as the harmonic ratio between the seed and final FEL output becomes too high and the conversion process breaks down. In the X-ray region there is currently only one solution; self-seeding, in which an X-ray monochromator is inserted some distance along a SASE FEL to filter the noisy pulse, which then acts to seed a second FEL section. Even with this the output pulse is still not fully coherent.

The duration of the FEL pulse is also of critical importance to users as it sets the minimum timescale of dynamic process that can be studied. In a SASE FEL this is normally the same as the length of the electron bunch. Shorter pulses can be obtained through 'slicing', in which a fraction of the bunch is preferentially selected to lase. However, there remains a fundamental limit due to slippage between the radiation (travelling at the speed of light) and the electron bunches (travelling just less than the speed of light) which restricts the minimum pulse duration of X-ray FELs to 100 attoseconds.

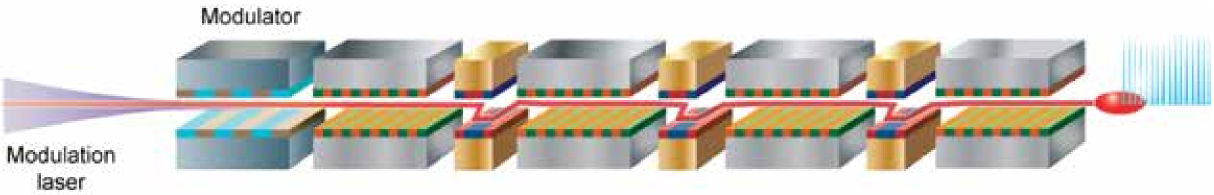
One of the main research goals of CLARA is to demonstrate new techniques to solve the problem of noisy SASE FEL pulses and overcome the limits on FEL pulse durations. This would enable a future UK-based X-ray FEL to be truly world leading. One such technique invented by ASTeC researchers is High-Brightness SASE (HB-SASE): this aims to produce FEL pulses with full temporal coherence and transform-limited bandwidth by slowing down the electrons in a series of magnetic delay chicanes inserted along the undulator. This technique does not rely on optics and may be more adaptable to wavelength tuning than self-seeding.



A comparison of FEL spectra for SASE and HB-SASE where the HB-SASE spectrum is effectively a single line, indicating a close to transform-limited pulse with full temporal coherence

Another FEL technique originally proposed by ASTeC researchers and to be tested on CLARA is Mode-Locked FEL. Similar to the concept of mode-locking in conventional lasers, adapting this technique to X-ray FELs may allow pulse durations to break existing limits by several orders of magnitude. The technique again relies on a series of chicanes to periodically delay the electrons; this modulation is equivalent to generating a comb-like series of wavelength modes, much like in an optical cavity. By adding a small periodic modulation to the energy of the electron bunch these modes can be made to overlap and become phase-locked; at this point the FEL pulse forms a train of extremely short, evenly spaced spikes. When applied to an X-ray FEL this may allow the unprecedented generation of single-attosecond duration pulses of radiation.

The layout of the CLARA FEL has been carefully thought out to allow both HB-SASE and Mode-Locking to be studied. There are many other FEL R&D topics of interest, such as multicolour pulses and new seeding schemes that have the potential to reach even shorter wavelengths. Flexibility is at the heart of CLARA; as new ideas emerge in the coming years – and they inevitably will – CLARA is in the position to remain a leading international FEL test facility.



Schematic layout of a Mode-Locked FEL where a laser is used to add a periodic energy modulation to the electron bunch and decay chicanes are inserted periodically along the length of the undulator

CompactLight

During 2017 a number of leading European accelerator centres, including ASTeC, agreed to work together on the joint design of an X-ray FEL called CompactLight. CompactLight aims to pool international expertise in areas such as magnet design, high gradient RF cavity fabrication and electron source development to design a compact and affordable facility taking advantage of the very latest accelerator technologies and concepts. The design is not for any specific country; rather it is a generic design that many countries (including the UK) could choose to take up or possibly modify for their own national requirements. Since CompactLight has the potential to deliver wide ranging benefits for many countries, the European Union has agreed to fund the design study under the Horizon 2020 programme.

The design study formally started on 1st January 2018 and will be completed within three years. There are 24 partners contributing to the project, each with their own area of expertise. CERN will be providing leadership for the RF accelerating sections, which they have been developing intensively for a possible future electron-positron linear collider. ASTeC is providing expertise on all aspects of FEL design and is responsible for coordinating the full technical design across all the partners. The Conceptual Design Report for CompactLight will be published in December 2021, a timescale that is compatible with the UK making informed decisions regarding a possible national FEL in the early 2020s.

EuPRAXIA

Particle accelerators have become powerful and widely used tools for industry, medicine and science. Today there are some 30,000 particle accelerators worldwide, all of them relying on long-proven and highly developed methods for increasing the energy of charged particles using radio-frequency (RF) technology. The maximum achievable accelerating gradient from RF technology is generally limited to 100 MV/m due to breakdown in the metallic cavities. There is substantial interest in a new type of accelerating technology based on exploiting the incredibly large electromagnetic fields formed in the wake of a high energy laser travelling through a plasma. A plasma has essentially no breakdown limit, allowing for accelerating gradients over a thousand times greater than those for RF structures to be achieved. Such technology has the possibility to revolutionise particle acceleration, allowing high beam energies to be realised on length scales as short as a centimetre (compared to several kilometres with RF technology). This technology could be applied readily throughout academia and industry and dramatically expand how particle accelerators are ultimately used.

The goal of the EuPRAXIA project is to produce a conceptual design report for a worldwide first high-energy plasma-based accelerator that can provide beam quality suitable for industrial use integrated with user exploitation areas. It is the important intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or even particle physics at the energy frontier.

One of the possible applications of EuPRAXIA is as the driver for a free electron laser; ASTeC is applying our expertise in FELs to this design study to understand how the electron beams from EuPRAXIA can be matched to the needs of an FEL. This is not simple, as this new type of accelerator produces quite different beam parameters to conventional accelerators making it very challenging to then drive an FEL. We plan to use our test facility, CLARA, in collaboration with other EuPRAXIA partners, to gain a deeper understanding of the practical challenges involved and to try out some possible solutions. The design study is funded by the European Union and has sixteen partner institutes.

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International Collaborations and Programmes

Credt: CERN - Robert Hradil,Monika Majer/ProStudio22.ch

The field of accelerator physics and technology is large and highly diverse. Many labs worldwide are working towards goals which will ultimately lead to a new generation of particle accelerators required for high energy physics, radiation sources and industrial applications. Because of this diversity, no one laboratory can cover the whole range of research and development required to push forward the state-of the art; collaborations are absolutely essential in driving innovation and technological progress in this field. In addition, collaboration helps to keep all parties up to date with the latest developments in their respective fields, ensuring that the newest technologies are integrated into both existing accelerators and designs for new facilities.

Collaborative projects funded by the European Union under the Horizon 2020 initiative form a key part of ASTeC's research portfolio. Here we outline three such projects where the department is playing an important part in both the leadership and delivery of specific milestones and objectives.

The ARIES programme is the spiritual successor to the EuCARD and EuCARD2 grants that funded pan-European research into accelerators from 2009 to 2017. The ARIES programme has a more focussed range of research objectives, with ASTeC participating in two key areas: thin film materials for superconducting cavities (see page 15) and transnational access, where the VELA test accelerator is being made available to collaboration members across Europe for the testing and commissioning of new accelerator hardware and the evaluation of novel techniques and applications.

The development of cutting edge hardware for use in accelerator applications is enhanced through close collaboration between research labs and high technology industries. However, the participation of industrial partners is complicated by the high cost involved and the risks associated with developing a product that might find limited application. The AMICI programme hopes to solve some of these problems by enabling dialogue between industrial manufacturers and research labs across Europe.

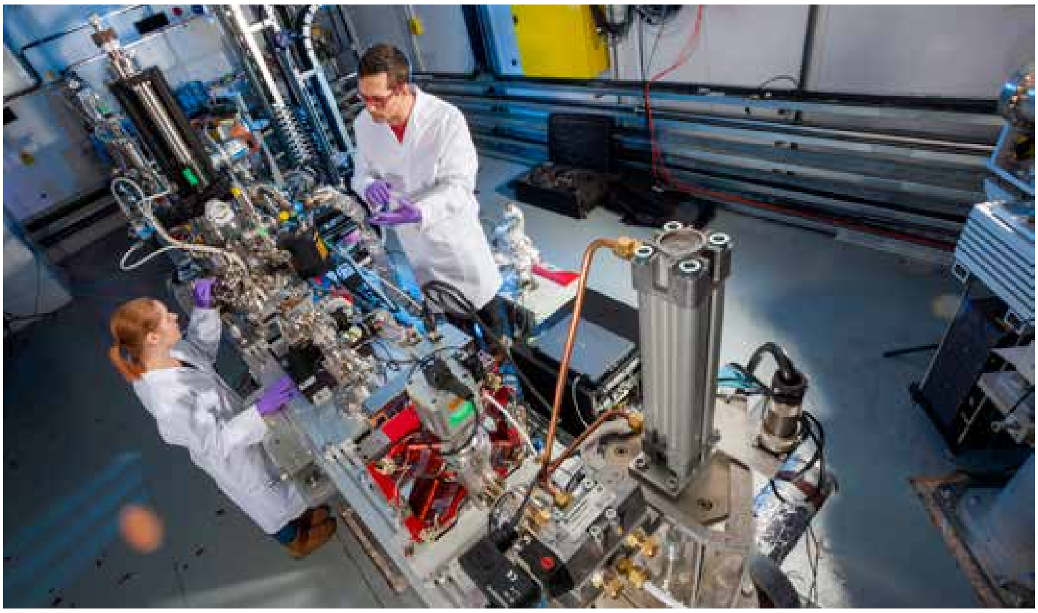
The EuroCirCol collaboration is a project set up under the future circular colliders programme to look at the options for post-LHC high energy physics machines. Any future machine beyond the LHC will require innovative solutions to achieve the highest possible performance while still maintaining affordability. As with all accelerators, the vacuum system is a key sub-system and ASTeC's expertise in this area has enabled us to play a large part in the work package on Cryogenic Beam Vacuum System Conception with multiple ongoing research projects as part of this programme.

ARIES

The Accelerator Research and Innovation for European Science and Society (ARIES) programme is an Integrating Activity project which aims to develop European particle accelerator infrastructures, co-funded under the European Commission's Horizon 2020 Research and Innovation programme. Over its 4-year duration starting in May 2017, ARIES will work towards improving the performance, availability, and sustainability of particle accelerators, transferring the benefits and applications of accelerator technology to both science and society.

ASTeC is leading a work package on Thin Films for Superconducting Cavities. Eight partners from seven countries have a 4-year programme of works with agreed aims, objectives, milestones and deliverables. These partners are CEA (Saclay, France), CERN (Geneva, Switzerland), INFN (Legnaro, Italy), Helmholtz-Zentrum Berlin (Berlin, Germany), IEE-SAS (Bratislava, Slovakia), Universität Siegen (Siegen, Germany) and ASTeC/STFC (Daresbury, UK). The aim of this work package is to develop superconducting thin film materials for use in superconducting RF cavities which can be competitive with bulk Niobium cavities. Further details of this work are given on page 15.

ARIES also offers TransNational Access (TNA) to 14 different testing facilities across Europe. The programme supports users to conduct testing within five separate domains: magnet testing, material testing, electron and proton beam testing, radio frequency testing and plasma beam testing. ASTeC has provided the Versatile Electron Linear Accelerator (VELA) as a platform for accelerator science and technology research purposes, with an expectation to deliver 10-days access provision per year. Details for the ARIES TNA programme can be found at https://aries.web.cern.ch/ta.



VELA accelerator which contributes to the ARIES transnational access programme

AMICI

STFC staff are playing a key role in a European Union-funded programme which is harnessing the cutting-edge technologies, test facilities and know-how of national laboratories to both underpin the next generation of European particle accelerators for research in partnership with industry.

Alongside in-house capabilities, European research institutions are heavily reliant on their supply chain to develop innovative technology solutions and build capacity to support the construction of large-scale particle accelerators for research. As the scale, complexity and cost of the planned facilities increases, so too does the challenge for the supply chain. Whilst numerous ambitious facilities are proposed and evaluated by the international research community, only a small number are ultimately financed and constructed, making the future market size for suppliers very difficult to predict. Particle accelerators often drive component technologies beyond the current state-of-the-art, helping to stimulate innovation, but this often requires investment in development, prototyping and tooling for projects that may not come to fruition.

In an ideal scenario, industry would play a critical role in co-developing innovative technology solutions for future accelerators as part of a stable, robust and scalable supply chain. The research institutions in return would provide technical support, test and validation capabilities to assist industry with development of these products, including for other applications beyond research accelerators. This innovation pathway would ultimately help transfer accelerator-driven technology developments into a broad range of high impact societal applications and help to even out production demands. The 30-month Horizon 2020 AMICI (Accelerator and Magnet Infrastructure for Cooperation and Innovation) is investigating ways to co-ordinate technology platforms, share knowledge and identify barriers to innovation, so that both the research community and the supply chain are mutually strengthened.

ASTeC staff participated in a two-day workshop in Padova, Italy to discuss the challenges attended by the European research institutions, large multinationals and SMEs. The workshop highlighted industry's problems achieving a viable return on investment within timescales that are much shorter than typical facility development and construction phases. It also highlighted the research institutions' difficulty with ensuring the availability of suitable production capacity for specialised components. Further activities will specifically look at barriers to engagement such as regulation, skills transfer and intellectual property. By the close of the AMICI project, models will be proposed for coordinating access to the technology test and validation infrastructure of the European research institutions, and potentially those within European commercial organisations.

EuroCirCol

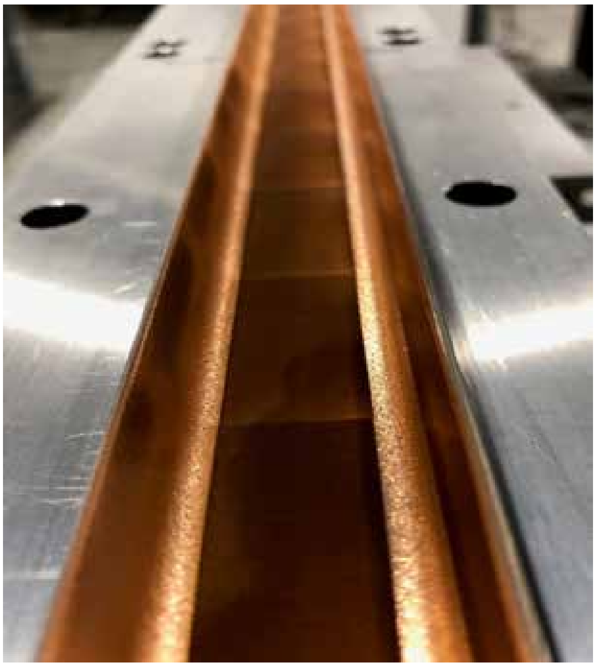
The EuroCirCol collaboration is a part of the Future Circular Collider (FCC) study under European leadership, enabling studies for post-LHC accelerators and technologies. ASTeC's Vacuum Science group is involved as a partner in the work package on Cryogenic Beam Vacuum System Conception. The FCC-hh cryogenic beam vacuum system was identified as one of the most critical sub-systems, and a number of problems need to be addressed to ensure trouble free continuous operation of FCC-hh. The beam vacuum pipe of FCC-hh will be exposed to conditions that do not exist in any existing machines. The cryogenic vacuum chamber will be irradiated with high intensity synchrotron radiation (SR) and could suffer from beam induced electron multi-pacting and electron cloud problems.

Within this task, the ASTeC team is working on mitigation of beam-induced vacuum effects. Two promising technologies are being evaluated.   Option 1 is a low secondary electron yield (SEY) laser treated surface recently developed by ASTeC . Option 2 involves a non-evaporable getter (NEG) coated surface where ASTeC has a world-leading expertise.

In collaboration with University of Manchester, ASTeC is developing Laser Ablating Surface Engineering (LASE). Tens of samples have been produced and tested demonstrating that for LASE surfaces an SEY of less than one can be produced with various lasers and with different sets of parameters. Emphasis was has also been paid to particle control, low surface resistance and low electron stimulated gas desorption. LASE samples have been produced for various work package partners by Micronanics Ltd under ASTeC supervision. These samples will be tested at LNF/INFN, Frascati, Italy for primary and secondary electron yield at cryogenic temperatures, at BESSY, Berlin, Germany for photon reflectivity, and at BINP Novosibirsk, Russia for primary and secondary electron yield in a strong magnetic field.

For FCC-hh, the SR power is much greater than in the Large Hadron Collider (LHC) which thus requires a new solution. The photon critical energy is also much higher than in the LHC. To address these two problems, an experiment with an FCC vacuum chamber prototype has being carefully designed and prepared for testing in the KARA experiment on ANKA, KIT, Germany.

With Loughborough University, ASTeC is exploring NEG coatings, which in addition to low SEY provide important vacuum properties. Initial experimentation has proven successful and these results, combined with the simplicity and lower cost of Zr (in comparison to multi-component films), suggest a good alternative solution to existing NEG coating technology.



The FCC vacuum chamber prototypes after LASE treatment

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Exploiting Superconducting Technologies

The phenomenon of superconductivity was first discovered by Heike Kamerlingh Onnes in 1911 and is evidenced by the electrical resistance of a material falling to exactly zero when cooled below its critical temperature. There are more than one type of superconducting material, with some such as pure Niobium and pure Lead requiring temperatures as low as 4 Kelvin to achieve the superconducting state. While many supercondutors have a higher critical temperature, even here there is an advantage to using these extreme cryogenic temperatures as it maximises the amount of current that can flow without disrupting the superconducting state. For this reason the use of superconducting materials depends very strongly on the field of cryogenics to obtain the required temperature. Vessels designed to obtain and maintain extreme cryogenic temperatures are typically based on an inner cooling system using liquid Helium surrounded by an outer shroud cooled by liquid Nitrogen. The design and implementation of such cooling systems is a key strength of the ASTeC department.

Superconducting technologies have been employed in the accelerator science and technology area for a number of years and applications include high strength magnets for beam manipulation and synchrotron radiation generation and superconducting radio frequency cavities for beam acceleration. In this section we look at three examples of the department's current research into superconducting materials and systems.

Superconducting windings in magnet technology allow for very high currents to be sustained which in turn leads to very high field strengths. ASTeC in collaboration with members of the Technology Department at the Rutherford Appleton Laboratory are developing an undulator using this technology. As a result of the high field strengths involved, undulators based on superconducting windings will be capable of producing radiation with reduced length decreasing the size and cost of any potential free electron laser (FEL).

Because of its long experience in the design and use of superconducting RF cavities and cryogenic technologies, ASTeC has been chosen to play a major role in the provision of such cavities for our international partners at the European Spallation Source (ESS) in Lund, Sweden. A significant infrastructure investment has been made to establish a testing facility which can be used to qualify the high beta cavities for the ESS accelerator. This is a critical step in assuring that the cavities meet specification enabling the ESS to fulfil its design specifications.

Superconducting RF cavities are typically constructed of solid Niobium metal which is an expensive material making cavity fabrication extremely costly. In recent years there has been significant research into the possibility of using superconducting thin film coatings on conventional (non-superconducting) cavities to achieve the same effect. A large international collaboration is involved and although the project is in its early stages enlightening results are already being generated.

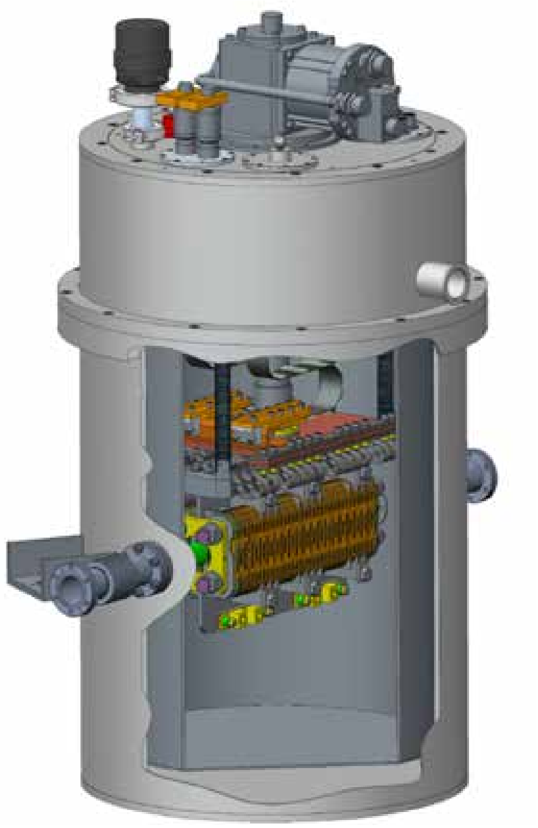
ASTeC with its partners in the Cockcroft Institute continues to have a large involvement with the provision of cryomodules for the superconducting crab cavities for the LHC high luminosity upgrade. This work is on-going and was reported in the 2017/18 ASTeC Science Highlights.

Superconducting Undulators

Undulators are periodic magnets which are used in electron accelerators to generate light through the process of synchrotron radiation, especially X-rays. The period and magnetic field of the undulator define the output characteristics of the light generated by the electrons and so undulator magnets are extremely important parts of synchrotron light sources and free electron lasers. Undulator designers strive to increase the magnetic fields generated whilst simultaneously reducing the period as this enables the X-rays to be produced by lower energy electrons. This is important because it is the energy of the electron which drives the final cost of particle accelerators to both build and operate; better undulators mean cheaper light sources.

Standard undulators are built using permanent magnet technology. Small blocks of permanent magnet materials are carefully arranged to produce the periodic fields required. This type of undulator is very popular but the magnetic fields are limited by the permanent magnet materials available.

The strongest magnets available are however built using superconducting wire (such as MRI scanners or LHC magnets) rather than such permanent magnetic materials; it therefore seems obvious that superconducting technology should be able to bring large benefits to undulators as well. ASTeC has been working on the development of superconducting undulators for a number of years now in order to take advantage of the higher field capabilities that they offer. This work is a collaboration with experts in Technology Department at RAL and with Diamond Light Source to carry out research and development on this type of undulator.



CAD model of the superconducting undulator prototype inside the cryostat.

The challenges associated with building high field strength, short period superconducting undulators are great. The engineering tolerances are extremely tight and these must be maintained as the magnet is cooled down to close to absolute zero, when the wire becomes superconducting. For the magnet to operate at these extremely low temperatures it must be installed in a large cryostat, which means that the magnet cannot be accessed once it is assembled.

The superconducting undulator prototype before insertion into the cryostat.

The focus of this work has shifted towards applying the technology to free electron lasers rather than storage rings. In this case some internal modifications to the magnet can enable even higher magnetic fields to be achieved. Our latest prototype, which has a very small period of only 15.5 mm, has been built and operated in its test cryostat at over 1 T, double the field that a typical permanent magnet undulator would achieve. The next step is to test the undulator with an electron beam and so it will be installed onto CLARA for beam testing in the near future.

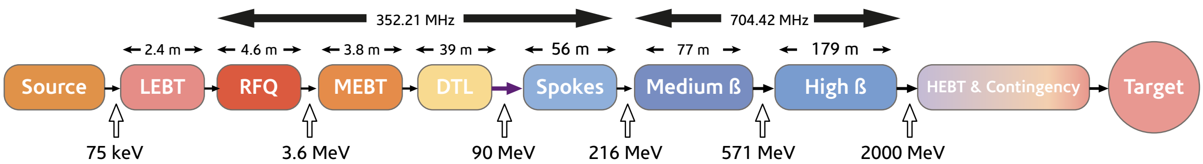
This new type of superconducting undulator could have a big impact on the potential UK XFEL, increasing the total wavelength coverage available and also reducing the required electron energy. This work has been presented recently at two international conferences and as a consequence a number of leading FEL facilities are considering implementing this type of technology on their facilities as well.

Superconducting RF for the ESS

The European Spallation Source (ESS) is one of Europe's largest planned research infrastructures and will be the world's leading spallation neutron source. The ESS in Lund, Sweden is a collaborative project supported by seventeen European countries, which will build capacity and increase proficiency in scientific research mainly driven by applications related to material sciences which will bring new insights to the grand challenges of science and innovation.

Being a single purpose facility, the design parameters of the accelerator are defined by the high level requirements of neutron users and the design of neutron instruments at ESS. The source, with an unprecedented power of 5MW, a proton pulse of 2.86 ms and a repetition rate of 14 Hz

accelerates 62.5 mA of protons up to 2 GeV in a sequence of normal conducting and superconducting accelerating structures. Superconducting RF (SRF) accelerator technology is employed in order to ensure efficient high gradient acceleration in a small physical footprint for such a long-pulse machine.



ESS Linac Layout (Courtesy: ESS)

ESS High Beta Cavity test Infrastructure at Daresbury

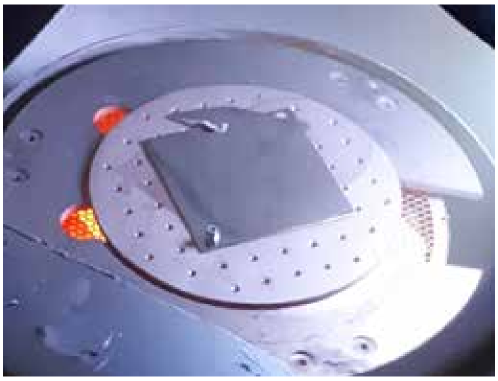
Daresbury Laboratory has the responsibility for providing all of the High-β accelerating structures. Each of the 84 cavities requires on-site testing to achieve the stringent performance requirements for ESS. They will then be shipped to CEA Saclay in France for final stage integration into the 21 operational cryomodules. In order to achieve appropriate qualification, an extensive amount of SRF testing infrastructure is being implemented, which includes: a large 2 m diameter, vertical test cryostat cooled by a 2 K liquid helium liquefier to house the cavities to be tested; and a radiation shielded enclosure implemented to perform the SRF cavity tests. In addition, local surface cleaning is also required for those cavities which are initially not able to reach the operational performance targets for ESS. As a result, these cavities will be subjected to a high pressure rinse cycle using ultra-pure water, which is intended to remove all small particulates which may exist on the SRF cavity internal surfaces and which ultimately degrade the achievable performance. All of this work will be conducted in a high classification cleanroom in order to protect the exposed surfaces of the SRF cavities during the preparation and processing procedure. Once high pressure rinsed the cavities will be reinstated for re-test and qualification. The ASTeC and Technology Department delivery programme is expected to be completed in early 2021.

Thin film technology for superconducting RF cavities

As part of the ARIES programme (described on page 9), ASTeC is leading a work package on thin films for superconducting cavities, which is tasked to explore alternative approaches to bulk niobium RF technology currently used in many modern particle accelerators. Bulk niobium cavities have been optimised over the past 50 years and have reached their theoretical peak performance. An improvement in higher accelerating fields and Quality factor beyond the present day limitations can be achieved by employing superconducting thin film coatings. Thin film SRF programmes exist in many particle accelerator centres in Europe and around the world; however no single laboratory can provide all the required expertise and resources alone. This requires close collaboration between teams with expertise in a wide range of fields, such as thin film deposition, surface analysis, superconductivity and RF.

The main emphasis of this project is a systematic study of the correlation of surface preparation, deposition parameters, film structure, morphology, chemistry with AC and DC superconductivity parameters of superconducting thin film materials deposited on copper and bulk Nb. Ultimately the final behaviour of these films will be evaluated using RF measurements on developed test cavities.

Initial work has been focused on determining the effect of copper substrate surface preparation on Nb film quality. In the following years the coating of other materials (i.e. NbN, Nb_3Sn, MgB_2) as well as multilayer coatings will be explored.



A niobium film deposited on a pre-prepared pure copper substrate

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Increasing the Energy Efficiency of Accelerators

Over the years the development of particle accelerators has adopted a philosophy which can be broadly characterised as 'bigger, better, more powerful'. Particle driven light sources have pushed for extended wavelength ranges (particularly into the hard X-ray region) and higher intensity, whilst colliders have typically sought increased collision energies with greater luminosity. However, these enhancements come with an increased burden in terms of both construction and day-to-day running costs.

In particular, the power requirements for running some of today's highest specification machines are extremely large with predictions of future machines even greater. For example, the LHC currently has a peak power requirement approaching 200 MW whereas the proposed CLIC facility (representing the next generation of high energy physics machine) has a potential requirement of 600 MW for the 3 TeV option. For this reason, the accelerator community is becoming increasingly aware of the need to look for more energy efficient solutions to implement on future generations of machine so that the higher specification accelerators required to drive forward scientific research can be built and operated with lower costs and reduced environmental impact.

In this section three projects which are related to energy efficient accelerator technology are explored.

Permanent magnets as an alternative to the electromagnets typically used in most accelerators are an attractive option for making energy savings in accelerator technology. Whilst permanent magnets have the significant advantage of being able to deliver high field strengths, the main issue is the ability to tune the magnetic fields. Tunability is achieved by using a highly accurate motion system to move the permanent magnets, keeping the poles fixed to maintain the field quality. Careful design is required to deal with the extremely strong forces between these magnets. The article outlines the progress that has been made both in the design of suitable devices and the commercialisation of this technology.

When specifying the proposed new UK FEL the first choice will be whether to use normally conducting or superconducting technology. In the event of using the more expensive superconducting option which requires the use of cryogenic systems there is an exciting opportunity to exploit recirculation to achieve higher energy from the linac sections used and energy recovery to extract the energy from the spent beam thus requiring less power compared to a normal FEL to get the equivalent beam energy and thus short wavelength photons. This option also offers higher repetition rate beams and a potentially smaller footprint than its lower repetition rate normally conducting competitor.

Finally, a new project has been initiated at Daresbury to use ground water cooling for the plant associated with the VELA/CLARA accelerator complex and the Scientific Computing Department/ Hartree Centre computer rooms. This technology has been around for some years and exploits the fact that ground water typically sits at a constant temperature all year long. Schemes of this type have been successfully implemented in many other industrial areas, but this is the first attempt to apply this to a particle accelerator at a UK national laboratory.

Permanent Magnets for Energy Savings

Since 2011, ASTeC has been working in collaboration with CERN to develop a novel type of accelerator magnet based on permanent magnets. This collaboration has resulted in the ZEPTO project: Zero-Power Tunable Optics. ASTeC has built two prototypes of these magnets, which could replace the standard electromagnets used in most particle accelerators. The ZEPTO magnets require no power to provide a constant magnetic field, and could dramatically reduce the running and infrastructure costs of accelerators.

ASTeC scientists and engineers have developed a pair of prototype tunable permanent magnet quadrupoles for the CLIC design study. The CLIC drive beam would require around 41,000 quadrupoles along its 40 km length, so the idea of replacing conventional electromagnets with a permanent magnet based option is highly attractive. The two prototype quadrupoles were tested at STFC's Daresbury Laboratory and at CERN, and performed very well. Following the initial collaboration, ASTeC was tasked with developing a permanent magnet dipole based on the same concept, which could be used on CLIC's drive beam turnaround loops. The engineering design of this magnet is complete. It uses an extremely large (500 x 400 x 200 mm) permanent magnet at its core to drive the magnetic field, and needs very careful handling to manage the huge magnetic forces involved. The magnet is currently being assembled in a dedicated facility at Daresbury.

Permanent magnets are often used in accelerators where fixed fields are required, but the ZEPTO project is a breakthrough that allows permanent magnets to be used as variable-field devices in an accelerator. STFC has a patent on this invention which has been licensed to Danfysik A/S, a Danish company specialising in accelerator magnets. They have some experience with building permanent magnet dipoles, and are now marketing the ZEPTO quadrupoles, which have generated a great deal of interest from the wider accelerator community. STFC and Danfysik are considering building a third quadrupole prototype to install on part of the CLARA beamline as a technology demonstrator, to show that these could be used as drop-in replacements for conventional electromagnets.


High-strength prototype quadrupole ZEPTO-Q1 and low-strength prototype quadrupole ZEPTO-Q2

Recirculation and energy recovery options for the proposed UK-XFEL

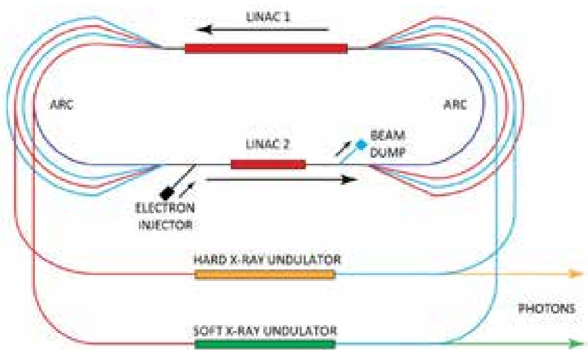
As part of the UK XFEL R&D project ASTeC has been assessing the different technology options which exist to deliver a state-of-the-art machine for UK scientists to exploit in their research endeavours. CLARA is an integral part of this effort, being a dedicated FEL test facility aimed at developing techniques to improve the radiation output of FELs. In addition, ASTeC is exploring alternative options for what a final full-scale UK-XFEL facility might look like and how to make the proposed facility more energy efficient.

The first major decision that must be made in defining any XFEL accelerator is whether it should be based on a warm, pulsed normally-conducting linac or a cold, continuous-wave superconducting linac. The normally-conducting route offers lower risk and likely lower cost, but also reduced pulse repetition rate. The superconducting route offers potentially unprecedented scientific reach, albeit with higher risk and cost. ASTeC is developing and comparing solutions for both paradigms, so that when a decision to construct a UK-XFEL is taken, an informed technology choice can be made swiftly.

An exciting possibility exists to simultaneously surpass synchrotrons in terms of average brightness and cut construction and operational costs through the deployment of recirculation and energy recovery. Recirculation involves using the linac to accelerate the beam more than once by turning the beam around and re-injecting, each time gaining more energy. Recirculation in superconducting linacs has been well established by the near three decades of operation of the CEBAF accelerator at Jefferson Laboratory in Virginia, USA. Energy recovery allows the average current of the beam to be greatly increased by extracting the energy in the spent beam after lasing. This relies on the nature of the superconducting structures which by virtue of their zero-resistance efficiently pass the energy from spent beam to accelerating beam. ASTeC has more than a decade's experience of construction, commissioning and user operation of an infra-red FEL based on a superconducting energy recovery linac; the recently decommissioned ALICE at Daresbury.

Application of ER in the multi-GeV electron, hard X-ray regime would not only enable high average power (of particular interest to the semiconductor industry), but also allow for the development of X-ray oscillator FELs (XFELO). These would be capable of high powers in harmonics of the fundamental, perhaps reaching to 100 keV with multiple applications in material science. Non-FEL science would also benefit; narrowband gamma-ray sources would be possible through inverse Compton scattering with potential applications in nuclear physics and industry. Fundamental physics could also be served through internal target experiments at high beam current searching for dark matter.

The deployment of recirculating, energy recovery superconducting linacs are not only of interest as potential XFEL drivers, such machines are also being considered for future particle colliders. At CERN, one possible development of the LHC involves enabling electron-proton collisions. The favoured approach for this is called LHeC and would involve the construction of a recirculating, energy recovery superconducting linac. A test facility is seen as a necessary stepping stone and ASTeC is involved in the design of this machine called PERLE, currently foreseen to be constructed at Orsay near Paris. In the US, the next facility on the Nuclear Physics roadmap is an Electron-Ion Collider. This project calls for the application of energy recovery in two contexts; as provider of the high energy colliding electrons, but also at very high currents to cool the circulating ion beams. The demonstrator for this project is C-BETA based at Cornell University, developed jointly with Brookhaven. ASTeC will be contributing to the commissioning and development of C-BETA.

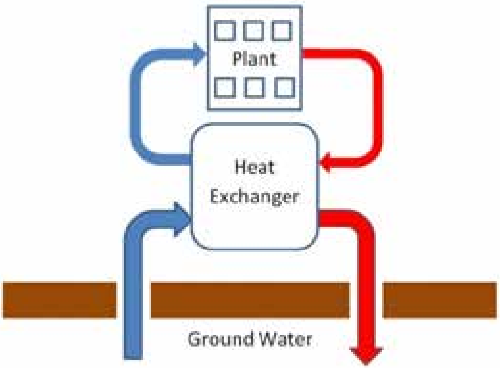


Schematic of a generic recirculating energy recovery accelerator with multiple arcs for different energy beams

Ground Water Cooling for Accelerators

One important consideration when planning a new particle accelerator is the on-going running costs, including the potentially high costs of the energy required for day-to-day operations. A key part of this energy requirement is the need to keep an accelerator at constant temperature using a combination of refrigerant based cooling systems and traditional air conditioning. The cooling systems effectively remove any excess thermal loads before they can adversely affect ambient temperature. Cooling of components such as magnets and collimators is therefore an important part of accelerator infrastructure and thus the pursuit for more energy efficient ways of achieving this goal can contribute greatly to operational efficiency and a reduction in running costs.

ASTeC staff, working with consultants from Envireau Water ltd, have proposed an energy efficient ground source cooling scheme. This project is funded through the STFC "Invest to save" initiative which has been set up to try to develop efficiency savings of this type. The project involves abstracting ground water from a borehole at a low temperature, pumping through heat exchangers which will cool the necessary plant and returning to the ground at an elevated temperature via another borehole located downstream.



Schematic of a typical ground water cooling system

Although energy is needed for pumping because of the requirement to generate a high water pressure, this is insignificant when compared to the potential savings which can be realised. For the proposed scheme at Daresbury, the ground water temperature is a virtually constant 12 °C all year round and the plan is to return the water at around 22 °C via the second borehole. The installation aims to provide up to 2 MW of cooling water to the CLARA particle accelerator and also to the Scientific Computing Department/Hartree Centre computer room(s). Currently both installations, at least in part, rely on the use of traditional refrigerant based water chillers to satisfy cooling requirements. These systems are relatively inefficient requiring around 0.25 kW of electrical input per kW of thermal load. This 'Green' scheme is projected to generate savings of £250,000 per annum (from year 5 onwards).

Although the project is still in its early stages a trial borehole has been drilled to a depth of over 240 m on the Daresbury Site. Initial stress testing has indicated an abstraction yield rate which is in line with the modelling expectations providing further evidence that the high level of predicted savings can be realised.

Drilling of the trial borehole underway at Daresbury

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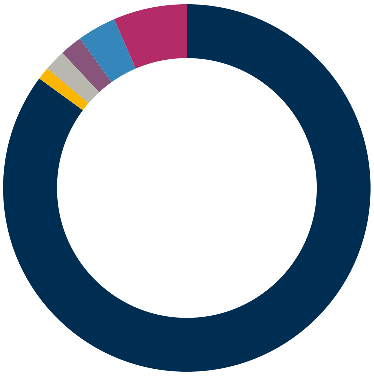
Finances

FINANCIAL SUMMARY 17/18

Activities 16/17

Income source	£K
STFC ASTeC core	£11,071
STFC other funding	£61
EU	£432
International Laboratories	£952
Industry	£305
Other (CI Grant and events)	£349
	£13,170

INCOME SOURCES

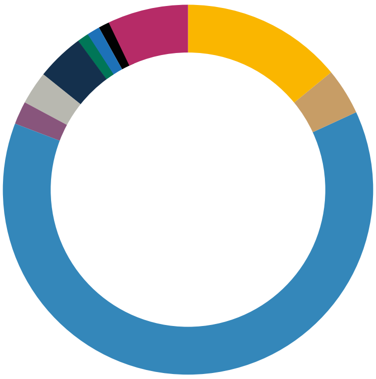


Expenditure Type	£K
Scientific & Engineering Staff Costs	£5,719
Consumables	£3,075
Capital Expenditure	£4,376
	£13,170

EXPENDITURE TYPE

Expenditure By Programme	£K
High Brightness Electron Accelerators	£1,858
EU Programmes	£485
CLARA Project	£8,318
VELA Project	£324
Cockcroft Institute & New Initiatives	£442
Underpinning Research	£580
UK_NF Programme	£195
Photon Studies	£123
High Power Proton Accelerators	£47
Other Repayment work	£897
	£13,170

EXPENDITURE BY PROGRAMME



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Boulby Mine, Cleveland.

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