ASTeC SCIENCE HIGHLIGHTS 2015 - 2016

Science & Technology Facilities Council

CONTENTS

1 FOREWORD

Once again we are proud to highlight the work of the ASTeC department has carried out across a broad range of accelerator physics and technology application areas. The department is focussed on delivering a world class programme of research and development to ensure that STFC continues to provide the science facilities that UK scientists require to stay at the forefront of their research fields. The department's work contributes to a wide range of UK national accelerator activities such as ISIS and the Diamond Light Source and to international projects including ELI-NP, SwissFEL and many of the programmes at CERN; for example the high luminosity upgrade of the LHC.

ASTeC's chief asset is the dedicated and highly skilled group of scientists and engineers who work to develop cutting-edge ideas and innovations across the accelerator field. Through their participation in a variety of challenging research programmes they continue to develop the skills and know-how to deliver the cutting edge facilities that will enable future world-class science in the UK and beyond. Through staff development programmes and our membership of the Cockcroft Institute we continue to play a leading role in the training of the next generation accelerator scientists and technologists. We also participate enthusiastically in public engagement with events such as the 'Big Bang' and 'Particle Physics Masterclasses' to try to encourage young people to enter the exciting field of accelerator science and technology.

Photon science for investigating chemical processes, materials and biological systems remains an important tool for state-of-the-art research and hence the development of Free Electron Laser (FEL) technology is a key development area for the department. As a source of high brightness short pulse length tuneable radiation, FELs open up areas of science which are not accessible to conventional sources. That in turn can lead to both new science areas for academics and new innovation opportunities for UK business, with potential industrial areas including chemical processing, drug development and energy security. STFC has developed a FEL strategy outlining steps to meet future FEL facility based research needs of a UK community. Towards this goal, ASTeC is leading the development of the CLARA test facility, which will allow new FEL schemes and technologies to be developed that should ultimately deliver an exceptional performance machine at reduced cost. As a result of the ambitious programme of FEL research we have, the country will be ideally positioned to build a world leading UK FEL facility in future years.

Progress towards CLARA this year has included the development of a new high repetition rate photoinjector, the finalisation of the phase II design and a focus on the creation of the high level software that will be needed to control such an advanced accelerator. Work has commenced has commenced on the significant upgrade of the electron hall which will provide the environmental stability to enable such a precision machine to achieve its technical targets. The CLARA project continues to attract interest from labs around the world, including SwissFEL and CERN in Switzerland, SLAC in the USA and INFN and FERMI in Italy.

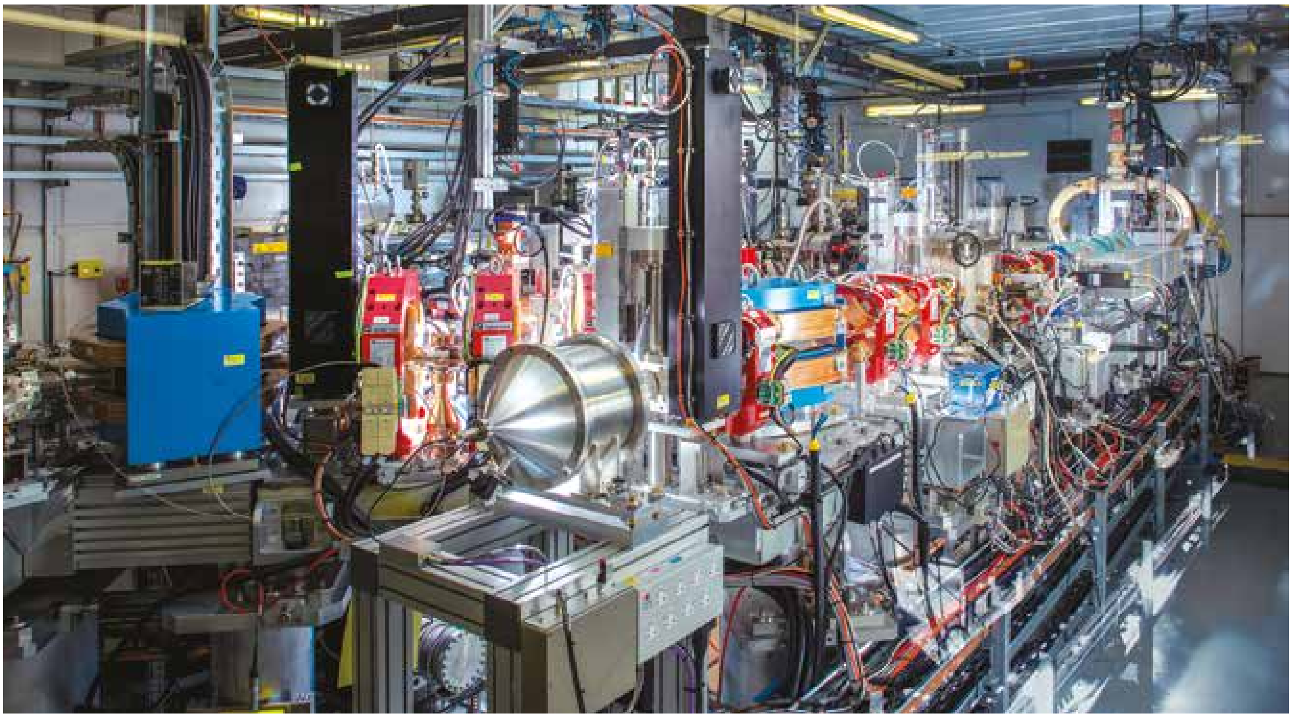
Alongside the development of CLARA ASTeC has continued to run the VELA electron beam test facility. A particular success this year has been the use of the Transverse Deflecting Cavity to measure the pulse length of the beam. Continued operation of the ALICE facility for diagnostic imaging of cancer cells has also progressed with significant improvements in image quality in the last run. This together with developments in magnet technology for medical accelerators demonstrates the important role that accelerator science and technology is having the health care sector. The department continues to underpin the development of next generation particle accelerators, with research including photocathodes as electron sources, non-evaporable getter coatings for improved vacuum performance and low secondary electron yield surface treatments to supress electron cloud formation. This not only helps to drive forward accelerator developments at Daresbury and facilities in the UK, but also is an important enabler for many of our collaborations worldwide.

As ever the advances reported in these highlights are only possible because of the excellent support received from our many collaborators, including the Technology Department at Daresbury, our partners in the Cockcroft Universities and others in various institutions worldwide. We would like to take this opportunity to thanks them for their contributions and we look forward to continuing to work with them in the future.

Professor Susan Smith
ASTeC Director & Head of Daresbury Laboratory

CLARA

Planning for a UK based X-ray Free Electron Laser



Installation of Phase 1 of CLARA has dominated work during the year.

In recognition of the UK's future science research needs by academia and industry, the STFC has prioritised an X-ray Free Electron Laser (FEL) as the next large scale national facility . This next generation light source will enable research on ultrafast processes with excellent spatial resolution. This is hugely important in a range of disciplines from catalytic chemistry to life sciences and pharmacology and will potentially lead to developments of significant economic and societal importance, such as novel catalysts and the design of new drugs.

ASTeC has a major role to play in the coming years to prepare the way for the design and construction of such an advanced new facility. This year we have taken the initiative by leading the formation of an R&D programme for the future new UK FEL, bringing together accelerator experts from ASTeC, The Cockcroft Institute, The John Adams Institute, and Diamond Light Source. An agreement has been reached on a clear set of R&D goals that will position the UK accelerator community to be ready to design and build the best possible X-ray FEL for the UK. The goals are focussed around key technology areas, such as the injector, diagnostics, and RF systems as well as around the primary simulation needs for the accelerator and FEL itself. At the heart of the R&D plan is the development of the CLARA FEL Test Facility at Daresbury Laboratory which is now well under way, with the first phase installation nearing completion.

CLARA is an essential step on the road to the UK having its own FEL facility. As a scaled down version of an X-ray FEL containing all of the key technical components, all lessons learned from CLARA can be directly applied to any future UK FEL. The key objectives of CLARA are: to develop new methods for improving the quality of the light output from FELs; prove new technologies; develop the skill base; give UK

FEL researchers global leadership; lower the total cost of a UK FEL; and lower the risks associated with UK FEL. In short CLARA will facilitate a superior and more cost effective UK FEL which will enable UK HEIs and industry to lead the world in research on ultrafast atomic and molecular processes.

CLARA is of great interest internationally as any new technique we prove or technology we develop can be applied to new and existing FELs. CLARA has established formal links with SwissFEL (PSI, Switzerland), LCLS-II (SLAC, USA), CERN, INFN (Italy), and FERMI@Elettra (Italy). Examples of these collaborations include:

- Switzerland has provided ~£1m of equipment for CLARA in exchange for future beam time access, and support from STFC expertise in the design of various SwissFEL systems and FEL commissioning.
- The US wants to use CLARA to develop new FEL concepts beyond the capability of their test facility.
- CERN and Italy are developing novel accelerator technologies for more cost effective FELs and would like to prove this technology on CLARA.
- Italy is leading an H2020 proposal to make use of CLARA for innovative accelerator developments.

This year has been focussed on the installation of Phase 1 of CLARA (gun and first linac) alongside VELA, procurement of Phase 2 (to the end of the accelerator) and finalising the detailed design of Phase 3 (the end of the FEL itself). In addition the Electron Hall building in which CLARA is situated is undergoing major refurbishment which will enable excellent temperature stability of the entire test facility; this is essential to achieve the design tolerances demanded by a state-of-the-art FEL.

CLARA will be a flexible test facility capable of proving a number of new FEL schemes and must be capable of a number of different operating modes. Staff in ASTeC have been carefully checking the accelerator layout to confirm that all of these operating conditions can be achieved. This has led to some subtle changes to the layout and component specifications which must be understood before procurement of major systems, such as the magnets and RF systems, can proceed. These issues are now resolved for Phase 2, though work continues on the exact detailed layout of Phase 3. This process of finalising the design so procurement can proceed is typical for such a complex accelerator system as CLARA. In the coming year the CLARA injector system will be commissioned while remaining components are manufactured and assembled offline.

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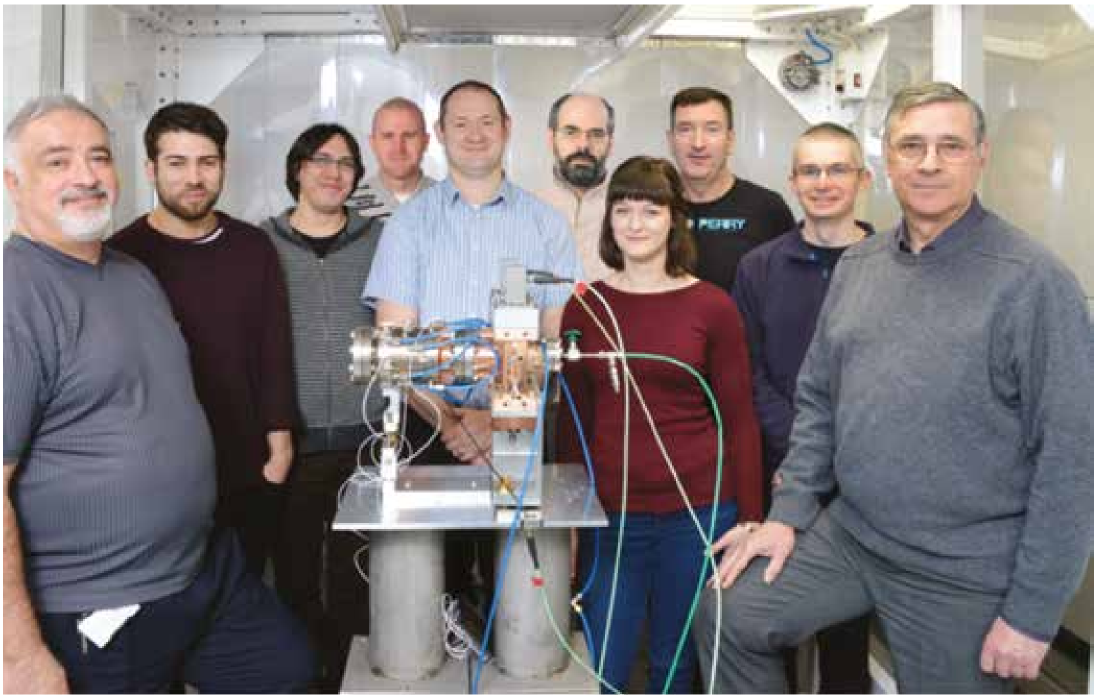
The refurbishment of the Electron Hall, which houses CLARA, in full swing.

High Repetition Rate RF Electron Injector for the CLARA/VELA accelerator test facility

Scientists and engineers at Daresbury Laboratory have developed a high brightness, high repetition rate electron injector to match the requirements of an envisaged UK X-Ray Free Electron Laser (FEL) facility. Designing and building a high repetition rate photo-injector for the CLARA FEL test facility at Daresbury has allowed scientists and engineers to research the challenges of creating extremely high quality electron beams with a combination of brightness and repetition rate, beyond those currently deployed on any normal conducting FEL facility in the world. 2015-2016 was the final for the project.

The project, comprising delivery of a 6.8 kW high power 1.5 cell RF cavity with a photocathode interchangeable via Load-Lock system and an advanced photocathode production system was successfully completed. The cavity is provided with high resolution thermal stabilisation system.



High Repetition Rate Injector development and commissioning team in the RF laboratory.

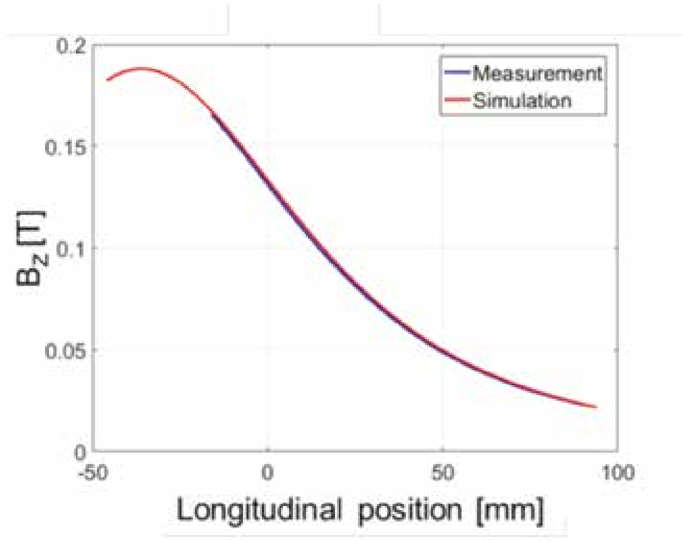
The photo-injector cavity has been designed by ASTeC and Technology Department with the Cockcroft Institute (Lancaster University) and the Institute of Nuclear Research in Moscow and has been manufactured by Research Instruments in Germany, with strong support from the ASTeC scientists. The cavity has now been delivered to DL and initial radio frequency tests confirm it achieves the challenging specifications. Due to the sophisticated tuning procedure developed at ASTeC and implemented during cavity manufacturing at RI, the measured parameters of the gun are very close to the design specifications. The quality factor of the cavity with a Molybdenum photocathode exceeds 13,000 with a field flatness of more than 98%. The required value of resonance frequency of 2998.5 MHz is reached at an operation temperature of 48 °C; that is only 2 °C less than its design value of 50 °C.

The injector RF cavity upon delivery at Daresbury Laboratory

As the required field phase stability in the gun cavity is less than 100 fs RMS, its temperature should be maintained with a stability of better than 0.009 °C RMS. This will be provided with a precision multichannel water thermostabilisation system developed at ASTeC. The operating temperature will be maintained by mixing hot and cold water in a duel valve cascade. The water will be heated with an electronic process heater and the temperature maintained to within 1 oC. It will then be mixed with cold water via a 3-port control valve to approximately one degree below the required control temperature of 50 °C. This water will then be mixed through a second 3 port control valve with hot water from the heated circuit to control to the set point. Each channel on the cavity has its own remotely operated flow regulating valve to separately control the flow giving the ability to match any variations in load around the cavity shown by any of the eight PT100 temperature sensors.

The magnetic system of the gun consists of a pair of coaxial, water-cooled solenoids – the main focusing solenoid and the bucking solenoid. The solenoids are magnetized in opposite directions such that the fields they generate at the location of the cathode cancel each other out. The bucking solenoid is stationary and the main solenoid is capable of translation towards and away from the cathode plane. Whilst the main solenoid was available from another project, the bucking solenoid had to be designed, built and tested. It relies upon an asymmetric steel yoke that shifts the peak axial field away from its geometric centre towards the cathode to allow for a more efficient use of the available ampere-turns. The magnetic system will be operated at variable solenoid currents and at variable separation between the solenoids to produce optimum parameters for the emitted beam.

Before installation both solenoids were extensively tested, both when operating alone and simultaneously and were found to perform exactly as expected. In order to provide high degree of alignment between two solenoids they are mounted on one bench and prior installation aligned off-line in the ASTeC magnet laboratory.



Two solenoid focusing system in the magnet laboratory (left) and comparison of simulated and measured values of the longitudinal magnetic field in the bucking solenoid (right)

In the course of last year, a Photocathode Preparation System, which is based on the ESCALABII analytical facility, was reconfigured to prepare photocathodes for the new electron injector. The photocathode plugs, which are machined from a block of molybdenum and whose emission tip and outer body are polished to nm flatness, are degreased and will be introduced to Metal Photocathode Preparation Facility (MPPF) via a vacuum transport vessel which can hold up to four photocathodes. The MPPF comprises two separate chambers, each being pumped to vacuum of 10-10 mbar. The first chamber is a preparation chamber, which has surface cleaning component such as hydrogen gas cracker and low energy ion flood gun to remove any residual hydrocarbon and surface oxides. The cathode can then be deposited with other predefined metals with lower work function than molybdenum such as copper or magnesium to yield a higher Quantum Efficiency (QE). The films can be synthesised with magnetron sputtering and the deposition conditions can be varied to yield a dense or columnar structure.

After deposition, cathodes are introduced into the analysis chamber where they can be fully characterised in terms of surface composition and chemistry with X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES) as well as making measurements of surface work function using UV photoelectron spectroscopy (UPS) and a Kelvin Probe (KP). The QE of the prepared cathode is measured with a 266 nm UV laser. Cathodes can then be transferred back to the ultra-high vacuum transport vessel so they be transported the photoinjector Load-Lock system.

Photocathode preparation system: a - analytical chamber, b-deposition chamber, c- photocathode transport vessel.

Molybdenum photocathode plug

In addition to the previously mentioned collaborators, substantial assistance to the project was also provided by DESY (Germany), LASA-INFN(Italy) and LBNAL and FNAL (both USA).

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High Level Software Development: Software Improvement Plan

Controlling hardware, data acquisition and analysis is a fundamental requirement of owning, operating and experimenting on a particle accelerator.
Having good software to accomplish that should improve the performance, reliability and repeatability of such machines, increasing their impact. ASTeC has identified a need to have a broader range of higher level software capabilities, especially with regards to machine operations. To improve things over the longer term a more coherent approach to application development is required that will help and encourage people to get involved. Therefore, a series of workshops have reviewed the current state of affairs and concluded:

- Good software development is essential for operating a well-run machine
- There are many people with a limited to zero software development experience
- There is no one size fits all solution, everyone has their personal preferences
- Applications tend to be written by self-motivated people using different tools
- Development is often ad-hoc to achieve a short term result, resulting in a lack of long term planning and often resulting in solutions that cannot be extended or easily adapted to new situations

Based on the conclusions a number of decisions were made:

1. Limiting the number of languages to Python and c/c++.

2. Implement a two phase plan: the Software Improvement Plan with the aim of standardising tools and increasing participation in application design.

Phase 1: Standardised Hardware Interfacing - An application programming interface (API) was developed, to be used by everyone, that forms the foundation of any 'conceivable application' required for machine operation. The API is a suite of python modules, built on a robust c++ source, allowing easy communication with the main types of hardware controlled and monitored through the EPICS control system: magnets, cameras, RF, BPMs, charge monitors etc. Each module provides a set of simple, human readable function names and parameters that completely screen end-users from the intricacies and peculiarities of lower level systems. For example, the magnet module function 'degauss' knows how to degauss each magnet type. Constituted this way the API should increase the participation in application development by allowing end-users to concentrate on the procedures, data analysis and the physics.

Phase 2: Application Development Using the API - In the time the API was built efforts have concentrated on implementing it through a series of GUI based control room applications written by a broad selection of staff. These applications will handle the main day-to-day operational tasks, such as beam orbit set-up, feedback, monitoring and characterisation methods ensuring consistent methods and best practises followed.
This phase is still being implemented and will take a number of years to complete.

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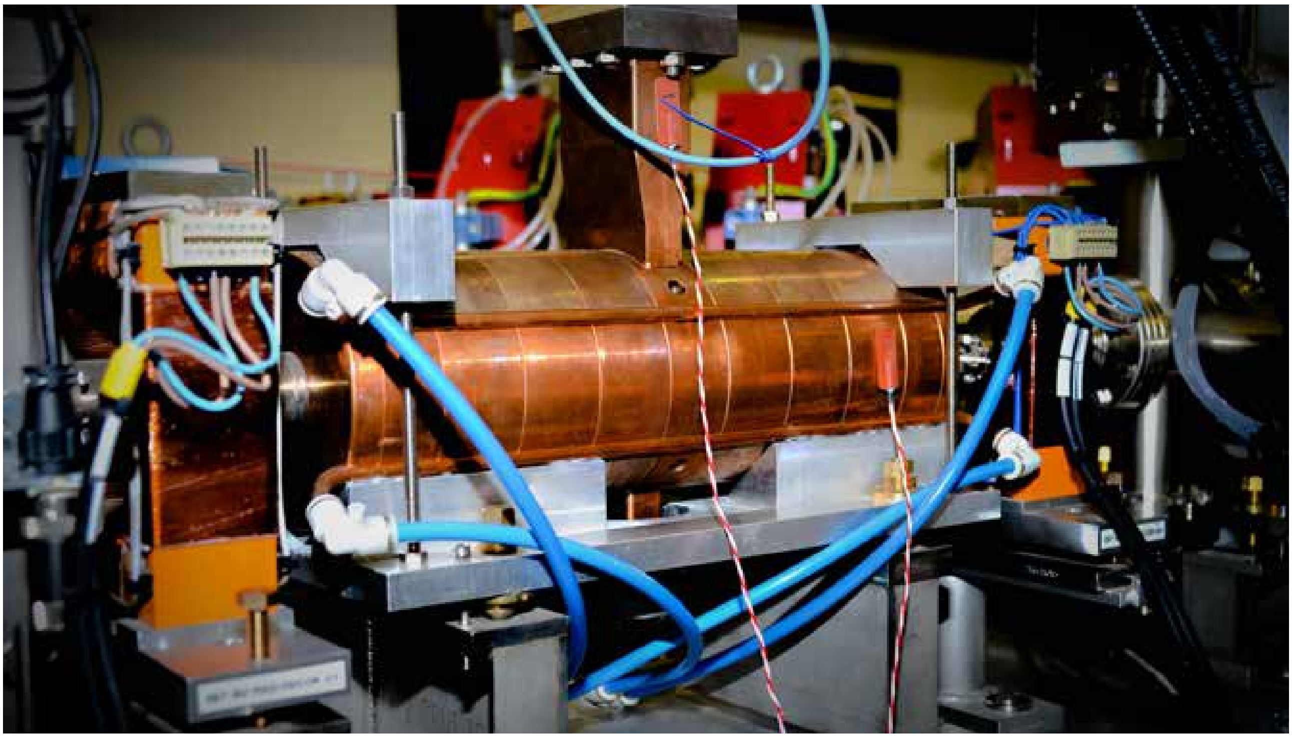
Electron Bunch Length Measurements with the VELA Transverse Deflecting Cavity

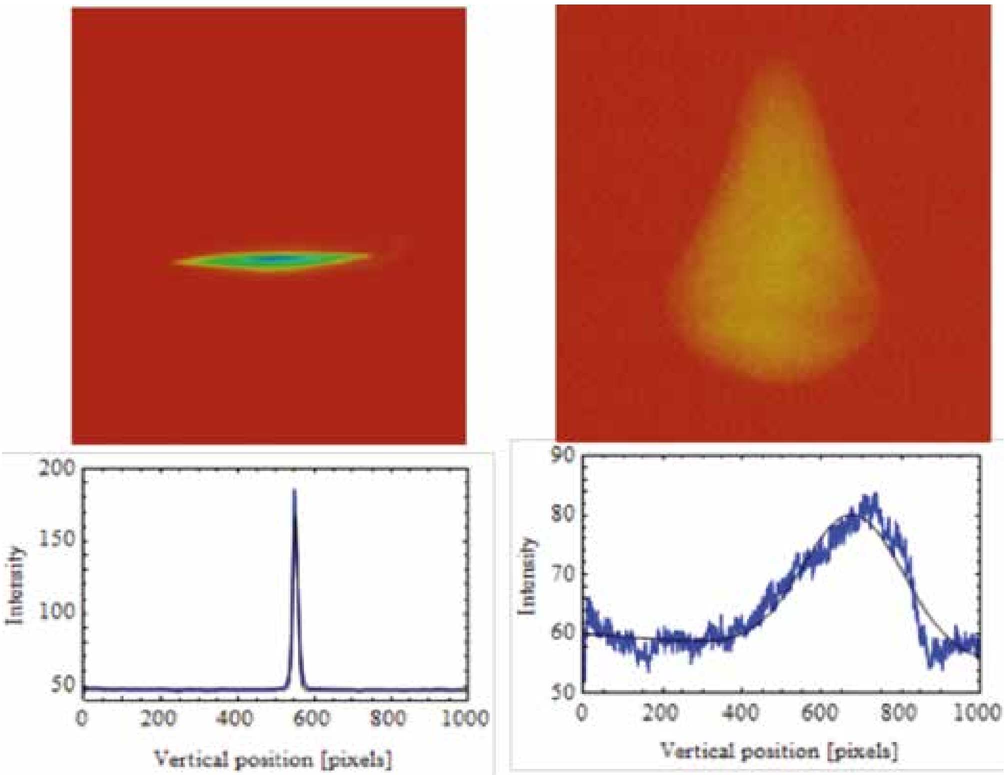
A 9-cell, S-band transverse deflecting cavity (TDC) has been designed and installed onto VELA for the purposes of measuring the bunch lengths down to sub-picosecond levels. Last year the cavity was installed on and commissioned with high power RF up to 5 MW; this year the first measurements were performed to characterise the electron beam from the VELA photoelectron gun. The TDC works by imparting a vertical deflection to particles dependent on their time of arrival to the cavity. The electron bunch length can be re-constructed from the vertical beam profile on a screen downstream of the cavity.

VELA uses a drive laser with pulse length 180 fs FWHM. In this mode the electron beam operates in the so-called 'blow-out' regime where space charge forces cause the beam to expand longitudinally directly after being emitted. Measurements were taken to characterise this regime (see figure) which showed the bunch length varying from 0.9 ps at 2 pC bunch charge up to 3 ps at 215 pC, in agreement with simulation trends. Further measurements were taken at the very low charge regime, which showed electron bunch length down to 190 fs at 60 fC.

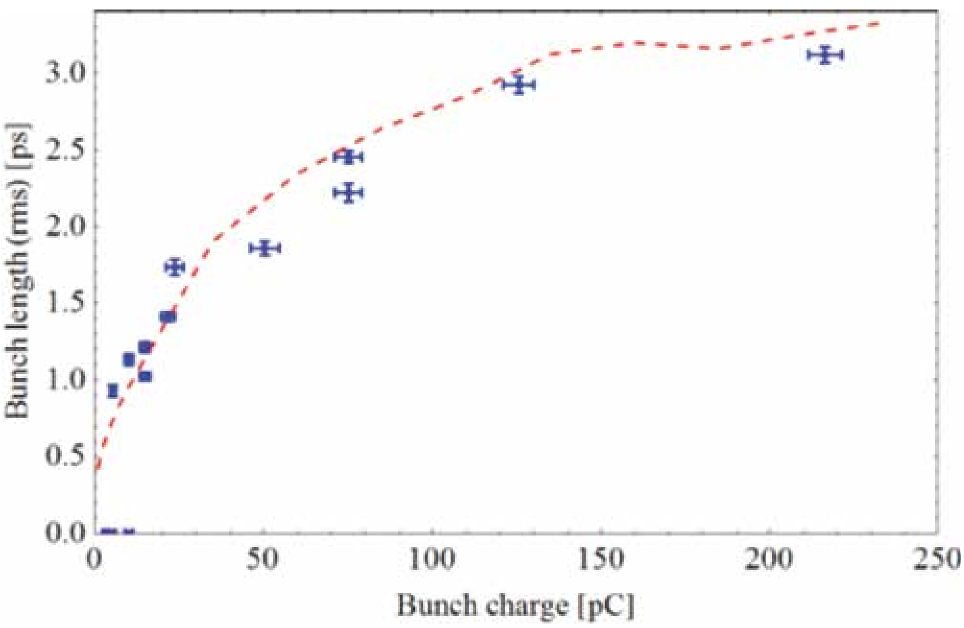
In addition to measuring the bunch length and temporal profile, the TDC can be used in conjunction with momentum spread and transverse emittance measurements to measure how those properties vary along the length of the electron bunch. This is important for free electron lasers as only the portions of the bunch with the correct slice properties will generate light. An iteration of this cavity design will be used on CLARA to diagnose the beam both before and after the free electron laser down to 10 fs resolution.



The Transverse Deflecting Cavity installed on VELA.



Example images of the beam with the TDC off (left) and with the TDC on (right) giving it the vertical streak in proportion to the electron bunch length. The lower plots show the vertical projections with Gaussian fits.



Dependence of the bunch length in VELA as a function of charge, measurements (blue crosses) against simulations (red dotted line).

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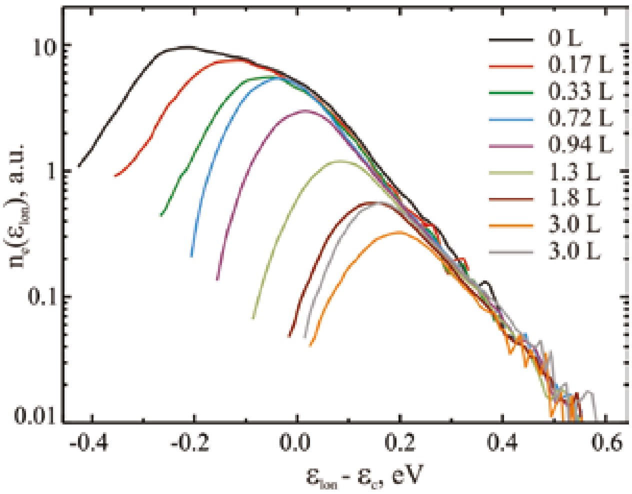
Photocathode Research and Development

Underpinning research into photocathode materials for use in next generation electron accelerators continues to play an important part in ASTeC's portfolio of scientific investigations. Improving photocathode performance is important to ensure performance, consistency and reliability of operations and thus minimise down time reducing the running cost of an accelerator. This year the focus has been on exploiting the targeted suite of advanced analytical equipment which the department has assembled for this work. In addition, significant modification has been made to some of the systems to increase the capability to investigate a wider range of materials and evaluate them in a 'real' accelerator environment. Meanwhile progress continues to be made on the theoretical modelling of photocathode materials in collaboration with researchers at Imperial College.

TESS – The Transverse Energy Spread Spectrometer, which can measure both transverse and longitudinal energy spread, has been used to characterise III-V photocathode materials, including for the first time GaAsP, which is an alternative to GaAs giving lower initial quantum efficiency but much greater resilience to degradation from residual gasses in the vacuum system. The system has been additionally enhanced through the addition of a white light source based on a high luminosity Xenon lamp.
Using a monochromator a range of wavelengths from 255 nm to 1.1um can now be accessed. This new capability has been qualified by measuring the transverse energy spread of a GaAs photocathode as a function of the wavelength with the results showing the expected dependence.
The system is now ready to analyse samples requiring higher energy (UV) photons including Cu, other metals and Cs2Te. Research on metal photocathodes will be important in supporting the VELA and CLARA accelerators at Daresbury.



Evolution of the longitudinal energy spread of a GaAsP photocathode with exposure to O.

Multiprobe system – The multiprobe surface analysis system has been upgraded with the addition of a compact UV laser system, similar to that on our ESCALAB Mk. II system, which provides higher luminosity to aid in the measurement of quantum efficiency. In addition, a new controller for the atomic force microscope has also been replaced to ensure the continuing availability of this important technique for characterising surface morphology. The system has continued to provide data on metal and metallic thin film cathodes, with studies this year including Cu, Zr and Pb thin films deposited on both Cu and Mo substrates using magnetron sputtering. Quantum efficiency measurements have shown that it is essentially independent of the substrate used with the best values being obtained for Pb films. It is hoped that thin film deposited photocathode will be usable in the VELA and CLARA accelerators sometime in the near future.

ESCALAB Mk. II – This instrument has been completely rebuilt this year in order to make it compatible with the photocathode pucks which will be used in the VELA and CLARA accelerators. A cathode puck transport system has been designed, fabricated and tested and the instrument has also had a new preparation chamber added in addition to the pre-existing analytical chamber for sample characterisation. This new chamber incorporates facilities for sample cleaning including sputtering, annealing and atomic hydrogen cleaning and two new magnetrons for thin film growth. A vacuum suitcase arrangement is provided to allow photocathodes prepared in this system to be introduced into the high repetition rate gun being developed for CLARA. This upgrade will provide a virtually unique capability to evaluate a wide range of different photocathode materials in a 'real' accelerator environment.

Theory Collaboration – This collaboration with Imperial College has continued to progress with further modelling of Cu and other metal photocathodes. An important development this year has been to extend the studies to much larger models, which has required the use of high performance, multi-processor computers, as the computing time typically scales with model size.
The advantage of larger models is that it enables the evaluation of the effect of lower coverages of adsorbates, such as O, H and Cs, on both the work function and ultimate quantum efficiency. It is also hoped that the larger model size will allow the effect of surface roughness to be evaluated in the near future.

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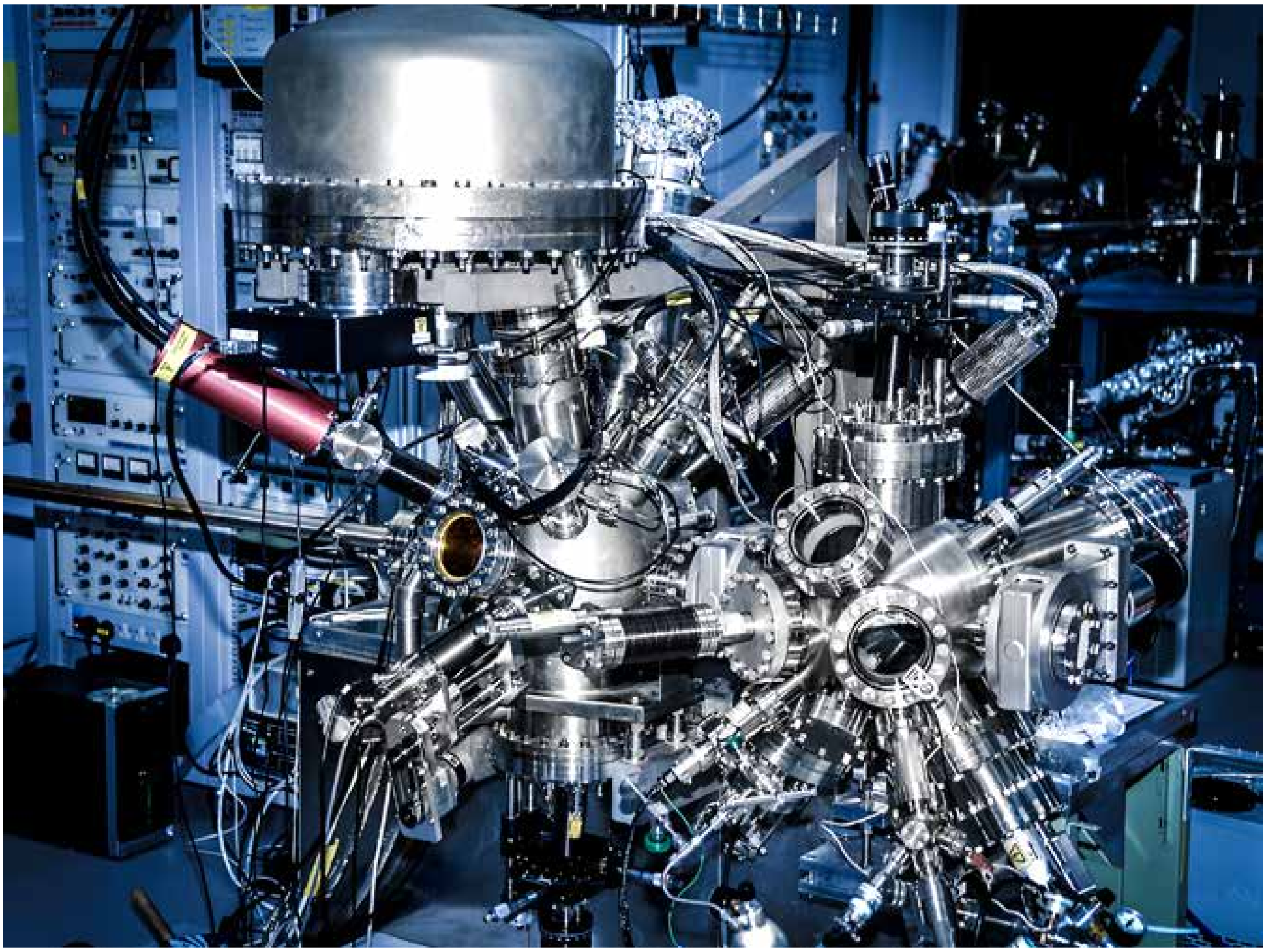

The modified ESCALAB Mk. II instrument.

Secondary Yield Measurements of Laser Treated Surfaces

The electron cloud and its negative impact on beam emmitance of positively charged beam machines were discovered over 50 years ago. Since then scientists and engineers in many research centres have sought various mitigation techniques. Among those techniques the reduction of secondary electron yield (SEY) of vacuum chamber walls is a very effective way of mitigation of electron cloud (e-cloud) and electron multipacting.
In previous work we have demonstrated that SEY can be efficiently reduced by surface engineering through laser ablation. The major limitation of our original treatment was high surface resistance, therefore the further work aimed at producing low SEY surfaces with a smaller increase in surface resistance (R_S).

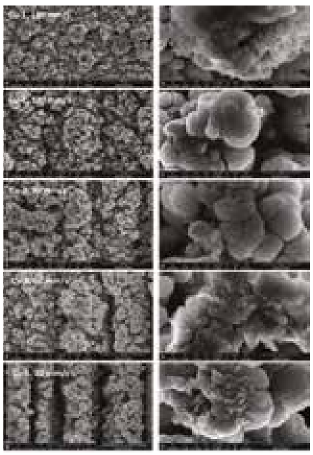

Figure 1: Low (on the left) and high (on the right) resolution planar SEM micrographs of 1-mm thick Cu samples treated with laser.

New samples were made of oxygen free copper (Cu), aluminium (Al) and 316LN stainless steel (SS) plates, cleaned treated using a Coherent Aviva NX laser. The low and high resolution planar scanning electron micrographs (SEM) of treated Cu surfaces are shown (see figure). The laser treatment resulted in a topography that consists of a microstructure of grooves superimposed with submicron and nanometre sized structures. These grooves were much shallower than previously demonstrated elsewhere.

The SEY measurements were performed after installing and overnight pumping in the dedicated facility for SEY study in ASTeC vacuum laboratory. The results of SEY measurement of Cu as a function of primary electron energy, Ep, are shown in Fig. 2. Sample Cu-3, treated at 90 mm/s, has the lowest or equal lowest SEY over the measured range of primary electron energy. A lower scanning speed of 60 mm/s (sample Cu-4) results in an increase of SEY at low primary electron energy. Con-versely, a higher scanning speed of 120 mm/s (sample Cu-2) results in the increase of SEY at high primary elec-tron energy. The further reduction of scanning speed to 30 mm/s (sample Cu-5) and increase to 180 mm/s (sample Cu-1) both result in further increases in SEY over the entire measured range of primary electron energy. The results of this and our previous study show that laser ablation surface engineering has a large window of laser treatment parameters to produce different types of surface topography which reduces SEY below 1. For all three materials studied (Cu, Al and SS), laser ablation can pro-duce surface topographies which can reduce the SEY to below or near 1. In all cases, the processing applied re-sulted in a grooved topography, on which is superimposed submicron and nanometre sized structures.

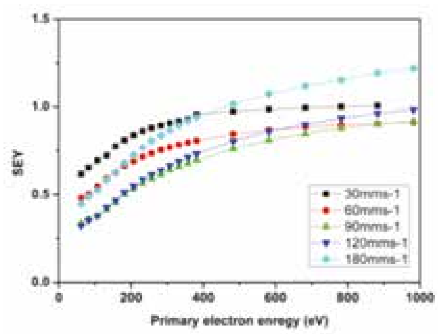

Figure 2: SEY measurement of Cu samples as a function of primary electron energy.

The surface resistance of the samples was measured with a 7.8 GHz circular choked pill-box cavity. The re-sults show that the surface resistance reduces with laser scan speed, which is directly associated with the depth of the grooves.

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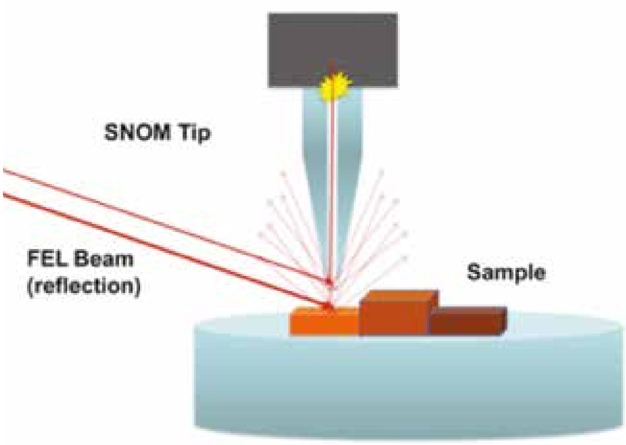
Cancer Research with ALICE: New Imaging Methods for Medicine

Remarkable advances have been made in the diagnosis and treatment of cancers. Cancer Research UK reports 10 year survival rates in England and Wales of 50% across all cancers, but this varies quite drastically from around 80% for prostate and breast cancers down to 12% for oesophageal cancer*. The key to improving survival is early detection; this requires good diagnostics coupled to screening programs and promotion of early presentation of cancer symptoms at clinic level.

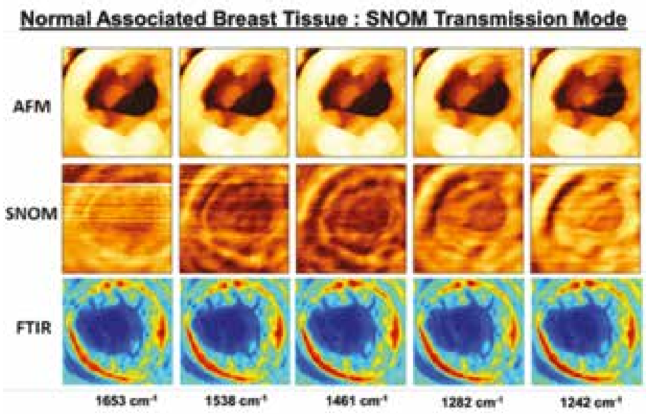
Prof. Peter Weightman leads a team of scientists from the Universities of Liverpool, Lancaster, Manchester and Cardiff and clinicians from the Christie, Lancaster and Liverpool NHS Hospital Trusts exploiting the ALICE accelerator facility at Daresbury to image the chemical structure of cancerous tissue. These groups have complementary expertise in the diagnosis and treatment of breast, cervical, oesophageal and prostate cancer.



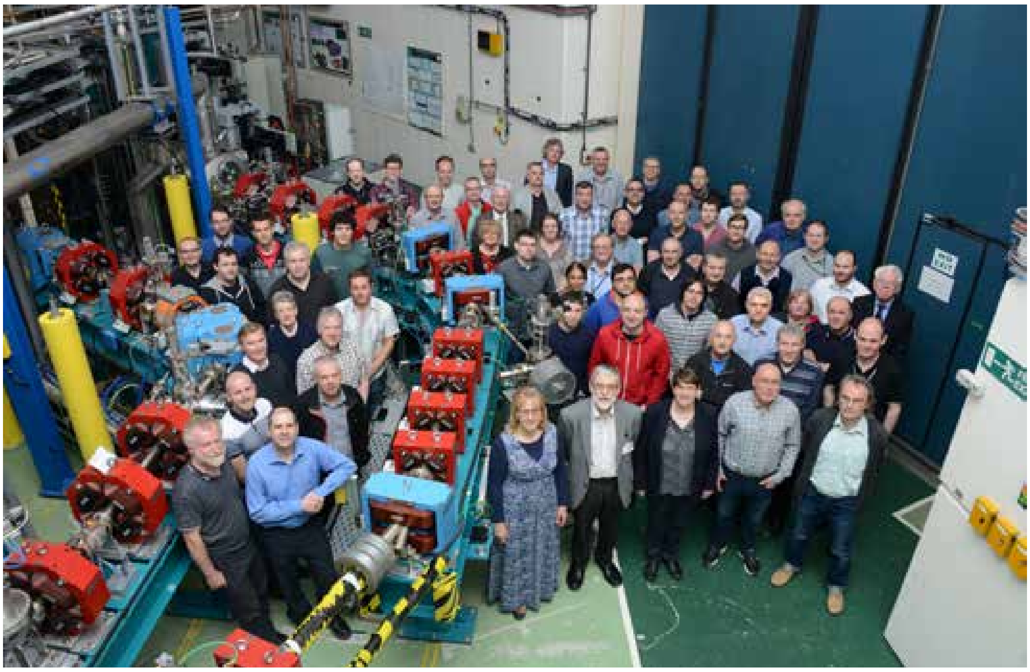
Schematic of the SNOM instrument. The aperture of the SNOM tip is typically 0.1 microns diameter and therefore detects the local absorption of infrared light with sub-micron spatial resolution, below the diffraction limit.

The spatial resolution of conventional microscopy is limited to the wavelength of light used - the so-called diffraction limit. Infrared microscopes operating with light of a few microns wavelength will therefore provide a spatial resolution of microns, while optical microscopes at shorter wavelength provide sub-micron resolution. The infrared microscope however has the advantage of providing a chemical map by exploiting the local absorption characteristic of the particular chemical structure at that point. The high intensity infrared light from the ALICE FEL coupled into a SNOM microscope (see caption) provides a significant benefit to scientists and clinicians by simultaneously combining both sub-micron resolution (below the diffraction limit at infrared frequencies) and chemical contrast in determining the composition of tissue samples.

The spatial resolution obtained in practice depends on the type of sample and the infrared source stability. Considerable R&D by ASTeC has minimised wavelength and intensity variations in the FEL output; world leading stability has been achieved, allowing extremely high quality SNOM chemical mapping of human tissue samples provided by pathologists.



70µm x 70µm area of normal breast tissue imaged by the combined AFM / SNOM microscope obtained by Prof. Gardner and colleagues from the University of Manchester



Celebrations to mark the end of beamtime on the EPSRC funded cancer diagnostics program. Lead scientist Dr. Michele Siggel-King (immediately on the right of the accelerator on the front row) standing next to project lead Prof. Peter Weightman, with members of the ALICE team.

A number of infrared microscope techniques have been evaluated in this program. Some provide ultra-high spatial resolution with others providing high throughput. It is expected that such techniques will become increasingly important in screening. The ALICE FEL combined with advanced SNOM developments has enabled chemical images of healthy and diseased tissue to be obtained with a significantly higher degree of detail than on a laboratory-based infrared microscopy system.

ALICE started life as an accelerator test facility but has provided the UK with a remarkable resource for cancer research. ASTeC have proposed design modifications which would allow ALICE to operate as a turn-key FEL light source with much lower running costs, dedicated to such research programs.

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* http://www.cancerresearchuk.org/health-professional/cancer-statistics

ALICE Digital Low Level RF Systems (LLRF)

During 2015 the LLRF team installed digital LLRF on the ALICE superconducting LINAC. This was the culmination of 5 years of research and development, and covered the areas of oscillator and clock design, low noise amplification, the study of environmental factors that affect RF components and cables and the programming of field programmable gate arrays (FPGA) with software that could regulate the field in superconducting cavities with external quality factors of 107 and a bandwidth of 200 Hz.

Two methods of cavity control where tested during this period. The self-excited loop (SEL) uses the cavities natural frequency to create an oscillator, with the LLRF effectively locking to the cavity frequency. This method of control is very good under noisy environments, as the system will follow whatever happens to the cavity. It is also very useful when performing cavity processing, where numbers of cavities need to be operated all with slightly differing frequencies; with such a small bandwidth this control method easily locks on to the cavity without the need for frequency tuning.

The second method is generator driven regulation (GDR) which is used to accelerate particles in our machines. This method takes its main signal from a very low noise stable oscillator and the LLRF drives the cavity in a phase locked loop to lock the cavity to the oscillator signal. Obviously the cavity and the oscillator need to be very close in frequency for this process to start and be maintained. It is this control loop that was used in the ALICE LLRF system on the LINAC. When the cavities where at 2 K for the first time in January 2015, the LLRF was optimised to provide controlled filling and stable operation at 10 MV/m for each of the LINAC cavities. The machine went into operation conditions a short time later and the stability and reliability of the digital LLRF was exceptional, with no coupler trips due to the controlled filling algorithm and very stable machine operation over months of machine time.

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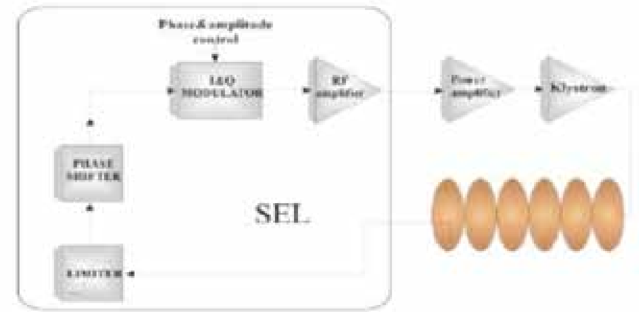

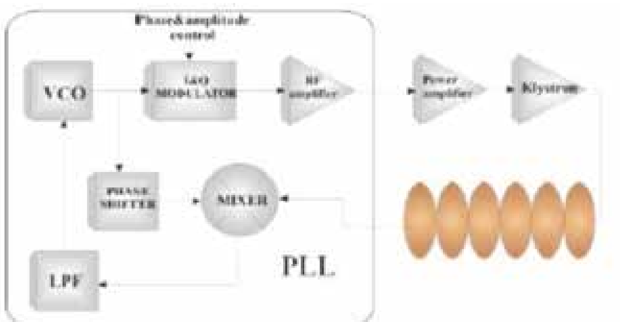

Magnets for cancer therapy

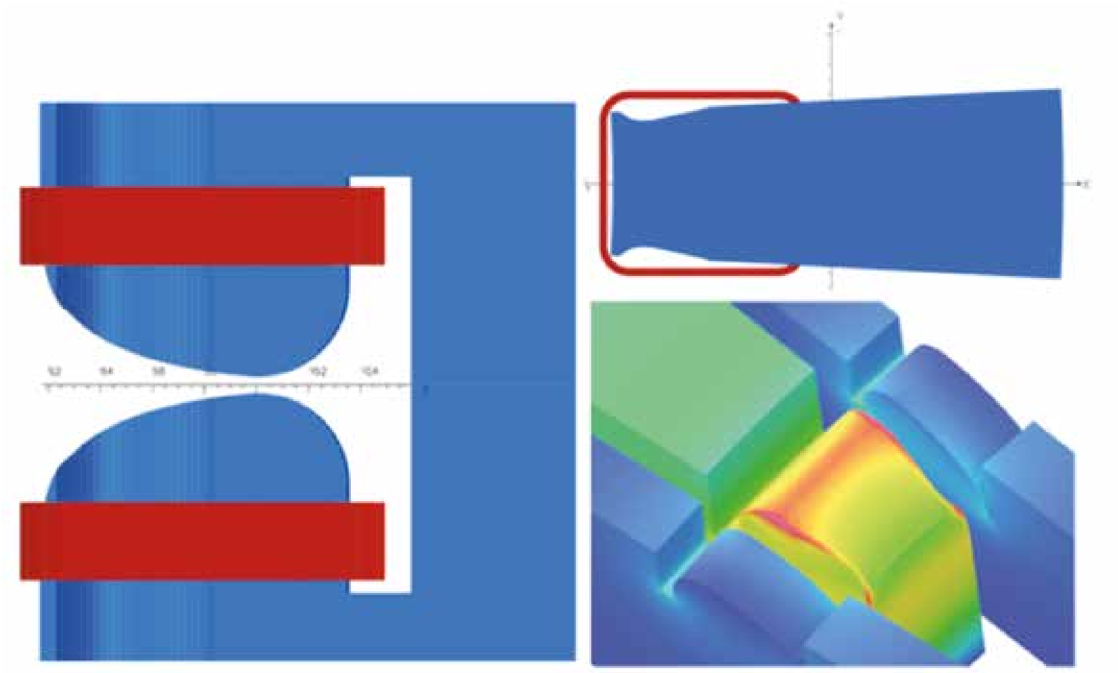

Figure 1: One of the NORMA magnets. (left) Pole area viewed from the side. (right) Magnet viewed from the top, without the clamping plates (top). Pole area with the clamping plates (botom).

Over a 100 000 people undergo radiation therapy for various types of cancer every year in the UK. Traditional radiotherapy relies upon beams of energetic photons (X-rays) generated by electrons decelerating upon impact with a metal target. The dose deposition mechanism of an X-ray beam is such that a relatively broad absorption peak is formed near the surface of the tissue and then the dose decays by following a nearly exponential law. This means that both the tumour and the adjacent healthy tissue are subjected to radiation damage. This is not optimal for tumours that are relatively far from the surface of the tissue. In addition the radiation damage to healthy tissue can even cause secondary cancers, particularly in children. An alternative approach is to abandon photons altogether and replace them with charged particles such as protons, or heavy (e.g. carbon, boron or neon) ions. Charged particle therapy takes advantage of the Bragg peak, a mechanism where the peak of the dose is located deep inside the tissue.

Thus by adjusting the relevant parameter values accordingly the tumour can be more accurately targeted without damaging the nearby healthy tissue and organs. Accelerating protons to energies in excess of 250 MeV requires specially designed accelerators that are suitable for clinical use.

NORMA (NOrmal-conducting Racetrack Medical Accelerator) is a proton accelerator currently being considered by scientists from the Cockcroft Institute. It accelerates protons from 30 MeV to 350 MeV – higher than any dedicated proton therapy machine to date. Energies above 250 MeV and up to 350 MeV are needed for proton computed tomography. NORMA is a scaling fixed-field alternating gradient (FFAG) – a type of machines that were first considered in the 1950s. These accelerators require extremely complex magnets that are difficult to design and for this reason the concept was abandoned. At present the availability of both sophisticated CAD simulation tools and considerable desktop computing power has stimulated the re-emergence of FFAGs.

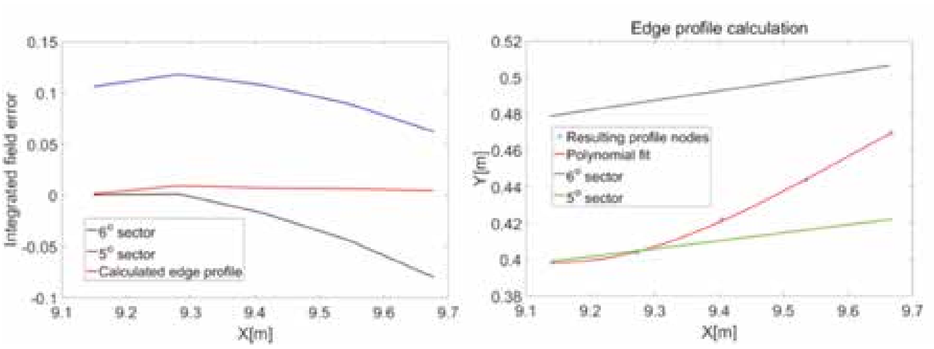

Figure 2: Magnet edge optimization process. (Left) Field errors resulting from three different magnet shapes – a 5-degree, 6-degree sector magnets and from a specially computed edge shape. (Right) The resulting magnet edge shape is shown in comparison with a 5 and 6-degree sector-shaped magnet.

FFAGs offer a number of advantages, which make them suitable for charged particle therapy like increased reliability due to fixed field operation, variable-energy operation with repetition rates of up to 1 kHz, ability to reach 350 MeV and beyond.

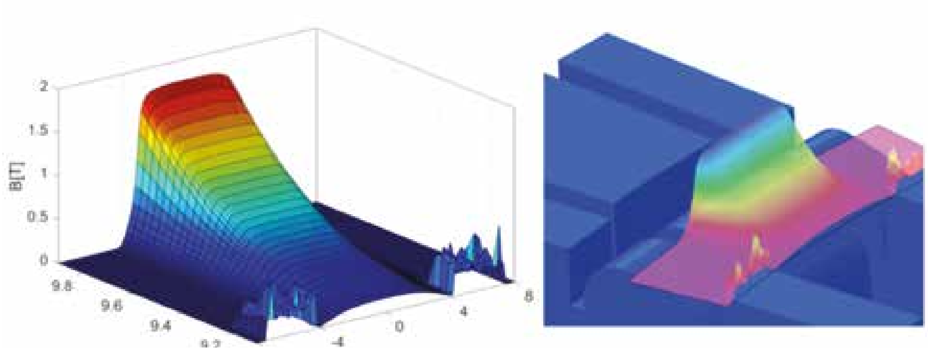

Figure 3: Field generated by a NORMA magnet (Left) A Surface plot of the field in the central symmetry plane. (Right) A surface plot superimposed onto the pole area.

In the case of NORMA an additional benefit is that the machine does not need super-conducting magnets and relies on normal-conducting technology instead, which adds to its reliability and lowers the overall cost of the project. As NORMA is a scaling FFAG it needs two types of complex combined-function magnets with large apertures in order to cover the entire energy range of interest. In addition, at the stage at which the lattice layout is designed the magnetic field is known only approximately. Realistic magnetic field distributions can be obtained through magnet design work and rigorous finite element simulations. This is the aim of the present study.

The MaRS group of ASTeC has been asked to perform a feasibility study of the magnets that generate the field needed to maintain the protons circling inside the accelerator and one of the resulting designs is shown in Fig. 1. The pole shape (left-hand side plot on Fig. 1) is obtained through an iterative optimization procedure whereby the field error (the difference between the desired field profile and the field actually obtained) is used to calculate a correction to the current pole shape and the field it generates is then used to calculate the field error. This procedure was iterated in 2D until accuracy better than 10-4 was obtained and to speed up the process the optimization procedure was automated. The resulting pole shape was then extruded in 3D to create an actual magnet and the magnet edge (Fig. 1, top right plot) was then calculated by using an optimization procedure illustrated in Fig. 2. Again the field error generated by two straight pole edges (Fig. 2, left plot) was used to calculate the pole shape that would minimize the error by using a procedure similar to the Newton-Raphson algorithm. Fig. 3 shows the obtained field distribution in the central symmetry plane of the magnet. The accelerator performance with the obtained field distributions is currently under investigation.

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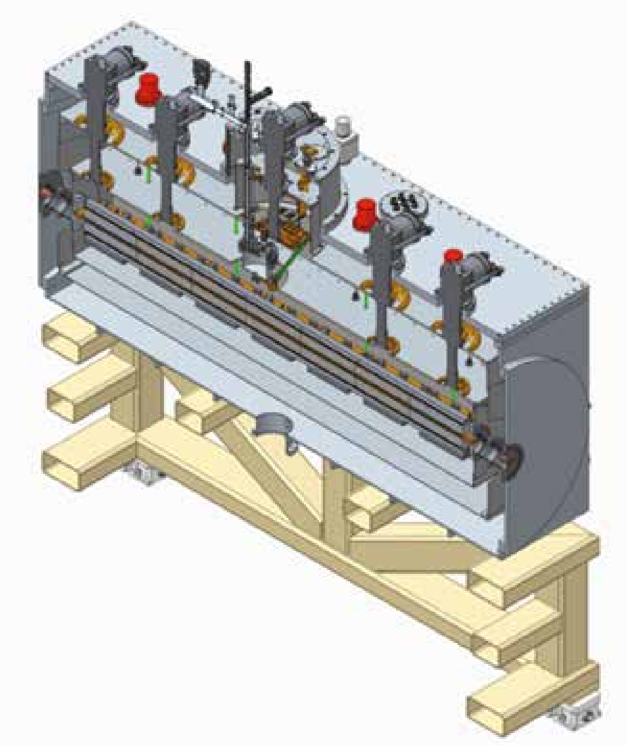
Superconducting Undulator for Diamond Light Source

Development has continued in 2015/16 on a superconducting undulator (SCU) for Diamond Light Source at Rutherford Appleton Laboratory (RAL). This ambitious project aims to develop a short-period, high-field, 2m long undulator that would generate high-brightness beams of X-rays with a range of photon energies from 2-40 keV.



A cutaway view through the cryostat, showing the undulator in the centre. The Diamond beam goes through the vacuum chamber in the centre, shown in orange, and the undulator is split into seven sections surrounding the chamber.

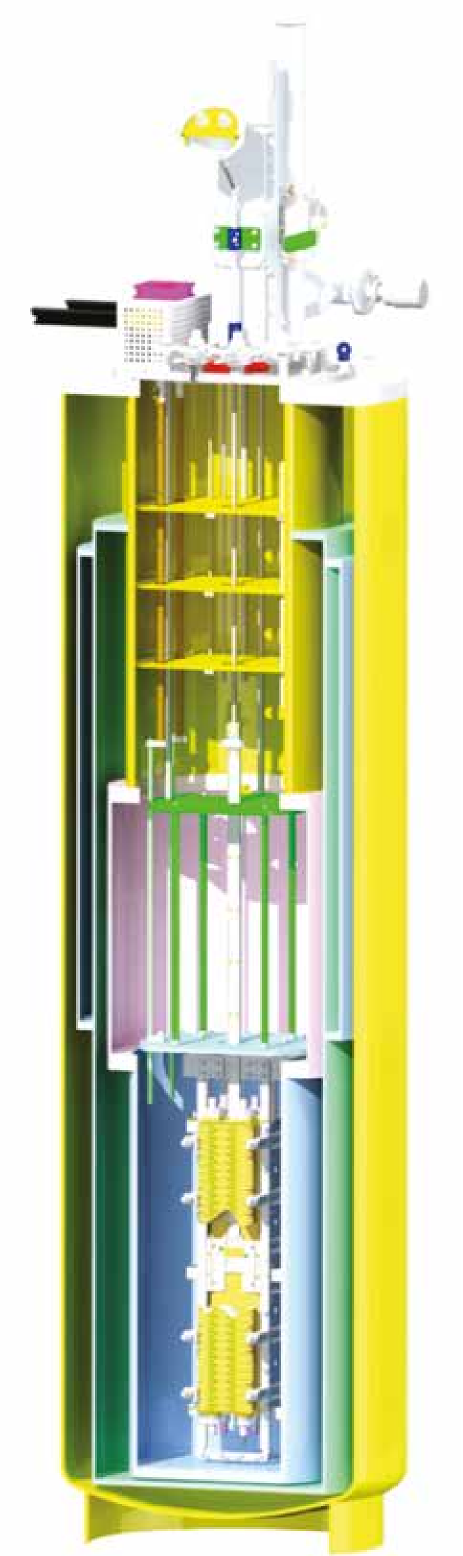
There are many challenges faced by this project. The whole undulator must be cooled to 1.8K in order to support the high currents in the superconducting wires. These wires are wound around a set of 30 cm long steel formers. The field quality in the undulator – measured by the phase error – determines the quality of the photon beam produced. This undulator has a very demanding requirement that the phase error should be no more than 3°. To achieve this, both the position of the wires and the steel formers must be very tightly controlled.

Experts from ASTeC's Magnets and Radiation Sources group have analysed the design of the undulator, examining the tolerances on each part of the steel former and the placement of the coils. The tolerance of each element has an effect on the overall phase error of the undulator, which has an impact on the quality of the photon beam emitted when the device is installed on Diamond. By performing this analysis, it is possible to work out which tolerances should be tightened, and which (if any!) is possible to relax.

The project overall is progressing well. Several short prototypes have been built, wound with superconducting wire, impregnated with insulating resin (potted), electrically tested, and finally cut into sections so that the metrology lab can assess how well the tolerances have been met. The former is built from a solid piece of steel and grooves are cut into it – this ensures the coils can be placed with the highest possible precision.

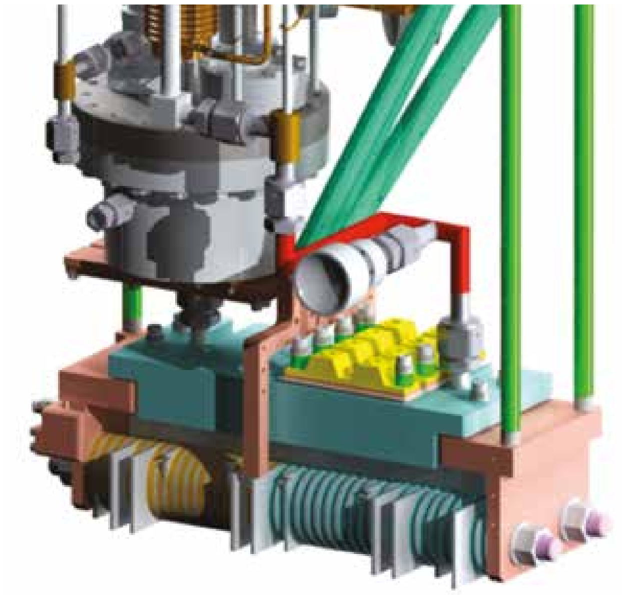
Manufacture of the steel former is extremely difficult due to the very high precision required. We have worked closely with several steel manufacturers to refine the process, which is achieved with a combination of conventional machining and Electric Discharge Machining (EDM). A great deal of time has been spent on refining the machining process.

The next stage of the project is to build two 30 cm undulator formers. These will be wound and potted as before, but this time they will be suspended in a liquid helium bath in a vertical test cryostat (VTC), cooled to 4.2 K and a superconducting current through the coils. This will allow us to test our magnetic measurement facility as well as providing valuable information about the effectiveness of the overall undulator manufacture process. Any manufacturing errors will show up as field errors in the magnetic measurement results. The VTC has been tested with a permanent magnet array at liquid nitrogen temperatures (77K) and performs very well.



The vertical test cryostat (VTC). The insert (blue section at the bottom) holds the undulator formers.

A second test system, known as the 'turret' – a continuous flow cryostat – provides a more realistic look at the cooling of the undulator as it would be done on the accelerator. The formers are suspended horizontally rather than vertically, and they are cooled to <2K in a 'dry' fashion using cryocoolers. This system has been designed, manufactured and tested. The system was cooled down to its operating temperature in around 2.5 days, and remained stable for 22 days. The system is working well and will be able to cope with the heat loads expected from the undulator.



The 'turret' test system used to cool the undulator to 1.8K. The undulator formers can be seen at the bottom of the picture.

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Introducing the Intense Beam Experiment (IBEX)

The IBEX experiment is not your usual accelerator experiment. In fact it's not a particle accelerator at all but a precision device called a linear quadrupole ion trap, in this case one designed to mimic the physics of high intensity particle beams. The motivation for the experiment came from challenges in studying fundamental effects in high intensity beam dynamics. A high intensity accelerator is subject to both internal forces and external electromagnetic forces, creating a complex and fascinating dynamical system, one which has no analytical solution.

To date our understanding of fundamental intensity limitations in hadron accelerators comes from two main directions; accelerator based experiments and computer simulations based on theory. Of course, one cannot explore every parameter in experiments using existing accelerators where beam time is limited. On the other hand, simulations are limited by computational power and spurious artefacts from noise that can obscure real beam physics effects.

To circumvent both computational and experimental limitations, the IB group have been collaborating with the University of Hiroshima since late 2013 to use tabletop-sized ion traps to study fundamental accelerator physics concepts such as resonance crossing. This 'scaled experiment' relies on the fact that the transverse focusing effects and intense beam dynamics of a non-neutral plasma confined in an electrodynamic trap is almost equivalent to that in an accelerator focusing channel.

The IBEX apparatus was designed in 2015 in collaboration with the University of Hiroshima based on their 'Simulator of Particle Orbit Dynamics (S-POD)' system (See ASTeC Science Highlights 2013-14). IBEX was engineered by Daresbury Technology Division with specialist advice and assistance from ASTeC Vacuum group and ISIS vacuum, rf and electrical engineering groups. The rf electronics are being designed by Oxford Physics Central Electronics.

The Metrology group at Rutherford Appleton Laboratory precisely measured the completed ion trap in March 2016. A Coordinate Measurement Machine was used to measure rod alignment with micron level accuracy. This detailed survey of the rod geometry will allow the strength of various resonances to be predicted and compared with experimental results.

The various subsystems will be integrated and assembled at RAL in the coming months with commissioning to begin shortly thereafter. It is expected that beam physics studies will commence in the following year.

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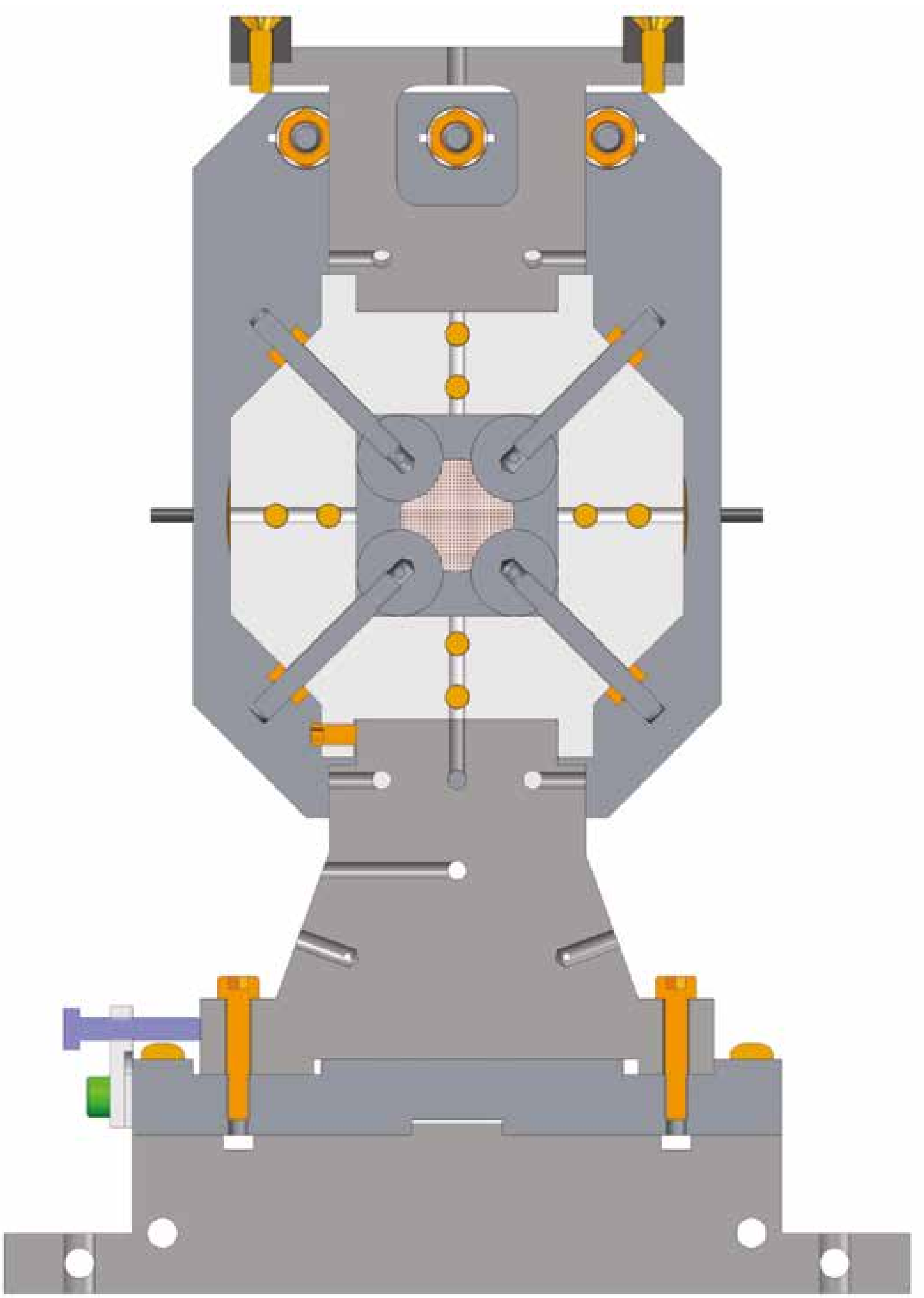


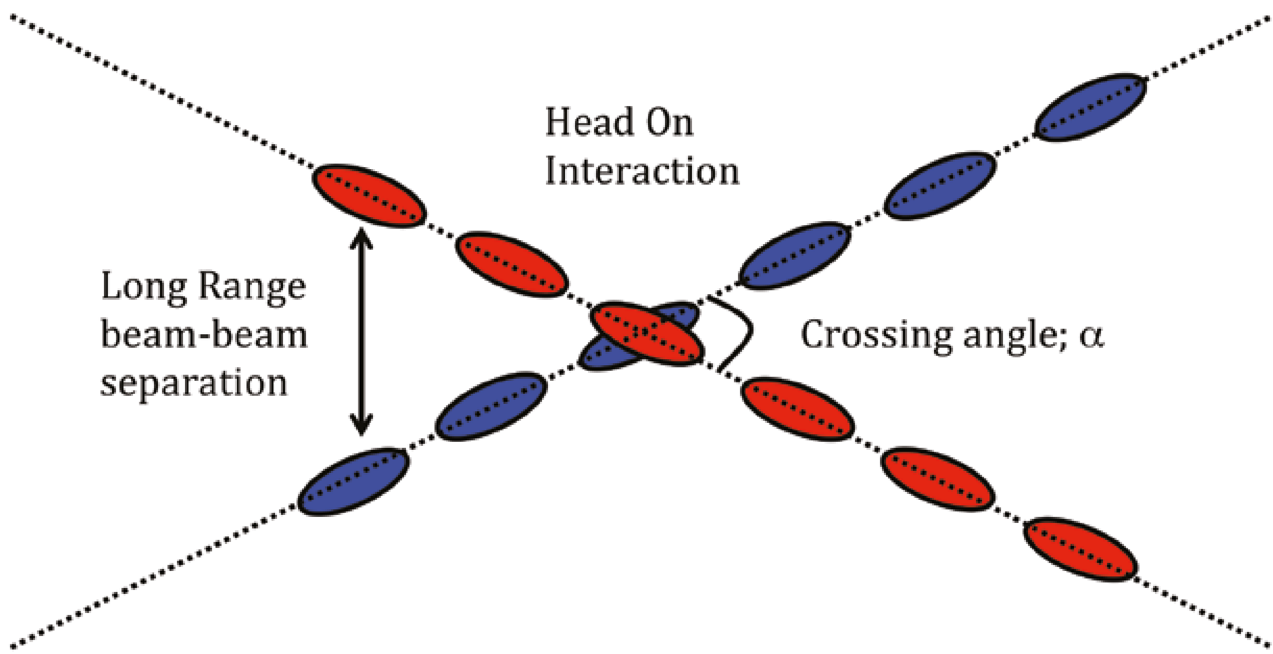
Cross-sectional view of the mechanical design of the IBEX Paul trap.
Image courtesy of Daresbury Laboratory Technology Division.

3 INTERNATIONAL COLLABORATIONS

HL-LHC Collaboration

ASTeC was involved in the High Luminosity upgrade for the LHC (HL-LHC) at CERN from November 2010 until October 2015. This involvement consisted primarily in the examination and study of the beam-beam instability together with various luminosity levelling scenarios. The HL-LHC project should achieve even higher luminosities than those of the LHC. In the interest of avoiding substantial 'pile-up' or unplanned interactions in the detectors, luminosity levelling was proposed so as to be able to keep it constant for a longer time than has so far been achieved in colliders. This means artificially spoiling the luminosity at the start of an experiment and gradually compensating for the natural decrease in intensity thereafter in such a way that the luminosity remains constant for as long as possible. One of the proposed methods to achieve this is beam size levelling at the interaction point; this means reducing the beam size as the luminosity naturally decays so as to keep it constant in the detector. Another method of levelling involves starting with a larger crossing angle than the nominal one and then reducing this as the intensity naturally decays to achieve as constant a luminosity for as long as possible.

Several trips were made to CERN by both students and ASTeC staff members to investigate the issue of crossing angles while participating in shift-work at the LHC. This was also done with a view to as what could be learned from LHC operations to inform the HL-LHC. Identifying the minimum crossing angle achievable in the LHC is a key parameter required to know what the maximum luminosity reach is. One of the effects that can limit luminosity is the beam-beam interaction; this increases as the crossing angle is reduced and can induce additional losses due to the nonlinearity of beam-beam force. An illustration of the long-range beam-beam interaction versus the standard one is shown (see figure 1).



An illustration of the long-range beam-beam interaction versus the standard one is shown (see figure opposite).

The aim of the studies was to determine the minimum crossing angle at which the LHC can operate whilst retaining good lifetimes and minimising the losses. As the crossing angle was reduced the lifetimes remained approximately constant from 370 μrad to about 260 μrad, (see figure), and suggests that the LHC can operate at a smaller crossing angle than it presently performs.

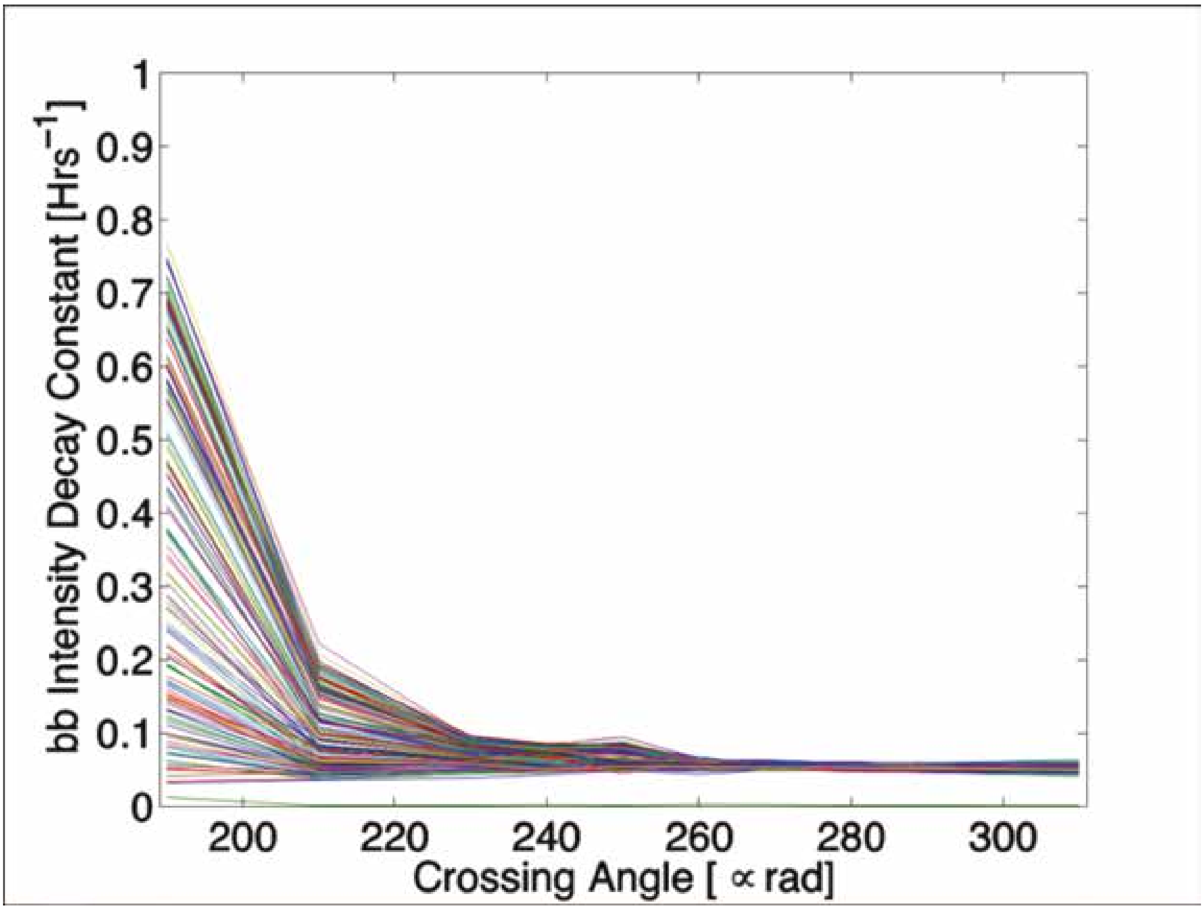


Figure 2: Intensity as a function of crossing angle for the LHC.

Operating at a smaller crossing angle was found to be beneficial by reducing the impact of the geometric luminosity loss factor. For crossing angles below 260 μrad the strength of the long-range beam-beam interaction became strong enough to cause additional losses via a diffusive mechanism. This mechanism transported particles from the core of the bunch to the tail of the bunch, whereupon particles are scraped off by the collimators. Operating the machine below this limit means that particles are lost due to nonlinearities in the beam-beam force and not from collisions between opposing beams; this is not ideal as lifetimes will be bad but will in turn not produce luminosity data for the high energy physics community. This study has resulted in a change of operational procedure for the LHC during luminosity production fills to a reduced crossing angle of about 280 μrad.

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3 INTERNATIONAL COLLABORATIONS

Recent developments in the SwissFEL Collaboration

SwissFEL is an x-ray Free Electron Laser (FEL) facility currently under construction at the Paul Scherrer Institute (PSI) near Zurich, Switzerland. It features two separate FELs, named Aramis and Athos, to cover the wavelength range 0.1-7.0 nm. Under a formal Memorandum of Understanding (MoU) between STFC and PSI, ASTeC has contributed in a number of different areas in which ASTeC scientists have specific expertise.

Laser Heater Undulator

ASTeC scientists worked with the Technology Department at Daresbury to design and construct an undulator (which comprises two arrays of alternating polarity permanent magnets) for the Laser Heater system. The purpose of this system is to manipulate the properties of the electron bunches used in the FELs to ensure optimum performance. The undulator was constructed in the Engineering Technology Centre at Daresbury Laboratory and then measured in the Magnet Measurement Laboratory to ensure that the magnetic field met the required strength and tolerances (see Figure 1). Figure 2 shows a comparison between the measured and predicted undulator deflection parameter (proportional to the undulator period and on-axis magnetic field strength) as a function of the gap between the undulator arrays – the agreement is very good. The undulator is now installed in SwissFEL (see Figure 3) where it awaits commissioning.

Figure 1: The laser heater undulator being measured at Daresbury.

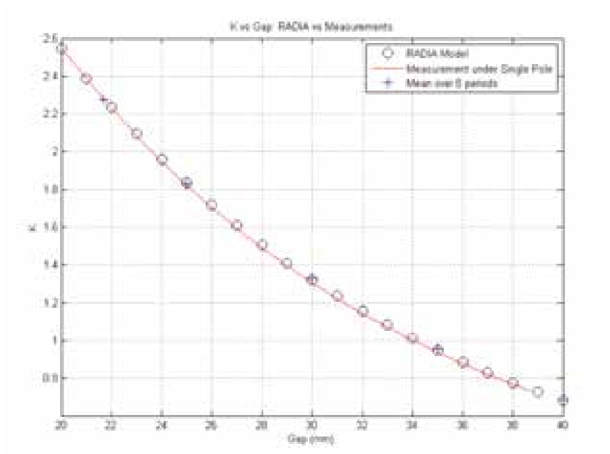

Figure 2: Comparison between the measured and predicted undulator deflection parameter (proportional to the undulator period and on-axis magnetic field strength) as a function of the gap between the undulator arrays

Figure 3: The laser heater undulator, now installed within SwissFEL.

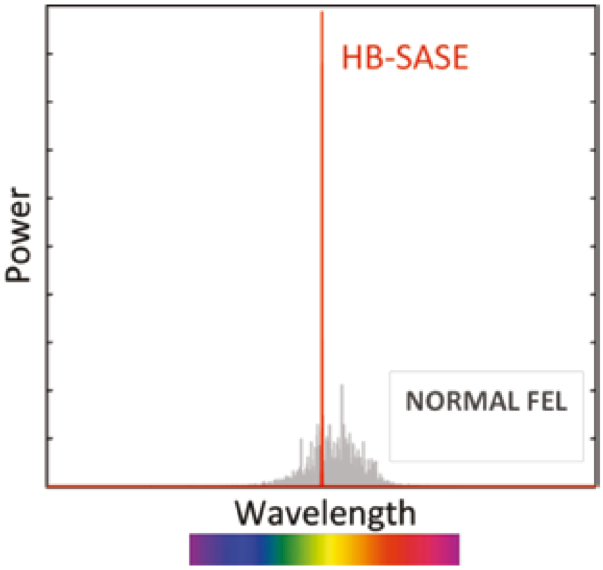

Figure 4: Comparison of the FEL power versus wavelength for a normal FEL (SASE) and High-Brightness SASE. For HB-SASE all the power is at a single wavelength.

Progress on Novel FEL Schemes

The Athos FEL will be installed and commissioned after the Aramis FEL. This means that the design of Athos is still subject to change. ASTeC were invited to attend an internal workshop at PSI in May to discuss a wide range of ideas for novel FEL schemes that could be incorporated into the FEL design, and to present the research programme for the CLARA FEL test facility at Daresbury.

One change that has now been made to Athos is to halve the length of each undulator module and incorporate electron beam delay chicanes between the modules. One of the reasons for doing this is to test a scheme called High-Brightness SASE (HB-SASE) which was originally proposed by ASTeC scientists working together with the University of Strathclyde. In this scheme, the delay chicanes are used to slow down the electrons with respect to the light they emit – the effect of this is to dramatically reduce the bandwidth of the FEL output compared to normal. This increases the spectral brightness, meaning that all the photons are much closer together in wavelength. Figure 4 shows a comparison of the FEL power versus wavelength for a normal FEL (SASE) and High-Brightness SASE - for HB-SASE all the power is at a single wavelength which can have a great impact on the usefulness of the FEL for scientific research. Compared to other schemes for improving the spectral brightness, such as self-seeding, no optics are required, so the scheme can be used at any wavelength and at any pulse repetition rate. HB-SASE may therefore be the best solution for superconducting-RF driven X-ray FELs which produce millions of pulses per second. ASTeC scientists will be able to help in the demonstration of the scheme on SwissFEL and the results will prove valuable for planning further experiments on CLARA.

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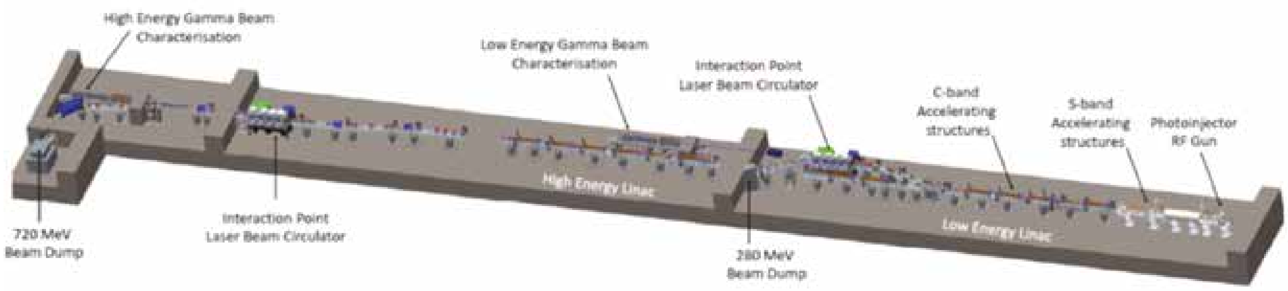
ELI-NP – High Brilliance Gamma Beam System

In March 2014 STFC won a major contract as part of a European consortium tasked with delivering the most advanced and powerful gamma beam facility in the world. It will specialise in both basic and applied research, from looking at the processes that take place in the heart of stars, to applications in industry and medicine. The €5.8M contract between STFC and INFN is part of a €68.8M contract awarded to the EuroGammaS consortium by the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Măgurele, Romania.

The project team brings together leading European scientific institutes (INFN, SAPIENZA University of Rome, CNRS, ALBA, STFC) and industrial collaborators (ALSYOM, A.C.P. Systems, COMEB, Cosylab, Danfysik, Instrument Technologies, M&W Group, Menlo Systems, Research Instruments and ScandiNova).

ELI-NP is one of three pillars of the Extreme Light Infrastructure, a multi-million euro project being carried out in the Czech Republic, Hungary and Romania, with the aim of implementing the world's largest laser research infrastructure. It is expected to be producing intense laser light and gamma beams by 2018. Once built, the ELI-NP will be the most advanced laser and gamma beam facility in the world. The gamma beam will be used to map the isotope distributions of nuclear materials or radioactive waste remotely via Nuclear Resonance Fluorescence measurements. At lower energies the high resolution of the beam is very important for protein structural analysis. In addition it will produce intense neutron beams and intense positron beams, which opens new fields in material science and life sciences. The possibility to study the same target with these very different brilliant beams will be unique and may advance science much faster.



Gamma Beam System Layout

Using the Inverse Compton scattering technique, laser pulses will collide with relativistic electron pulses to generate gamma beams with high peak brilliance, high spectral density, and tunable photon energy in the range 0.2 – 19.5 MeV.

STFC is responsible for delivering 21 of the 35 modules that make up the gamma beam facility with their power supplies, EPICs control and instrumentation. Teams in ASTeC and Technology Department, at Daresbury Laboratory, are working together to deliver the STFC work package, taking full advantage of the Engineering Technology Centre to assemble and commission the modules.

This is a technically complex system delivery, which involves integrating many accelerator components, some of which are supplied to STFC by INFN. RF accelerating structures, magnets, diagnostic devices and vacuum equipment will be assembled, aligned and tested prior to delivery to the ELI-NP site in Măgurele, Romania.

A typical module contains many diverse components including: C-band accelerating structures; dipole, quadrupole and corrector magnets; transverse deflecting cavities; beam profile screens; beam position monitors; and vacuum equipment. All magnets will be aligned to ±50 μm using a laser tracker. The assemblies will be vacuum leak tested and checked for cleanliness with a residual gas analyser. Each module will be cabled to its power supply, control and instrumentation rack to test the magnets, vacuum and interlocks.

The design of the facility is well advanced and the building is under construction. Handover of the building to EuroGammaS will take place in late 2016.

Photograph of the ELI-NP Facility construction site, Mâgurele (near Bucharest) in August 2015

On 5th November 2015, ASTeC and Technology Department staff at Daresbury Laboratory achieved a significant milestone by supplying the 1st stage of STFC deliverables to this project. The delivery consists of the design, construction and integration of accelerator modules, power supplies, control and instrumentation that form an essential section of the Gamma Beam System (GBS) facility accelerator linac.

IFIN-HH, INFN and STFC Daresbury Laboratory staff during an inspection of hardware and documentation during a sign-off of the ELI-NP stage I deliverables.

Further modules are currently undergoing acceptance testing in the Engineering Technology Centre at Daresbury. Following exhaustive testing, the modules will be loaded onto special vibration-damping trucks and sent to the ELI-NP site at Mâgurele. Construction, testing and delivery of modules will continue for the next two years, with the final delivery expected in October 2018.

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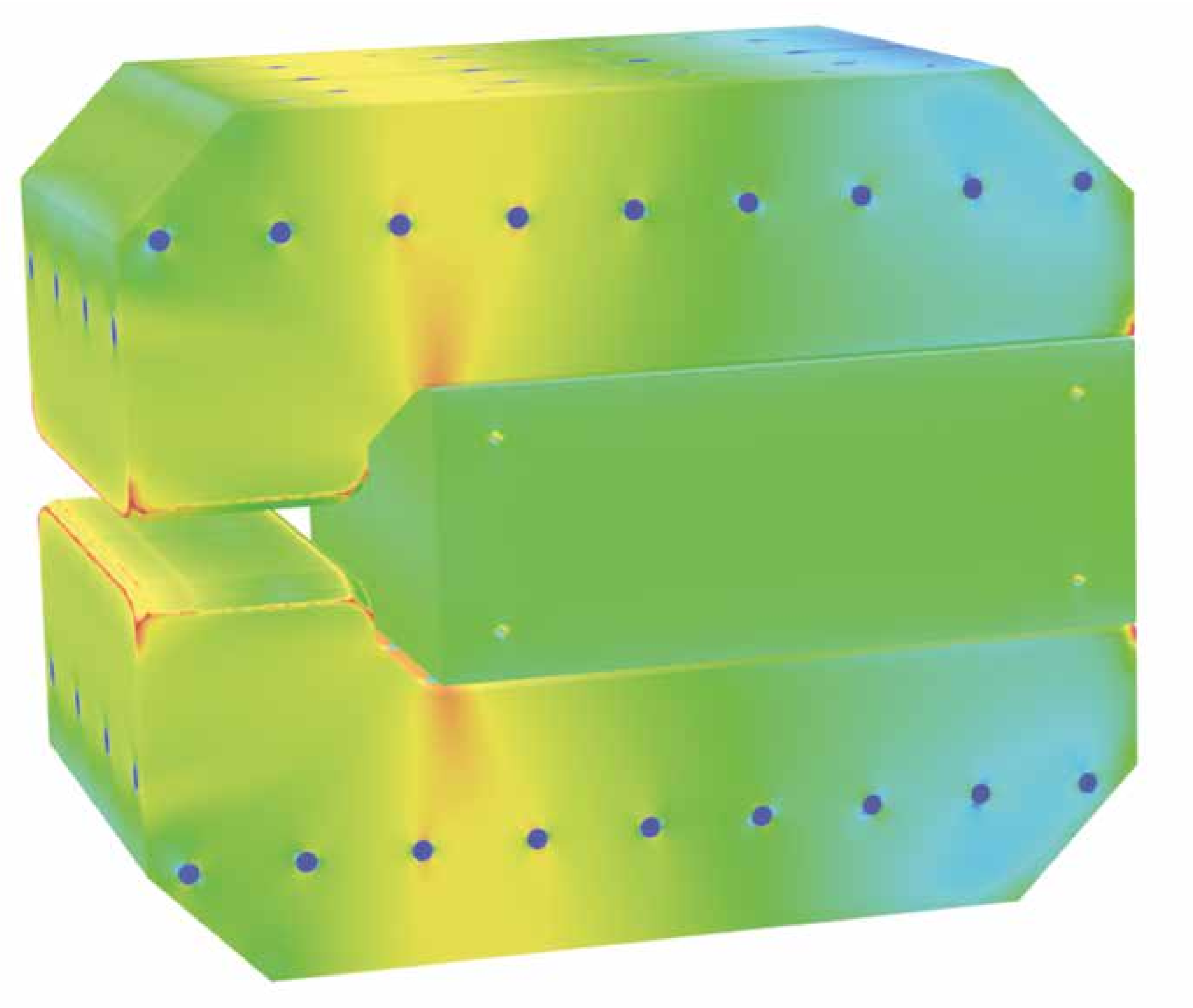
Zero-Power Adjustable Dipoles Prototypes

The ASTeC collaboration with CERN to develop 'green' magnet systems is continuing. Following the successes of the permanent magnet quadrupoles for CLIC, an adjustable permanent magnet dipole is being developed to save power on the CLIC drive beam, a 2.4 GeV system to run parallel to the main beam acceleration section. The drive beam features a large turnaround loop with 792 (planned) dipoles operating at 1.6 T over varying effective lengths and gap heights, alongside a number of weaker dipoles. Using conventional electromagnets the stronger dipoles alone would consume approximately 21 MW of power and so using adjustable permanent magnets in their place represents a significant long term saving in cost, infrastructure and emissions.

To test this concept a scaled down prototype has undergone a magnetic and mechanical design process and is under construction. The scaled down prototype is 0.4 m long with a central field of 1.1 T. This includes a gap designed to allow it to conveniently be used for steering into the dump at the end of CLARA, giving the magnet a practical purpose beyond simply testing the concept.

The prototype features a single large block of high strength permanent magnet material sandwiched between two pole pieces as shown (see figure). A gap is enforced between the surfaces of the magnet block and the pole pieces to allow free movement of the block; this slides horizontally in and out of the pole pieces to provide a tuneable field. Finite element analysis shows that the field can be varied from 1.1 to 0.47 T by sliding the block 400 mm. The force between the magnet block and each pole piece is over 120 kN, representing a massive engineering challenge!

The magnet will be tested by 3D Hall probe analysis to assess its tuning performance and field quality in early 2017.



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Year in Industry Students contribute to ASTeC Accelerator Physics

In 2015-16 three undergraduate physics students were recruited into the accelerator physics group for their year in industry placement. Competition was fierce with 15 excellent applicants for the available places. All three students performed exceptionally, with three research papers written by the students being presented by them at IPAC16 in Busan, South Korea.

Ryan Beech from Loughborough University constructed a tuneable broadband light source for the transverse energy spread spectrometer (TESS) under the guidance of Lee Jones. Ryan said, *"My short year working in the Photocathode group was a great experience, learning skills I can take into my final year of study and my future career"*.

Peter Tipping from Leeds University performed beam dynamics simulations in order to characterise dark current emission from RF photocathode guns under the guidance of Julian McKenzie and Boris Militsyn. Peter said, *"My time at STFC was a fantastic opportunity and one that really helped me to develop. I enjoyed many experiences that would never have been available to me had I stayed at university and I would sincerely recommend this to anyone wanting to gain experience in research."*

Matthew Toplis, also from Leeds University, contributed to the software framework for manipulation and data taking from VELA and CLARA, and also performed a detailed comparison between beam dynamics simulations and experimental data from VELA. He was supervised in this by Peter Williams and Duncan Scott. Matthew said, *"My year with ASTeC has been very enjoyable and has taught me a variety of skills that will help me both at university as well as in my future career. The best aspect of my placement was a trip South Korea to present my work at the International Particle Accelerator Conference 2016."*

IoP PAB Prize for Mike Poole

IoP Particle Accelerators and Beams (PAB) group 2016 prize was awarded to Prof Michael Poole, ex-Director of ASTeC at the annual meeting held in Huddersfield on 8th April 2016. Mike received this award for *"his world-class, internationally-recognised contributions to accelerator physics and the advancement of Free Electron Laser facilities worldwide; for his stewardship of the field of accelerator science in the UK, including his leadership of the Accelerator Science and Technology Centre; for his work for the institute of physics leading to the creation of the Particle Accelerators and Beams Group; and for his support and mentorship of his staff and colleagues."* Everyone in the UK accelerator field today owes a lot to Mike and the IoP prize was a great opportunity to acknowledge this in public.

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IOP | Institute of Physics
Particle Accelerators and Beams Group

Cockcroft Institute at the Big Bang Science Fair 2016

In March 2016 the Cockcroft Institute public engagement team attended the Big Bang Science Fair[1] held at the Birmingham NEC. This is the largest public science and technology fair in the UK and annually receives something in the region of 65,000 to 70,000 visitors over the 4 days of the event. It certainly felt that most of them visited our stand! A highlights video was published providing a great flavour of the show, its contents and the level of enthusiasm from both exhibitors and visitors alike.[2]

The Cockcroft Institute stand focussed on showcasing the key underpinning principles and technologies common to all particle accelerators, featuring real accelerator hardware; magnets from the EMMA accelerator and a superconducting linac module proved to be major talking points. Many of the Institute's Ph.D. students manned the stand and talked with passion and eloquence about their work, the work of the Cockcroft Institute and the STFC as a whole – the impact was clear from the expressions on the faces of visitors as they listened to us all talk, though it left everyone with sore feet after standing-up for most of the week and sore throats from talking endlessly to a constant stream of visitors.

The event was also a great opportunity to prepare the Cockcroft Institute 'outreach machine' for the Daresbury Open Week in July. Having experienced the Big Bang Fair, our Ph.D. students were keen for more and could look forward to their next chance to share their passion for science with the Great British public!

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Busy times on the Cockcroft Institute stand at the Big Bang Fair.

[1] Big Bang Fair - https://www.thebigbangfair.co.uk/

[2] Mid-week highlights - https://www.youtube.com/watch?v=J1lkHcuCdMc&feature=youtu.be

Delight and fascination at seeing the Meisner effect[1] demonstrated with a superconductor.

The most popular activity on the Cockcroft Institute stand was 'hair raising' with a Van de Graaff generator which was also used to drive a 'salad bowl' accelerator to show visitors why this effect is so important in particle accelerators.

[1] The expulsion of a magnetic field from a superconductor - http://en.wikipedia.org/wiki/Meissner_effect

5 OUTREACH

The Daresbury Laboratory Particle Physics Masterclass 2016

Daresbury Laboratory held its Particle Physics Masterclass between March 1st and 3rd. The event was organised and publicised by the Daresbury public engagement team, and hosted by the Cockcroft Institute (CI), with scientists from ASTeC and the Cockcroft Universities, ably-supported by CI Ph.D. students, delivering the Masterclass activities. This year, the Daresbury team trialled a new initiative intended to really fire the imaginations of a small group of students predicted to attain an A* grade at A-level and intending to study physics at university: the PPMC A*.

The Masterclass was opened by Dr. Lee Jones who gave a brief review of particle accelerators at the Daresbury Laboratory, and demonstrated how the NINA project had led to the SRS and then to Diamond, ALICE, EMMA and VELA, and how synchrotron radiation (and its applications) are such a fundamental part of this story. The talk highlighted how the evolution of the accelerator technology and the opportunistic exploitation of synchrotron radiation from the NINA accelerator had kick-started the development of electron accelerators to deliver synchrotron light, and ultimately the concept and realisation of the Free Electron Laser (FEL).

Following refreshments and a chance to chat with CI staff supporting the event, the students embarked on a series of activities, the highlight of which was a tour of the ALICE accelerator. In the weeks before the Masterclass, the students had been given a 2-part classroom exercise allowing them to make an accurate estimation of the total energy of the particle beam emerging from the ALICE electron injector. This pre-work was supported by a presentation enabling their teachers to lead students through a review of some basic physics principles and derive a mathematical formula for the beam energy based only on quantities which are easy to measure. During their visit to ALICE, the students were shown the parts of the accelerator on which the exercise had focussed, thereby putting it all into context, and they were given the measured values they needed to complete the second half of the exercise which would subsequently be done when they returned to school, giving them an estimate of the total energy of this relativistic electron beam.

Two of the other main activities for students attending this Masterclass were computer-based simulations investigating both accelerator and particle physics, intended to give a deeper understanding of the physics under-pinning these disciplines. The students firstly considered the challenges of effectively focussing the contra-rotating proton beams in the Large Hadron Collider (LHC) at one of the interaction (collision) points, seeking to optimise the process and maximise luminosity via a custom-designed MatLab interface which was both intuitive and informative, immediately showing the students the consequences of making even subtle changes to the collision conditions. The students then worked through the Lancaster Particle Physics Package - a web-based tutorial package which reviews essential basic principles of physics and particle physics, and goes on to apply these to real collision data from the LHC. Ultimately, the students were able to identify collisions which contain the signature of a Higgs-like particle.

Aspects of under-pinning particle accelerator technology such as vacuum, superconductivity, the use of high voltage to accelerate particles and the use of magnetic fields were also demonstrated to students in what was the most relaxing of the four practical sessions. Students and teachers alike were amazed by the Meissner effect in which a high-temperature superconductor is first seen to levitate above a magnetic track, and then 'hang' from the inverted magnetic track (it literally levitates below the magnetic track).

A viewing of the ALICE promotional video completed this activity, and gave the students a clear picture of how the FEL light and THz radiation generated by ALICE is used for scientific research.

In parallel to these four activity sessions, students attending the PPMC A* class had a different experience: This intrepid group of just 12 students spent their time under the supervision of Dr. Duncan Scott and Dr. Chris Edmonds, learning in detail about the ALICE accelerator and what it takes to actually operate a cutting-edge particle accelerator. The PPMC* group was only run on the middle of the 3 days of the event, but the impact on the students and their teachers was clear, and the concept such a success that we plan to run a parallel PPMC* group during each day of the 2017 Daresbury Masterclass.

The day was rounded-off with a lively talk by Prof. Fred Loebinger (University of Manchester) on the history of particle physics, and the significant part played in this by the Particle Physics department at the University of Manchester.

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The 13th IUVSTA School on Vacuum Gas Dynamics: Theory, Experiments and Applications

The 13th IUVSTA School Vacuum Gas Dynamics was organized in the framework of the IUVSTA educational program on 17-21 May 2015 in Thessaloniki, Greece. The School was designed for scientists, engineers and postgraduate students who are not experts in rarefied gas dynamics, but need to apply this field in their every-day work. The aim of the School was to train the participants in applying vacuum gas dynamics and also to fill the gap between complicated theory and practical needs.

The event was co-chaired by Prof. Felix Sharipov (Brazil), Dr. Oleg Malyshev (UK) and Prof. D. Valougeorgis (Greece) who was also the Local Organizer. The lectures and practical sessions were given by the co-chairmen, as well as by Dr. Karl Jousten (Germany), Dr. Roberto Kersevan (Switzerland) and Dr. S. Naris (Greece). Forty students attended the School coming mostly from various European countries and few from USA, Canada and China. They represented research centres, universities and industries. The majority of them were Ph.D. students, young scientists and engineers, while some were senior engineers or/and group leaders. Thus, the audience was very varied in terms of the level of knowledge in vacuum gas dynamics and in terms of professional needs. This diversity of the students made the lectures quite challenging in order to meet all the requirements of the participants and to answer their questions during sessions and coffee breaks.

In total, 10 lectures and 6 practical sessions were given, covering many topics in the field of Vacuum Gas Dynamics. The theoretical and computational parts were focused on kinetic theory, kinetic models, diffusion models, gas-surface interaction, test particles and direct simulation Monte Carlo methods, while the experimental part was dedicated to methods of measurement and standards in vacuum systems and vacuum metrology. The areas related to applications concerned gas flow through pipes, pumps and gauges, in small and large vacuum systems using Molflow software, diffusion modelling, numerical codes based on Monte Carlo and discrete velocity methods. During the practical sessions, the students were requested to carry out specific exercises related to the lecture material.
These sessions were run in two parallel groups supervised by 2-3 lecturers each in order to help the students more effectively and to increase the interaction between students and lecturers. The students were happily engaged in this process, trying hard to get the correct answers given to them for comparison purposes. All material related to the lectures and practical sessions has been uploaded to the School website about two weeks before its start and all registered participants had an access to it in order to better prepare themselves for the sessions.

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SRF2015

The 17th International Conference on RF Superconductivity (SRF2015) took place on 13th-18th September 2015 at The Whistler Conference Centre in Whistler, British Columbia, Canada. The SRF conference series provides a vibrant forum for scientists, engineers, students and industrial partners to present and discuss the latest developments in the science and technology of superconducting RF for particle accelerator applications. The program consisted of invited talks, poster sessions and 'hot-topic' discussion sessions. ASTeC staff and PhD students presented five posters related to the ASTeC thin film SRF programme.

PhD students benefited from attending traditional SRF2015 tutorial sessions held prior to the conference, which provided an in-depth overview of SRF related subjects.

At the conference a number of collaboration meetings took a place. One was for the existing CERN-INFN-STFC collaboration on thin film SRF. Another one was a first meeting related to a future international collaboration known as ARIES which is the successor to EuCARD2.

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The International Workshop on Functional Surface Coatings and Treatments for UHV/XHV Applications

The International Workshop on Functional Surface Coatings and Treatment for UHV/XHV Applications took place on 28th Sep – 1st Oct. 2015 at The Crowne Plaza Hotel located within the historic City walls of Chester in Cheshire. The aim of the workshop was to bring together the principle researchers currently working on the development, characterisation and practical applications of various surface coatings and treatment for UHV/XHV applications such as non-evaporable getter (NEG) coatings, low secondary electron yield (SEY) coatings, low outgassing coating and treatments, etc. The event provided an opportunity for the exchange of knowledge and experience of experts from various institutions and industries.

The Workshop is organised by ASTeC (with Oleg Malyshev as a Chair) with an endorsement of the IUVSTA and a support of Institute of Physics and commercial sponsors. The Workshop has attracted about 50 participants from 14 countries in Europe, Asia and Americas. The participants gave 27 talks covering the following topics: surface outgassing, barrier coating for reducing outgassing, TiN coating, transitional metal coating, carbon coatings, NEG coatings, laser treated surface, surface impedance, vacuum systems for new accelerators and machine operation experience with functional surface coatings and treatments. Four talks were given by ASTeC staff and PhD students: Reza Valizadeh gave an invited talk in low SEY laser treated surfaces, Oleg Malyshev on NEG coating development, Sihui Wang on SEY on transitional metal coating, Lewis Gurran on surface resistance measurements. The workshop also provided sufficient time for questions and discussion. The participant visited the STFC Daresbury Laboratory where they were greeted by ASTeC Director Susan Smith, then they visited ASTeC research accelerator facilities ALICE/EMMA and CLARA/VELA and vacuum science laboratories.

Overall the workshop was a very successful event.

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The International Workshop on Functional Surface Coatings and Treatment for UHV/XHV Applications.
28th September - 1st October 2015

ASTeC Publications 01 Apr 2015 – 31 Mar 2016

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* Author's names may appear here in a different order than in the journal or conference proceedings

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Spampinati, S et al.
Developments in CLARA Accelerator Design and Simulations.

P. H. Williams, D. Angal-Kalinin, A. D. Brynes, D. Dunning, J. K. Jones, J. W. McKenzie, B. L. Militsyn, B. D. Muratori & N. R. Thompson, S. Spampinati
Developments in CLARA Accelerator Design and Simulations

7 PUBLICATIONS

J.W.McKenzie, M.D. Roper, T.C.Q. Noakes, J. Jones, A. Kalinin, B.L. Militsyn, B.D.
Muratori, D. Scott, F. Jackson, P. Williams, Y. Saveliev, D. Angal-Kalinin, M.
Surman. D.A. Wann, P.D. Lane, J.G. Underwood
Single-shot Multi-MeV Ultrafast Electron Diffraction on VELA at Daresbury Laboratory

A.E. Wheelhouse , R.K. Buckley, S.R. Buckley, L. Cowie , P. Goudket, L. Ma, J. McKenzie, A.J. Moss, G.C. Burt, M. Jenkins
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P. Goudket, S. Pattalwar, O.B. Malyshev, L. Gurran, G. Burt, E.S. Jordan, T.J. Jones, D.O. Malyshev and Reza Valizadeh
Test Cavity and Cryostat for SRF Thin Film Evaluation.

P. Goudket, L. Gurran, G. Burt, M. Roper, S. Wilde, O.B. Malyshev and Reza Valizadeh.
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L. B. Jones, B. L. Militsyn and T. C. Q. Noakes.
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P. Pizzol, A. Hannah, R. Valizadeh, O.B. Malyshev, S. Pattalwar, G. B. G. Stenning, T. Heil and P. R. Chalker.
Superconducting coatings synthetized by CVD/ PECVD for SRF cavities.

S. Wilde, R. Valizadeh, O.B. Malyshev, N.P. Barradas, E. Alves, G. B. G. Stenning, A. Hannah, S. Pattalwar and B. Chesca.

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A facility for magnetic field penetration measurements on multilayer S-I-S structures.

L. Gurran, P. Goudket, S. Pattalwar, O.B. Malyshev, N. Pattalwar, T.J. Jones, E.S. Jordan, K.D. Dumbell, G. Burt and R. Valizadeh.
Superconducting thin film test cavity commissioning.

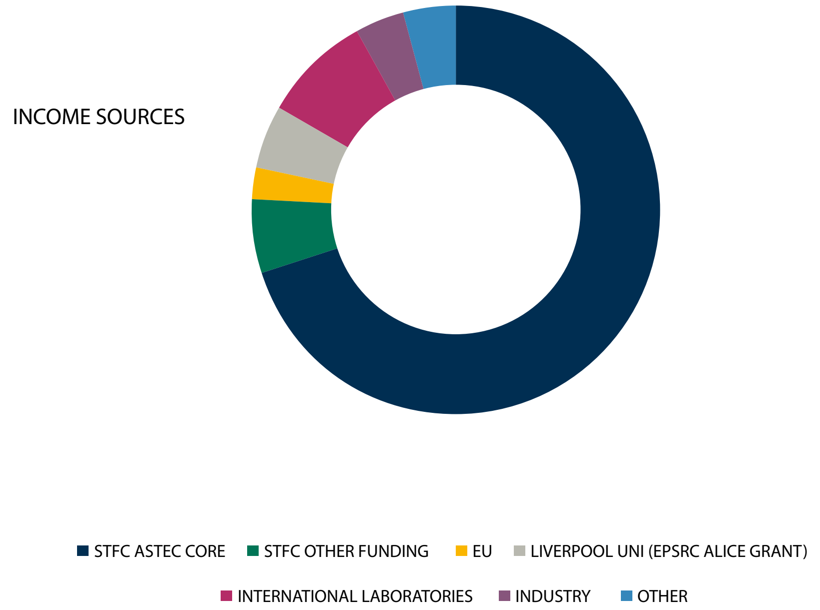
8 FINANCE

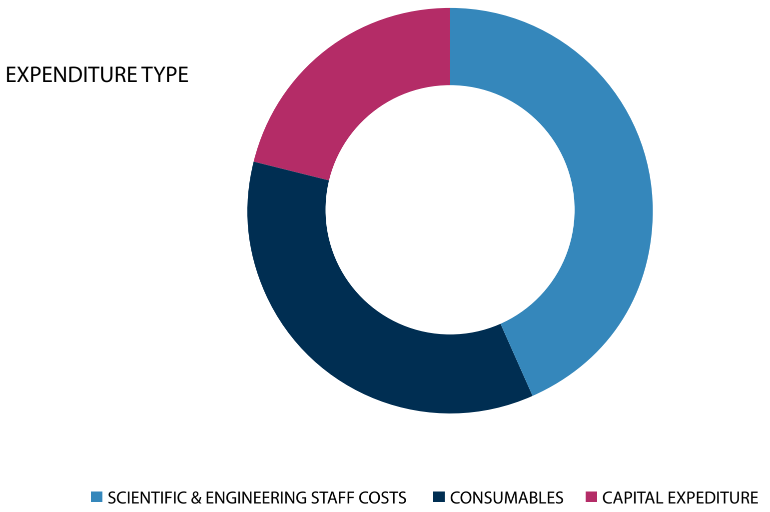
ASTeC ACTIVITIES 15/16

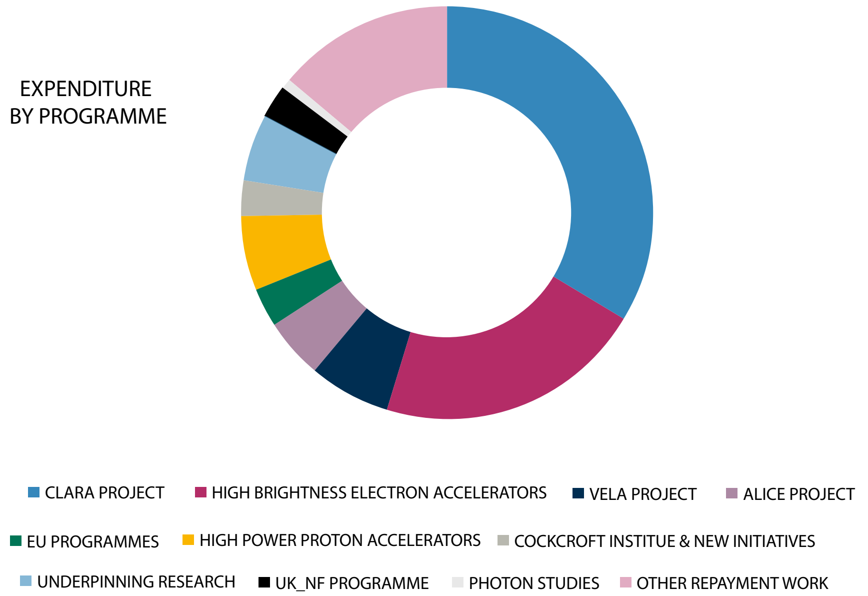
INCOME SOURCES 15/16	£K
STFC ASTeC core	£9,036
STFC other funding	£750
EU	£324
Liverpool Uni (EPSRC ALICE Grant)	£651
International Laboratories	£1103
Industry	£518
Other	£512
	£12,894

EXPENDITURE 15/16	£K
Scientific & Engineering Staff Costs	£5,616
Consumables	£4,564
Capital Expenditure	£2,714
	£12,894

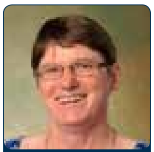
EXPENDITURE BY PROGRAMME 15/16	£K
CLARA Project	£4,353
High Brightness Electron Accelerators	£2,724
VELA Project	£814
ALICE Project	£613
EU Programmes	£382
High Power Proton Accelerators	£760
Cockcroft Institute & New Initiatives	£363
Underpinning Research	£690
UK_NF Programme	£296
Photon Studies	£137
Other Repayment work	£1,760
	£12,894


INCOME SOURCES
STFC ASTEC CORE
STFC OTHER FUNDING
EU
LIVERPOOL UNI (EPSRC ALICE GRANT)
INTERNATIONAL LABORATORIES
INDUSTRY
OTHER


EXPENDITURE TYPE
SCIENTIFIC & ENGINEERING STAFF COSTS
CONSUMABLES
CAPITAL EXPEDITURE


EXPENDITURE BY PROGRAMME
CLARA PROJECT
HIGH BRIGHTNESS ELECTRON ACCELERATORS
VELA PROJECT
ALICE PROJECT
EU PROGRAMMES
HIGH POWER PROTON ACCELERATORS
COCKCROFT INSTITUE & NEW INITIATIVES
UNDERPINNING RESEARCH
UK_NF PROGRAMME
PHOTON STUDIES
OTHER REPAYMENT WORK

Science & Technology
Facilities Council



Susan Smith
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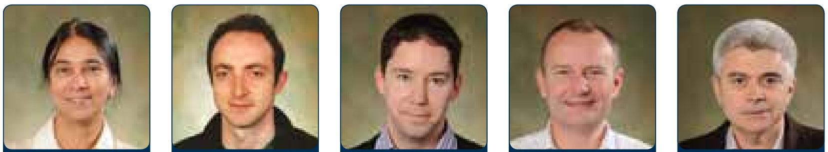

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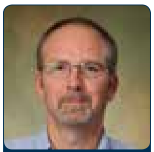

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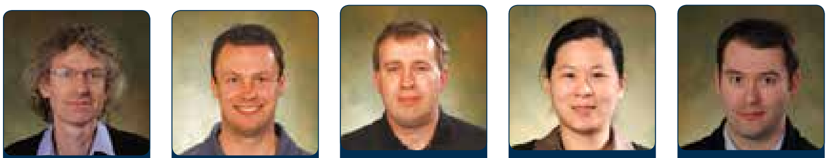
DIAGNOSTICS & LASERS



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Rob Smith
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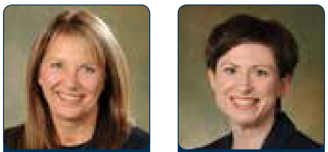
Trina Thakker
Laser Scientist

Edward Snedden
Laser Physicist



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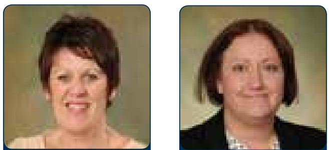

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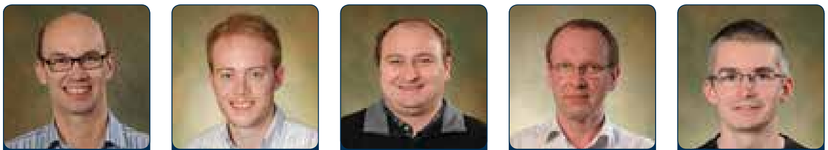
MAGNETICS & RADIATION SOURCES



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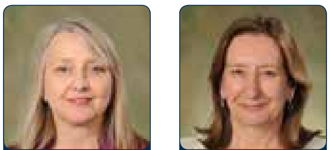

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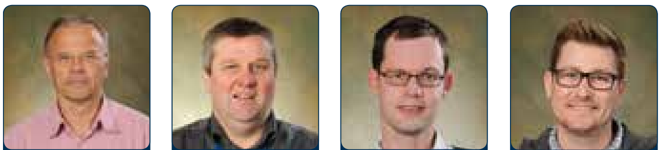
PROGRAMMES & FACILITIES



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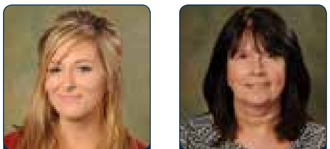

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Sue Waller
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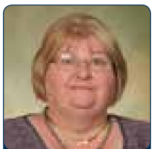
RF & Croyogenics Engineer

Louis Bizel-Bizellot
Cryogenics Engineer

Tim Stanley
RF Engineer

Louise Cowie
RF Scientist



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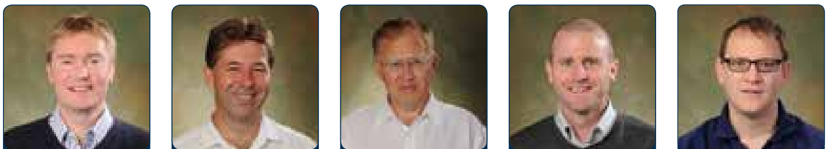

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Keith Middleman
Senior Vacuum Scientist

James Conlon
Laboratory Assistant

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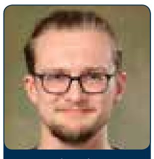
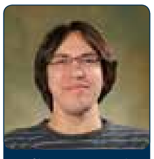
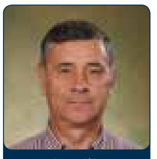
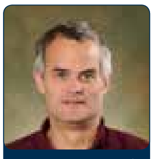
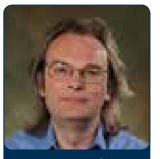

Tim Price
Scientific Software Developer

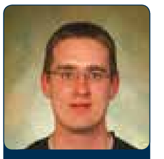

Julian McKenzie
Accelerator Physicist

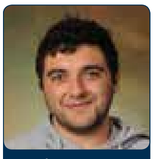

Boris Militsyn
Senior Accelerator Physicist

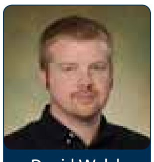

Bruno Muratori
Senior Accelerator Physicist


Yuri Saveliev
Senior Accelerator Physicist


Peter Williams
Senior Accelerator Physicist

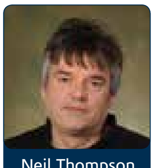

Duncan Scott
Senior Accelerator Physicist

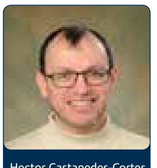

Alex Brynes
Accelerator Physicist


David Walsh
Senior Laser Scientist

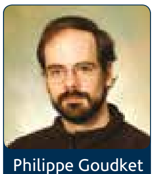

Rui Pan
Laser Physicist

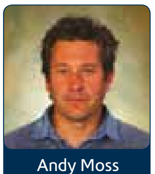

Mark Surman
Senior Scientist


Neil Thompson
Senior Physicist

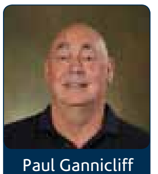

Hector Castanedes-Cortes
FEL Modeller

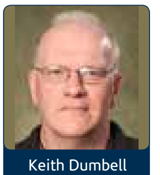

Alex Bainbridge
Magnetic Designer

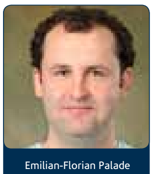

Philippe Goudket
RF Scientist


Andy Moss
Senior RF Engineer


Shrikant Pattalwar
Croyogenics Engineer


Paul Gannicliff
Technical Support Officer


Keith Dumbell
RF Engineer

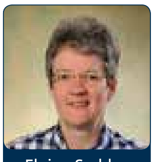

Emilian-Florian Palade
RF Engineer

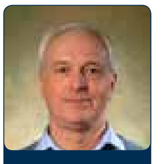

Mike Jenkins
RF Engineer


Reza Valizadeh
Senior Materials and Surface Scientist

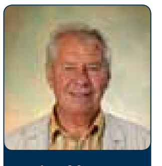

Kareem Hussein El-Abiary
Surface Engineer

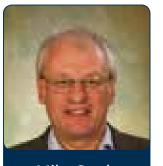
HONORARY SCIENTISTS

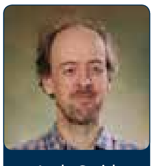

Elaine Seddon
Consultant

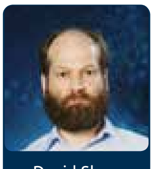

David Holland

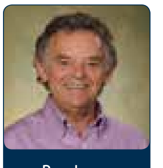

Mike Henderson


Ian Munro

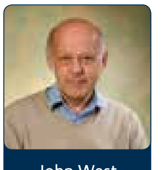

Mike Poole


Andy Smith

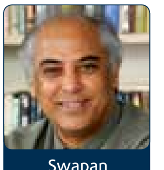

David Shaw


Ray Jones

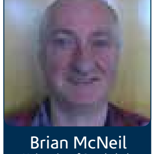

Neil Marks
Consultant

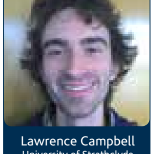

John West


Michelle Siggel-King


Swapan Chattopadhyay

ASSOCIATE APPOINTMENTS


Brian McNeil
University of Strathclyde


Lawrence Campbell
University of Strathclyde