ASTeC

Accelerator Science and Technology Centre

SCIENCE HIGHLIGHTS 2018 - 2019

Science & Technology Facilities Council
UK Research and Innovation

CONTENTS

DIRECTOR'S FOREWORD

Professor Susan Smith
ASTeC Director & Head of Daresbury Laboratory

This report presents ASTeC's Science and Technology Highlights for the financial year 2018-19. As seen in the **NEW DISCOVERIES FROM CLARA** section of the report, this was an important year for the CLARA accelerator test facility. From the seeds sown with VELA in 2011, ASTeC engineers and scientists have developed UK capabilities and skills through designing and delivering the technical systems for the first phase of CLARA. This year the short pulse electron beam was offered to researchers for a range of experiments. The success of that programme was demonstrated through the many exciting new results delivered. For example, insights into new cancer treatments, collaborative R&D with industry to develop commercial diagnostic systems, and the test of new methods for controlling and measuring particle beams. To deliver such a scientifically fruitful period of beam access, in the midst of a major test facility build, was highly challenging and only possible through the hard work and professionalism of all staff.

An increased emphasis on ensuring that science research directly impacts economic growth and productivity means our collaborative commercial activities are now more important than ever. The section **WORKING WITH INDUSTRY** describes our involvement in two major particle accelerator projects which are helping to bring accelerator technology to market. One of these projects, with Advanced Oncotherapy Ltd, is to demonstrate an advanced proton therapy system. The other is a partnership with Teledyne e2v to maximise the potential of the Compact Linac accelerator for developing new products while advancing ASTeC's own societal applications in healthcare, environmental science and security.

Accelerator science is an international activity but not all collaborations are formal or large scale. This year some ASTeC staff spent periods of time at laboratories overseas, working alongside international colleagues on finding solutions to shared problems. In the **PERSONAL PERSPECTIVES** section they share their experiences.

And finally we look ahead, reminding ourselves of the ASTeC mission to 'make a brighter future through advanced accelerators'. In the **FUTURE ACCELERATORS** section we describe our work in two critical stages of an accelerator life-cycle: the underpinning R&D on 'novel acceleration' which promises to one day revolutionise accelerators by shrinking them in size, and our work helping to build and test two new large-scale international facilities that scientists will eventually use to probe the nature of the universe.

NEW DISCOVERIES FROM CLARA

The CLARA accelerator at Daresbury produces a high brightness electron beam accelerated to an energy of 40 million electron volts. It is one of only a few places in the world where such electron beams can be used in scientific experiments. This year CLARA produced many exciting results, from research into new cancer treatments to the development of commercial diagnostic systems in partnership with industry, to completely new methods of controlling and measuring the properties of particle beams.

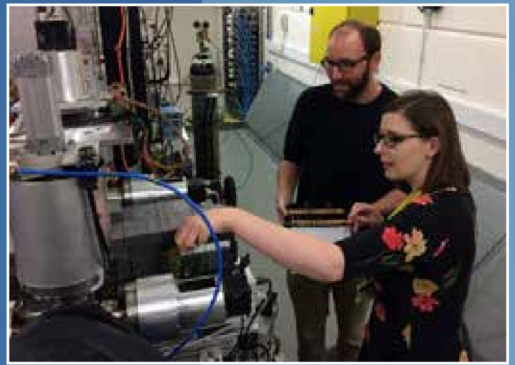
FIGHTING CANCER

A recent study by Cancer Research UK found that one in two people born after 1960 will suffer from cancer during their lifetime. About half of patients have their cancer treated using radiotherapy, which uses particles or waves, such as x-rays, gamma rays, protons or heavy ions, to destroy or damage cancer cells. The treatment works by damaging the DNA in the cancer cells so they can't function or replicate, and may even die.

A research team from the University of Manchester is evaluating the use of Very High Energy Electrons (VHEE) in radiotherapy. This could be more effective and potentially less expensive than existing radiotherapy treatments for specific cancers and regions within the body. This is because electrons are relatively light compared to protons or ions so it is easier to steer and focus them, giving rapid and precise delivery with less sensitivity to range uncertainty. Sub-second doses could 'freeze' physiological motion such as breathing, increasing the accuracy of the dose delivery and reducing damage to the healthy tissue surrounding the cancer cells.

CLARA was the ideal facility for two ground-breaking experiments in this area. The first experiment measured the radiation dose delivered by firing bunches of electrons at close to the speed of light into water phantoms representing the human body. ASTeC physicists operating the CLARA machine wrote bespoke control software to enable a series of beam energies and charge parameters to be rapidly explored. The measurements were compared to simulations, and excellent agreement was seen. These results helped resolve earlier discrepancies with dose measurements using electron accelerators at The Christie Hospital in Manchester and the CLEAR facility at CERN.

The second experiment fired the electrons into prepared DNA samples to precisely determine the level of DNA damage. The results demonstrated double strand DNA breakage in addition to single strand breakage, as predicted by theoretical models. The team plan to return to CLARA soon to develop their exciting work with further studies of DNA damage, dose penetration and image guidance techniques. Their research may open up a new paradigm in radiotherapy treatment.



University of Manchester PhD student Kristina Small and Nicholas Henthorn, a researcher from the University of Manchester and the Christie NHS Trust, setting up DNA experiments.

University of Manchester PhD student Agnese Lagzda setting up radiochromic films in a purpose-built water phantom to investigate dose penetration as the beam energy is varied.

James Jones, from the ASTeC accelerator physics group, transporting a Daresbury Laboratory purpose-built plasmid sample holder and helping to set-up the experiment.

DEVELOPING DIAGNOSTIC SYSTEMS

In particle accelerators high energy particle beams must be transported from where they are created to where they are used. This can be a journey of only a few centimetres, to many kilometres in the case of the Large Hadron Collider at CERN. On its journey the beam is precisely steered, focussed and accelerated through a vacuum inside a narrow beam tube. Advanced diagnostics are essential to measure the beam trajectory which sometimes must be controlled to within a few millionths of a metre - literally a hair's breadth!

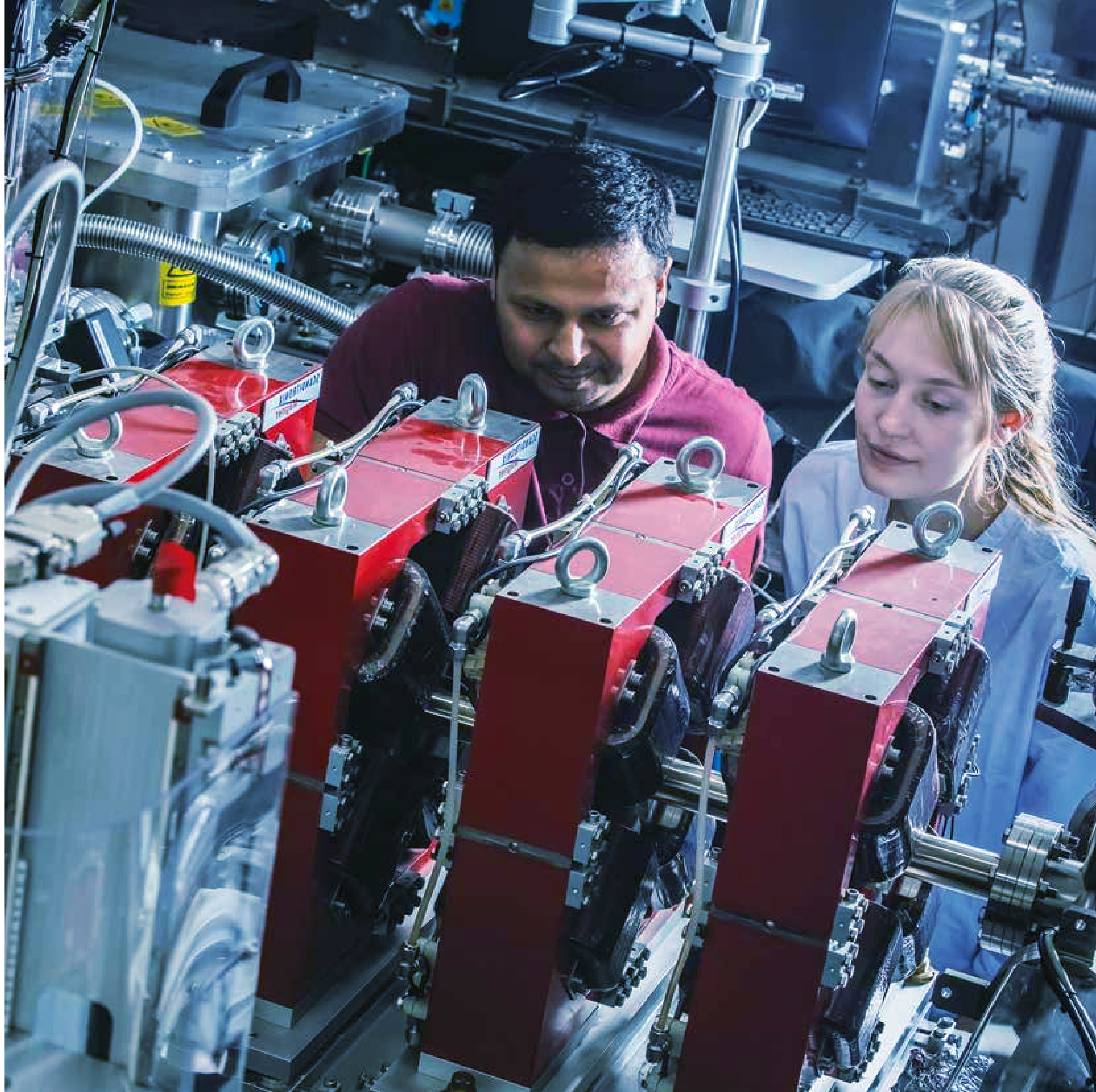
Usually some particles are lost during the journey, through scattering off residual atoms in the beam tube, or scattering off other particles in the beam. This can be a problem for accelerators producing powerful or high energy beams because the lost particles can collide with the accelerator components and heat them up, melt them or make them radioactive. Two advanced technologies were developed and tested on CLARA – cavity Beam Position Monitors (cBPMs) for measuring the beam trajectory, and optical Beam Loss Monitors (oBLMs) for measuring and locating any beam loss.

cBPMs are hollow cavities in the beam tube which pick up the electromagnetic signal of the passing beam. This signal can be analysed to determine the position of the beam to within a millionth of a meter.

The beam tests on CLARA allowed the team to develop and automate the processing electronics which calculate the beam position from the cavity signal.

oBLMs use optical fibres to detect showers of radiation given off when particles are lost in the accelerator. The fibres are connected to advanced photo detectors. When a stray particle crosses a fibre, it creates a light pulse that can be recorded giving high temporal and spatial resolution. The CLARA electron beam was used to calibrate and test a prototype oBLM system to probe the full range of its capabilities.

Because of the wide applicability of diagnostic devices for accelerators they are ideally suited for development into commercial products, generating both scientific and economic return. This is the aim for the cBPM system which has been developed by Royal Holloway University and FMB Oxford, with financial support from the STFC Innovations Partnership Scheme. The oBLM system has been spun out into the start-up company D-Beam which recently became a STFC CERN Business Incubation Centre Alumni. D-Beam worked in collaboration with ASTeC and STFC Technology department on the CLARA beam tests.



EXPLORING NEW DIAGNOSTIC IDEAS

The cBPM and oBLM tests on CLARA will help develop relatively well-proven diagnostic techniques into commercial products. Two other international research groups used the CLARA beam to do 'proof-of-principle' experiments to demonstrate more novel diagnostic techniques.

The first experiment was done by a group from the Paul Scherrer Institute in Switzerland. They aimed to demonstrate a new technique for measuring electron bunch durations. Accurately measuring the duration of a bunch has become increasingly challenging as scientists have learnt how to produce the ever shorter bunches needed to unlock new scientific discoveries. To measure femtosecond scale bunches new approaches are now required.

One existing method is to use a streak camera which rotates the bunch and images it on a screen - the measurement of the bunch duration is translated from an extremely difficult timing problem into a much simpler measurement of the width of an image. However, the radio-frequency wave used to rotate the bunch becomes less effective as the bunch duration falls below a few femtoseconds. In their new approach, the group rotated the CLARA electron bunch using a small split ring resonator energised by THz radiation generated by a high power laser, then imaged the rotated bunch on a screen. Once all the elements were perfectly synchronised and aligned, the team saw changes in the image width, validating the concept and providing a solid basis for further research.

The second experiment was done by a team from DESY in Hamburg, along with their UK collaborators. Here, a gas plume was ionised by a high power laser. Firing the CLARA beam through the plasma then enhanced the level of ionisation, producing a plasma afterglow that indicated the relative position of the electron beam with respect to the laser beam. In future experiments this could provide a reliable diagnostic for optimising the alignment of short-pulse laser and particle beam systems.

These two experiments were funded via the ARIES transnational access programme, one of a number of programmes STFC is involved in that are cofunded under the European Commission's Horizon 2020 Research and Innovation programme. ARIES aims to transfer particle accelerator technology innovations into industry for economic and societal benefit by providing free transnational access to R&D infrastructure across Europe.

WORKING WITH INDUSTRY

ASTeC has been working with industrial partners in two major particle accelerator projects, helping to bring accelerator technology to market.

ADVANCED ONCOTHERAPY'S LIGHT SYSTEM

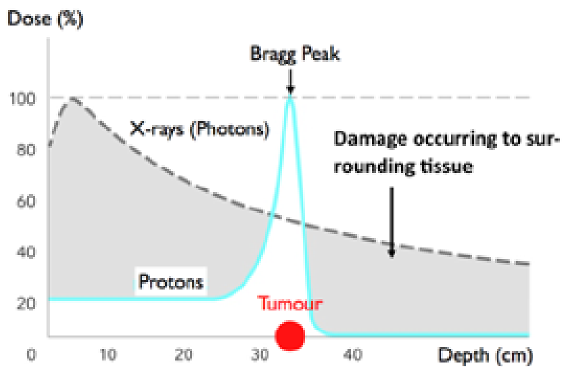
STFC began work in 2018 to prepare a major assembly and testing centre for Advanced Oncotherapy's LIGHT (Linac for Image Guided Hadron Therapy) proton therapy system at Daresbury Laboratory.

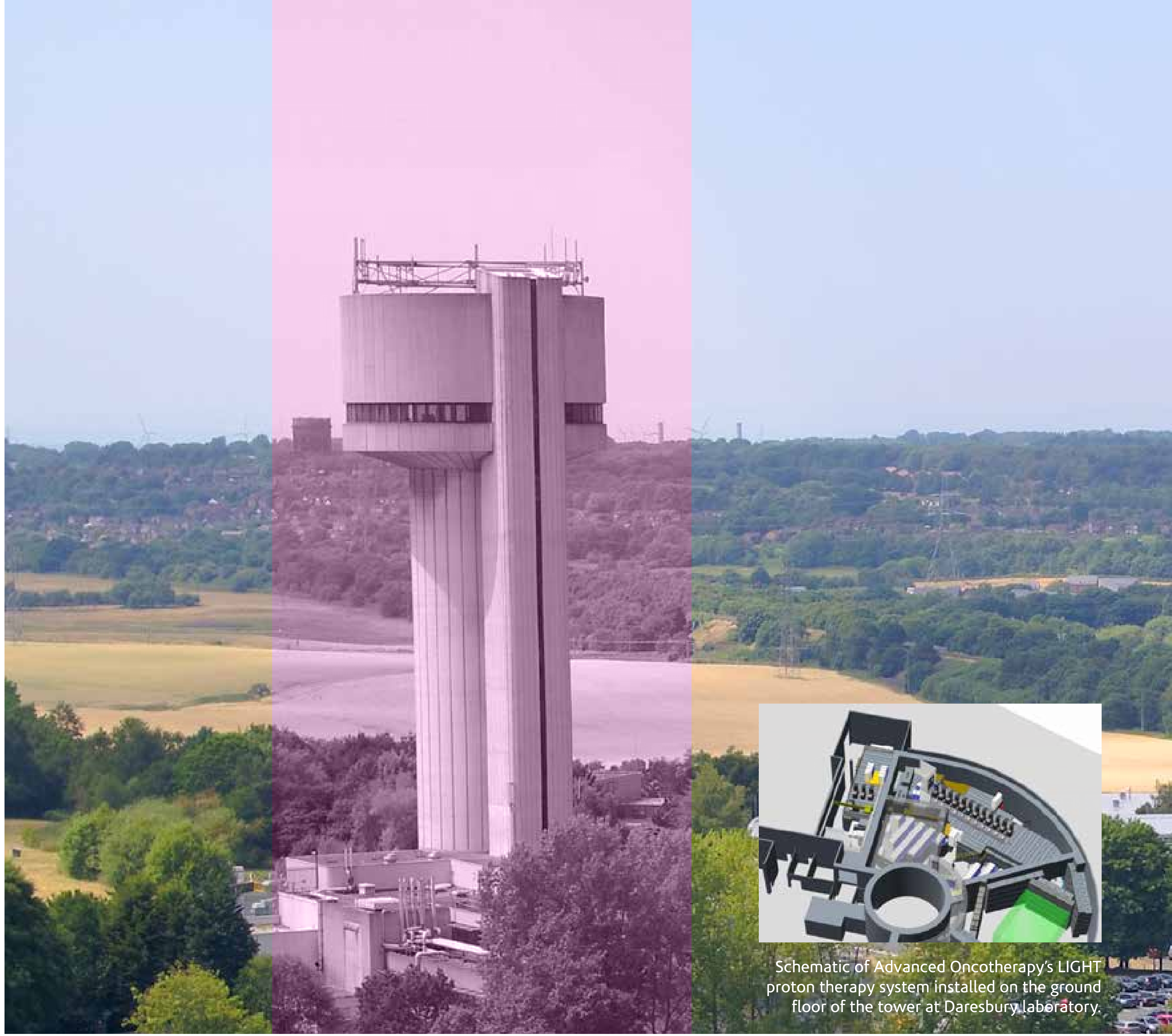
Radiotherapy is used to treat cancer. Ionizing radiation controls or kills malignant cells by damaging the DNA of cancerous tissue, which is vulnerable because of its high rate of division and reduced ability to repair DNA damage. However, healthy tissue can also be damaged in this process resulting in unwanted side effects.

The most common form of radiotherapy is X-ray (or photon) radiotherapy. Although effective, this does have drawbacks. X-rays are electromagnetic waves that have no mass or charge. They travel straight through the patient's body with the radiation dose gradually decreasing through the tissue, but cause unwanted damage to the surrounding healthy tissue. This effect is minimised by aiming the beam at the tumour from a number of angles, but inevitably healthy tissue is affected. An alternative is to use protons.
These are heavy particles that penetrate matter to a depth which depends on the energy of the beam. Unlike x-ray radiotherapy, proton therapy deposits the dose over a narrow range called the Bragg Peak.

Because of this, proton therapy is particularly useful when it is most important to avoid damaging surrounding healthy tissue, for example when treating head and neck tumours or paediatric cancers.

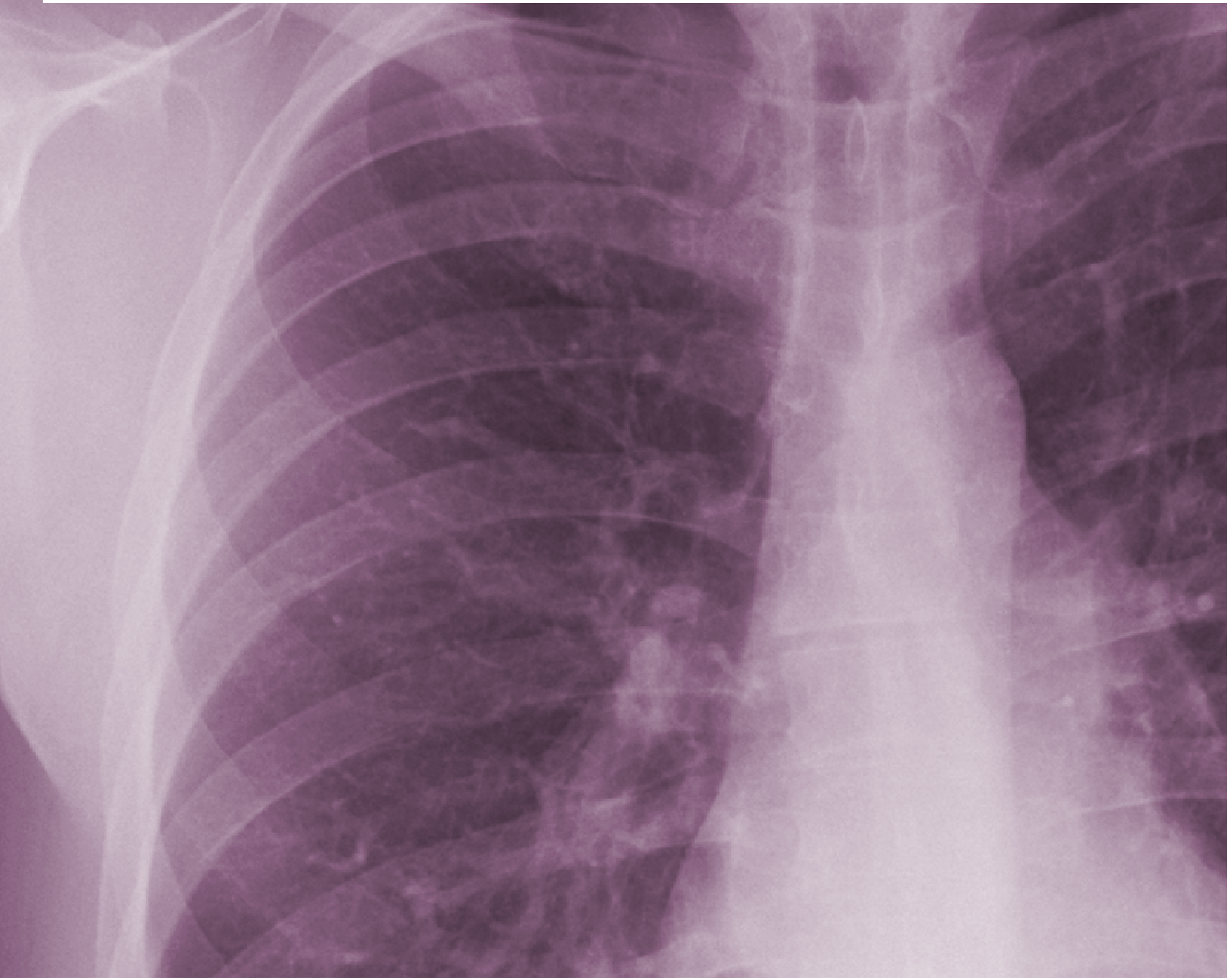
Commenting, Nicolas Serandour, CEO of Advanced Oncotherapy, said: "Our agreement with the Science and Technology Facilities Council is an important step towards the construction of our first fully operational LIGHT system, to be constructed within the UK's accelerator research and innovation hub. Having a facility with established infrastructure, a certified site and a huge wealth of shared knowledge in the area of accelerators allows us to quickly move forward the construction of the first commercial LIGHT system in a cost-effective way…"





Schematic of Advanced Oncotherapy's LIGHT proton therapy system installed on the ground floor of the tower at Daresbury laboratory.

STFC AND TELEDYNE E2V COLLABORATION



ASTeC, Technology Department and Teledyne e2v have formed a strategic relationship to advance the next generation of particle accelerator technologies and bring new opportunities for UK industry. Teledyne e2v are using the Compact Linac accelerator and radiation enclosure at STFC's Daresbury Laboratory to develop new products and integrated RF and X-ray systems, and will also deliver technical support to help ASTeC deliver its own programmes.

The Compact Linac is a small electron gun and linear accelerator which is housed in a fully supported radiation test enclosure. It is specially designed for industrial markets such as security scanning, healthcare and environment. Until recently it used a 3.5 MeV accelerating cavity designed by Lancaster University and STFC. Teledyne e2v have now provided a new 6 MeV accelerating cavity manufactured by one of its technology partners, Accelerad. This makes the facility better suited to testing new radiotherapy and security scanning technologies.

The flexibility of the system will enable Teledyne e2v to assess the impact of new products and system designs against the wider performance and reliability aspirations of its customers. In parallel, ASTeC can use the infrastructure to expand its societal application programmes in high impact sectors such as healthcare, environmental science and security.

Dr Ewan Livingstone, President of RF Power Commercial at Teledyne-e2v, commented: "Teledyne e2v is delighted to be collaborating with STFC. The collaboration provides Teledyne e2v with access to the Council's world class facilities and people. It is a fantastic platform for joint innovation and is already helping us to accelerate the development of new products and solutions for our customers."

PERSONAL PERSPECTIVES ABROAD

Accelerator Science is an international activity, with researchers across the world collaborating on shared projects. Sometimes these collaborations are formal and large scale, involving many scientists and engineers from each partner. Often however, small informal collaborations develop and scientists working on common problems visit each other's laboratories to work together on finding solutions. Here some ASTeC scientists report on their own personal experiences of such working visits.

DAVE DUNNING

ON HIS VISITS TO UPPSALA UNIVERSITY IN SWEDEN

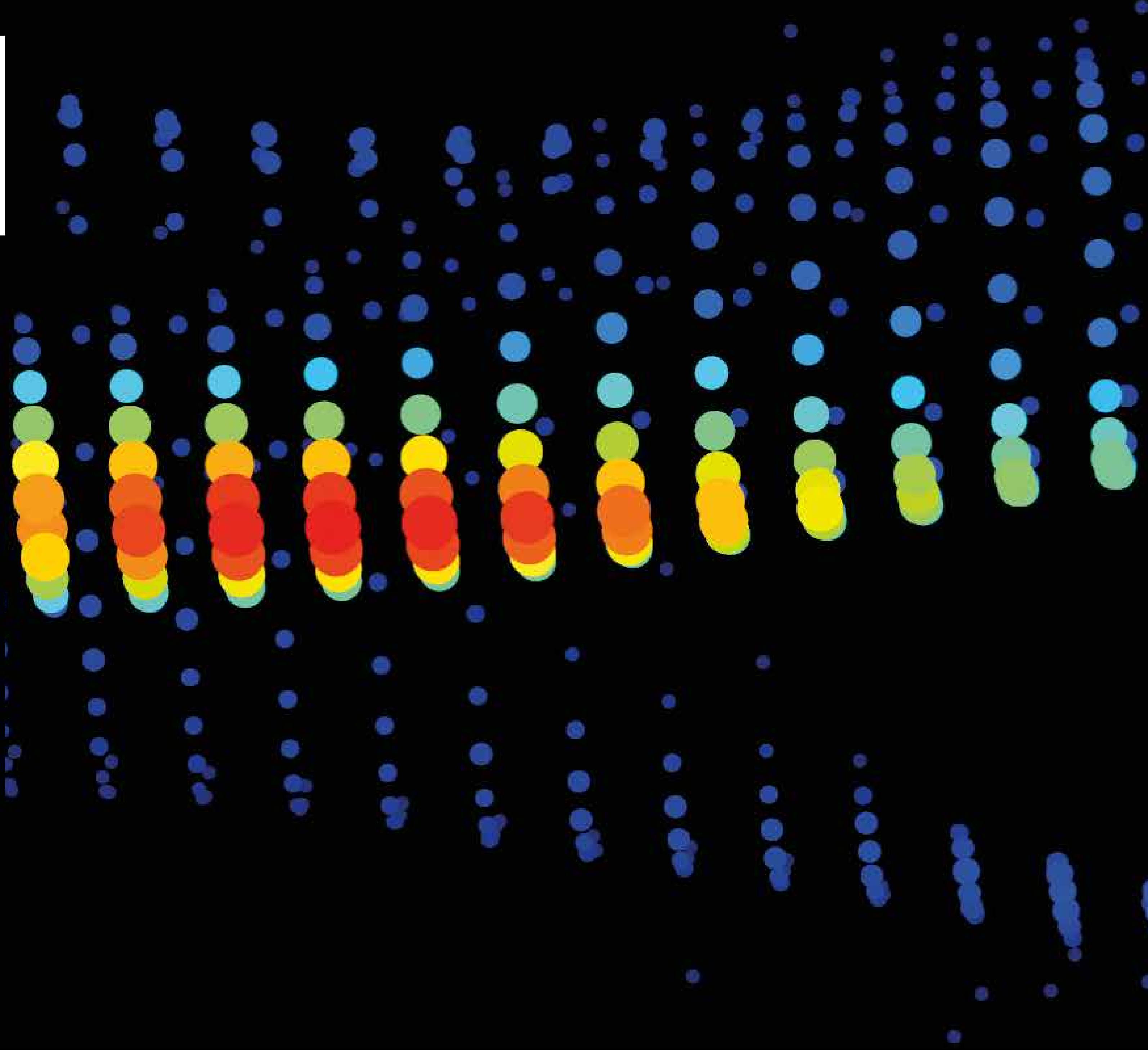
“One of our main aims in ASTeC is to improve the properties of FEL light pulses, for example to make them significantly brighter and shorter. FEL pulses are presently femtoseconds (10^{-15}s) in duration but over recent years we’ve developed ideas to improve this to attoseconds (10^{-18}s). To put this in context there are roughly as many attoseconds in a second as there are seconds in the entire history of the universe!

We recently co-founded an international consortium called LUSIA (Attosecond SIngle-cycle Undulator Light) led by Uppsala University in Sweden, so that we can work together to push the durations of FEL pulses toward the ultimate limits.

I have now made several visits to Uppsala as a visiting researcher. My first visit was for two weeks at the end of winter, with Uppsala under a layer of snow and ice. It was great to join the team at the Angstrom Laboratory and work on various topics including short FEL pulse techniques for Sweden’s proposed FEL facility at MAX IV laboratory. My second trip saw Uppsala transformed with the build-up to Valborg (Walpurgis Night) marking the arrival of spring – and hot, sunny weather.

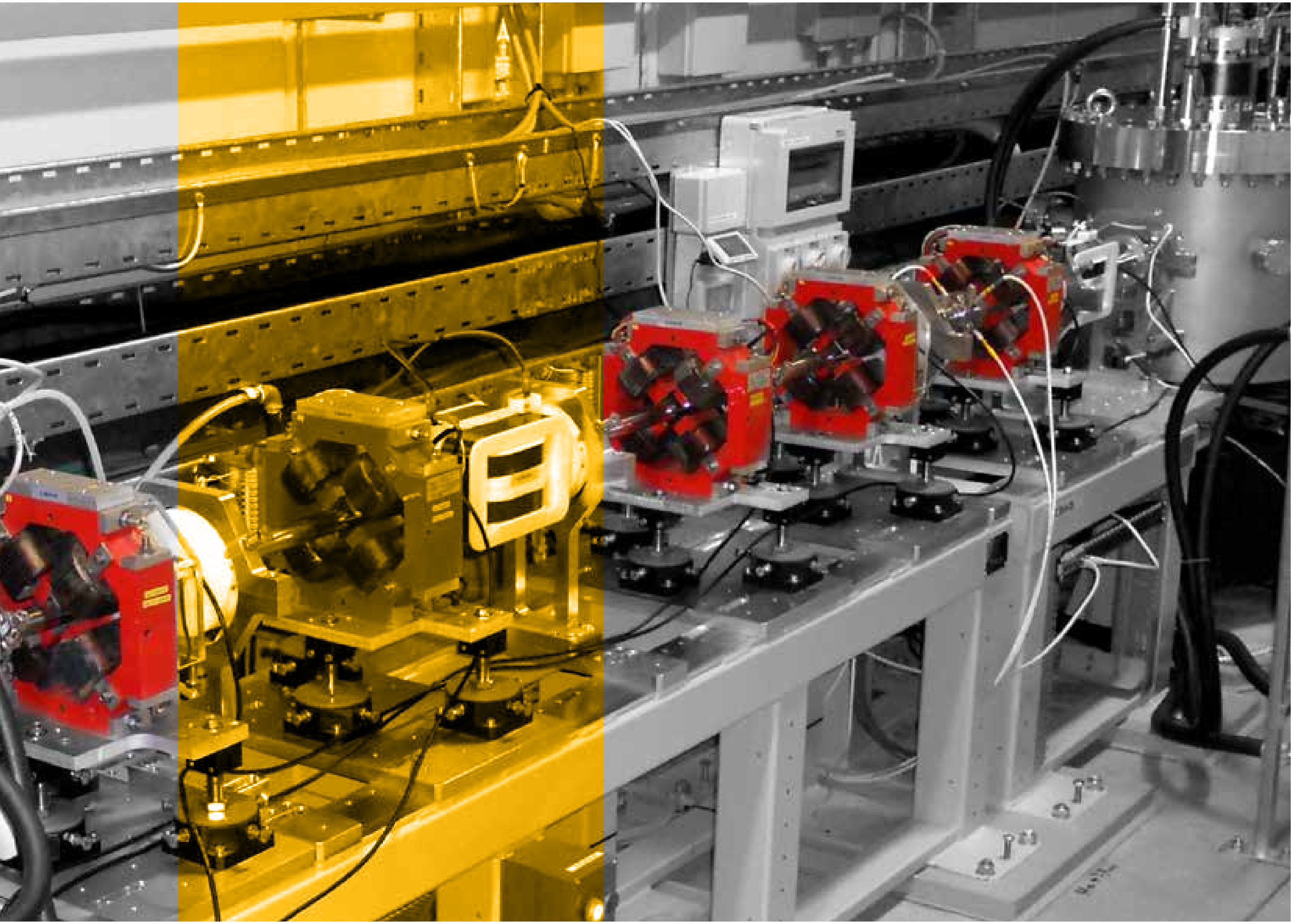
The lawn outside the laboratory was a hive of activity with students building boats to race down the Fyris River. Inside, our work included investigating how to deliver short FEL pulses to experiments in a compact, inexpensive way. In a later trip I also got the opportunity to visit MAX IV, tour their facilities, and discuss our work on FELs.The projects that I’ve worked on as part of this collaboration are very relevant for UK ambitions for a new FEL facility. It was very useful to spend time in another group to share different perspectives and generate new ideas.”

Dave Dunning in Uppsala University’s FREIA laboratory



ALEX BRYNES

ON HIS VISIT TO THE FERMI ACCELERATOR IN ITALY



“We started working together with the FERMI free-electron laser (FEL) team at Elettra Sincotrone Trieste in Italy in 2016, because we all wanted to understand ‘collective effects’ in high-brightness electron accelerators. These are the effects that arise when the particles in a bunch interact with each other, and can really degrade the beam properties, so it is important to do real experiments on an accelerator.

I spent a week at the FERMI accelerator in 2017 leading an experiment to study the influence of collective effects on the accelerator performance. It was valuable to work at a user facility, and I learned a lot about the technical operation of the machine and how the operators set things up to meet the demands of the experiment. There were some interesting parallels between the way that the Daresbury accelerators and FERMI are operated, and I learnt a few things during the week that we’ve now implemented on CLARA. The FERMI team were very accommodating, ensuring I was made to feel welcome during my visit and giving me full control of their accelerator.

I am still working on analysing the data and planning future experiments. One of the key results obtained during the week - a study of coherent synchrotron radiation (CSR) emitted in the first magnetic bunch compressor at FERMI, and how this affected the beam properties - was published in 2018, and I have now been invited to do a talk on the subject at the Free-Electron Laser conference in August ’19. The results showed the effect of CSR on the beam quality over a wider parameter range than had been studied previously and showed how the theory and simulations matched up to the experiment. We now know where the theory is valid and where it isn’t.

The second half of the experiment looked at how self-interactions between the electrons can cause unwelcome small-scale structure, or ‘microbunching’, to develop and grow as the beam is transported.
I developed a novel method of analysis which literally revealed another dimension to the problem – structure growth in the electron energy distribution as well as in the electron positions. Thanks to ASTeC’s role in planning, running and analysing these experiments we have made further steps towards building better accelerators in the future. "

JAMES JONES

ON HIS VISIT TO CORNELL UNIVERSITY IN THE USA

"The CBETA (Cornell-Brookhaven Energy recovery linac Test Accelerator) is an advanced accelerator concept currently being commissioned at Cornell University in upstate New York, and built in collaboration with Brookhaven National Laboratory.
The aim is to demonstrate an accelerator that simultaneously uses two advanced concepts in accelerator technology which will both enable smaller and cheaper accelerators.
The first concept is the Energy Recovery Linac - this accelerates a particle bunch, then after the particles have been used it decelerates them and recovers their energy which can be used to accelerate a new bunch of particles. Experiments done at Daresbury Laboratory on the ALICE energy-recovery-linac have demonstrated efficiencies of >99% in recovering energy from used electron beams. This represents a significant cost and environmental saving over regular linac-based facilities. The second concept is the use of FFA (Fixed Field Alternating gradient) arcs. These were first demonstrated at another Daresbury accelerator, EMMA, and enable the transport of multiple different energy particle beams in a compact area. This can save not only space, but also running costs for the accelerator, because fewer, smaller magnets can be used.
In fact, CBETA takes this concept one step further by utilising permanent magnets for its FFA arcs – making CBETA a "green", low energy, high efficiency accelerator.

I visited CBETA for three weeks in March, with two colleagues, Bruno Muratori from ASTeC and Joe Crone, a PhD student in the Cockcroft Institute working on advanced ERL concepts. The idea was to use our experience on the ALICE and EMMA accelerators to help with commissioning the accelerator complex, giving advice to the Cornell physicists and sharing in their successes. The main technical aim was to demonstrate the first energy-recovery in single-loop mode. In this mode the electron beam is accelerated, traversing the FFA arcs in one loop, and is then decelerated.

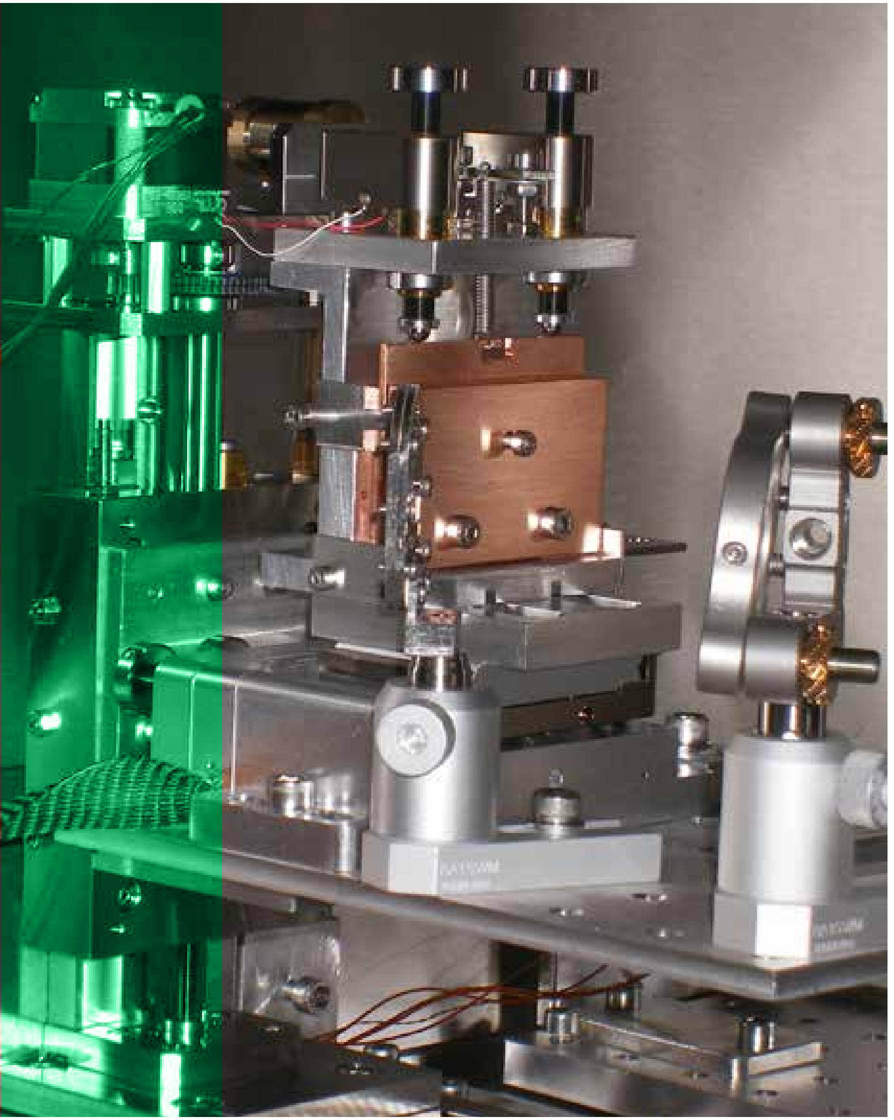
We achieved transport through both FFA arcs, correcting the beam orbit and measuring important properties of the permanent magnet sections, then got the beam all the way back to the entrance of the linac, where it would be decelerated, but we couldn't manage this final step to energy recovery because there was a small piece of vacuum pipe missing! Despite just missing this milestone event the visit was a great success, and in fact CBETA achieved energy recovery a few days later.

While in the USA Bruno gave lectures at Cornell, Jefferson Laboratory and Brookhaven Laboratory on a new model of fringe-field effects in magnets, which was very well received. I also went to Brookhaven and Cornell, having many fruitful discussions on accelerator working practices, and I think my seminars on running CLARA were well-received too! Joe's visit was also successful and he will be returning for six months in the Fall."

FUTURE ACCELERATORS

Particle accelerators are a vital tool for scientific research and industrial applications. This year ASTeC has been involved in two critical stages of the accelerator life-cycle: the underpinning R&D that generates those new ideas that improve or revolutionise the accelerators of the future, and the active involvement in building and testing two new large-scale facilities that scientists will eventually use to help us understand the nature of the universe.

NOVEL ACCELERATION USING DIELECTRIC WAKEFIELDS



The demand for higher energy particle beams will eventually become unsustainable due to the size and cost of 'conventional' radio-frequency (RF) accelerators. Methods of high-gradient novel acceleration could revolutionize research and innovation within the UK by providing high quality, high energy beams in a compact system. Novel accelerators could bring the benefits of particle accelerators – only realised at centralised national facilities – into the laboratory, hospital and factory environments.

Dielectric Wakefield Acceleration (DWA) is one novel concept to deliver much higher accelerating gradients than RF accelerators The method works by passing a sub-picosecond 'drive' electron bunch through a dielectric lined waveguide with a mm aperture.

This generates an electromagnetic field in the waveguide which is used to accelerate a smaller trailing bunch. In addition, DWA structures can generate powerful narrow band terahertz (THz) radiation and can be used as a diagnostic for ultra-short electron bunches.

This year ASTeC scientists conducted the first DWA experiments in the UK, using the CLARA facility. They showed they could generate continuously tunable THz with a dielectric lined waveguide (DLW) driven by short electron bunches.

The DLW was a planar structure with a variable 0.2-2.0mm gap and thin 25μm quartz dielectric plates. The THz was tuned over a wide frequency range, from 0.55-0.95 THz, and the radiation generated was single frequency with less than 50GHz bandwidth.

The scientists also used the DLW structure, and similar ones with thicker 100 and 200μm dielectric plates, to study the effect of the wakefield on the drive bunch and compare with simulated and theoretical predictions. They observed electron energy modulation along the bunch (which can be used for producing bunch trains and as a longitudinal diagnostic of longer bunches), transverse streaking when the bunch is off-axis (which can be used as a passive longitudinal diagnostic of ultra-short electron bunches) and energy dechirping (which can be used to reduce the effective energy spread of electron bunches). Nearly 8MV/m of decelerating wakefield was measured, implying approximately 15MV/m accelerating field behind the 70pC drive bunch.

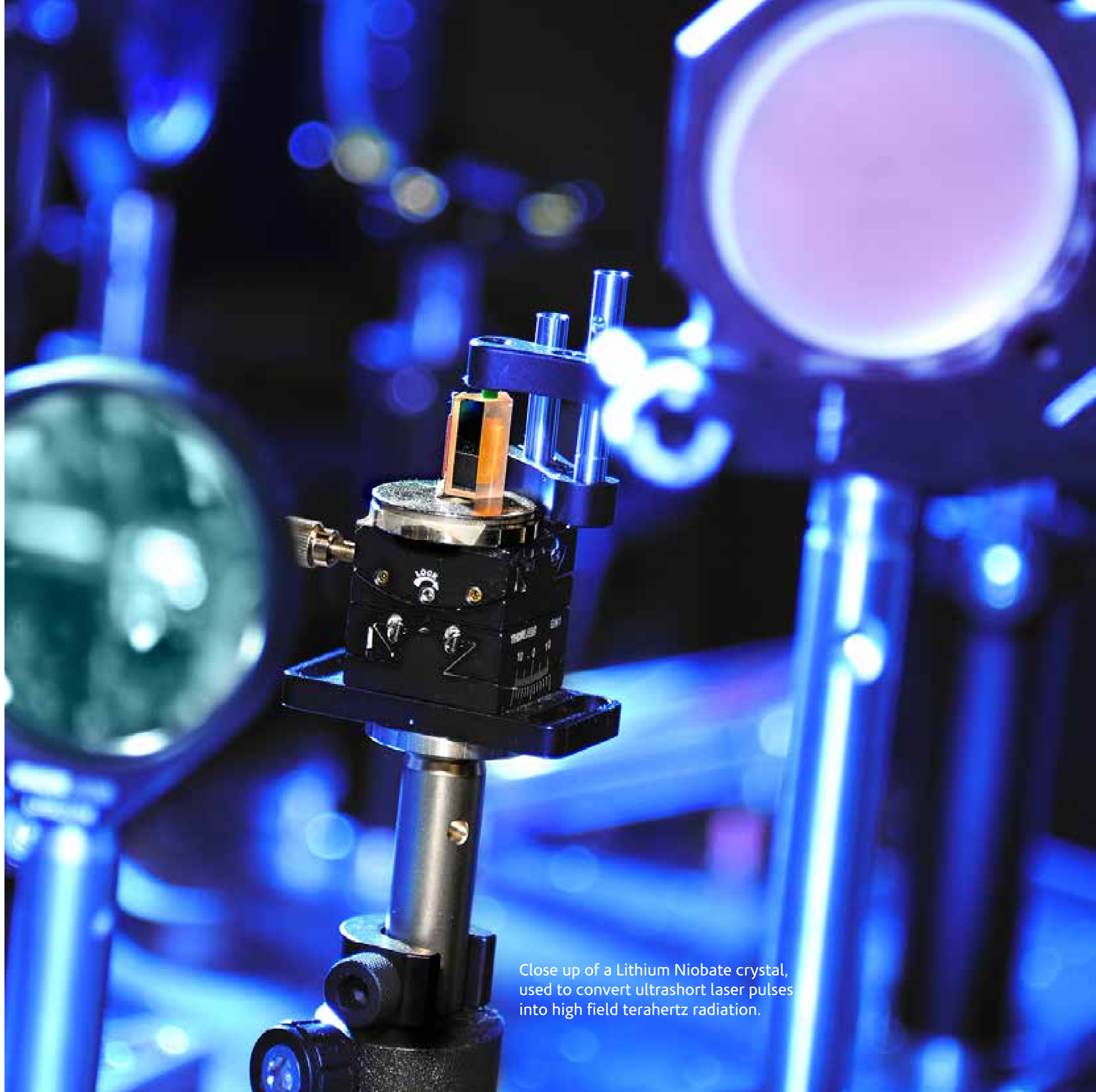
These first experiments confirmed CLARA's capability for DWA studies, opening up new research avenues for the facility and letting ASTeC join the international effort to develop the concept. They also pave the way to successful implementation of a full scale dielectric energy dechirper being currently developed for the CLARA FEL.

NOVEL ACCELERATION USING TERAHERTZ RADIATION

The strong electromagnetic fields needed to produce high accelerating gradients can also be provided directly by focussed high energy optical lasers. By coupling the laser into a dielectric structure, the laser radiation can interact with and accelerate charged particles. The size of the accelerating structure scales with the wavelength of the electric field which is 1 μm - this means that laser structures can be over 10000 times smaller than conventional RF cavities. The technique was demonstrated in the USA in 2013. However, progress since has been slow, because it is hard to inject the particle beam into these very small structures. Also, injecting a beam longer than the laser period of 3 femtoseconds will give as much deceleration as acceleration because the particle bunch sees both the positive and negative cycles of the electric field.

To address this issue ASTeC scientists in the Femtosecond Lasers and Timing Group, working with colleagues in the Cockcroft Institute, have been investigating particle acceleration using terahertz (THz) radiation with wavelength 100 μm – this is approximately 100 times larger than optical radiation which allows much easier injection of an external particle beam. The longer time period of the THz allows particle bunches of 100 fs in duration – such as those produced by the CLARA accelerator at Daresbury Laboratory – to be accelerated.

ASTeC scientists have been developing the high field (>1 GV/m) THz sources which are needed. These work by converting high energy, ultrashort (~100 fs) pulses of optical radiation into THz radiation through optical rectification. The Lasers, Terahertz and Terawatt Experiment (LATTE) Laboratory, adjacent to the CLARA beamline, houses a 800 mJ, 50 fs terawatt laser system which is ideal. The laser light is transported in vacuum to CLARA Beam Area 1 and the THz radiation is then generated close to the electron beam. This allows the exciting possibility of accelerating the CLARA beam with THz radiation, with first experiments planned for early 2019.



Close up of a Lithium Niobate crystal, used to convert ultrashort laser pulses into high field terahertz radiation.

PIP-II

Phase 2 of the Proton Improvement Plan (PIP-II) is a series of connected projects to deliver a high-energy proton beam source at Fermilab in Illinois, USA. The beam will be used to generate streams of neutrinos for the Deep Underground Neutrino Experiment (DUNE) that seeks to understand the origins of matter and provide a clearer picture of the workings of the universe.

The neutrinos generated at Fermilab will pass through the earth to detectors 800 miles away at the Sanford Underground Research Facility in South Dakota. The emitter and detectors (including a 'near-field' detector at the Fermilab site) comprise the Long-Baseline Neutrino Facility. The experiments will help scientists answer some funadmental questions about the universe. For example, by studying neutrino oscillations DUNE could help us understand whether neutrinos are the reason the universe is made of matter rather than antimatter. DUNE can search for signs of proton decay which could reveal a relation between the stability of matter and the Grand Unification of forces, moving us closer to realising Einstein's dream. And by observing thousands of neutrinos from a core-collapse supernova in the Milky Way scientists can peer inside a newly-formed neutron star and potentially witness the birth of a black hole.

The UK government is supporting PIP-II and the wider DUNE programme with a £65M in-kind contribution of equipment and technical expertise from STFC working in collaboration with UK industry. For PIP-II, Daresbury Laboratory will provide 3 of the 4 cryomodules which accelerate the protons to 90% of the speed of light. Each of these house 6 superconducting radio frequency (SRF) 650 MHz cavities and associated support systems including cryogenic cooling, cavity coupling, cavity tuning systems and magnetic & thermal shielding arrangements. To keep the frequency exactly at 650 MHz the cavities and their support systems will be mounted on a single strongback support within the cryomodule.

ASTeC is leading four work packages with tangible outputs, from installation of cleanrooms and RF power equipment to enable cavity testing to working with The Welding Institute to develop a UK industrial capability for large SRF cavity manufacture, to manufacturing cavities and qualifying them in the SuRFLab, to integrating and transporting the completed cryomodules.

THE EUROPEAN SPALLATION SOURCE

The first STFC superconducting cavity after welding, ready for surface treatment.

The European Spallation Source (ESS) being built in Sweden is one of Europe's largest planned research infrastructures and will be the world's leading spallation neutron source. It will produce neutrons by colliding the world's highest power proton beam with a five-tonne, helium cooled tungsten target. The neutrons will be scattered off samples such as high-temperature superconductors, polymers, metals, and biological specimens, and by counting the energies and the angles at which the neutrons scatter the molecular and magnetic structure of the sample can be revealed. ESS is supported by 13 countries, 38 in-kind contributors and over 120 collaborators globally. When finished, it will be used for scientific research in life sciences, energy, environmental technology, cultural heritage and fundamental physics.

As requested by users, ESS will provide long, high intensity neutron pulses to enable new science with small and complex samples. This means the protons which are used to produce the neutrons must also be accelerated in long (3 millisecond) bunches. This happens 14 times per second, up to an energy of 2 GeV, in a sequence of normal conducting RF and superconducting RF (SRF) linear accelerators. SRF is used to ensure efficient high gradient acceleration in what is a small physical footprint for such a long-pulse machine.

One of STFC's responsibilities is to provide the elliptical superconducting cavities. These will be made by industry and shipped to Daresbury Laboratory for qualification testing in the Vertical Test Facility (VTF) in the Superconducting RF Laboratory (SuRF lab), before being sent on to CEA Saclay in France for integration into the 21 linac cryomodules.

The VTF was built throughout 2018/19 with test operations on an early ESS prototype cavity in March 2019. Systems commissioned include the large 2m diameter, 4m high cryostat now integrated with the liquid helium supply; radiation shielding and personnel safety systems; UHV/XHV vacuum pumping systems for independent cavity pumping and monitoring; modular 'glovebox' cleanrooms for particulate-level cleanliness when connecting cavities; and the RF system with a bespoke low-level RF control system.

Preparations for cavity manufacturing have also gone well with the award of the manufacturing contract to RI Research Instruments GmbH and the receipt of the remaining high-purity Niobium for cavity manufacture – in total around 7600kg of 99.9% or greater pure metal. This material was tested for surface quality using a technique called Eddy Current Scanning, and work was started on fabricating components for the first cavity.

Next year the teams will commission, validate and optimise the VTF which will include testing with multiple cavities, automating processes where possible and performing benchmark cross-references with other laboratories. They will also finalise the first cavity, qualify all remaining production processes, and launch the series cavity production.

STFC and DESY staff inspecting high purity niobium disc blanks at OTIC Ningxia, China.

Another STFC contribution for ESS is the Beam Transport Module (BTM) project. This has many elements - cleanrooms for minimising the number of particles inside the vacuum system, 'dummy' cryo-modules which will go in place of the actual cryo-modules until they are ready to be installed, beam drift tubes, vacuum pumping systems and the 74 Linac Warm Units (LWUs). The LWUs are the short, non-superconducting (hence 'warm'), beam transport sections that go between the superconducting linac cryomodules. Each LWU contains diagnostics for measuring the proton beam, vacuum equipment and steering and focussing magnets, all of which need to be aligned to an accuracy of 100 millionths of a metre.

Each LWU has components from at least three other contributors, meaning that this is a crucial time where we find out if all interfaces match up and that there have been no communication errors along the way. Given that there are 15 variants of LWUs to produce it'll be another year before STFC Daresbury have delivered all the LWUs and confirm everything fits together as expected.

All the components have been manufactured in the UK which has provided an economic boost to UK vacuum technology and local manufacturing companies.

The first two Linac Warm Units (LWUs) ready for delivery to ESS. 74 of these will be installed.

PUBLICATIONS

JOURNAL PAPERS

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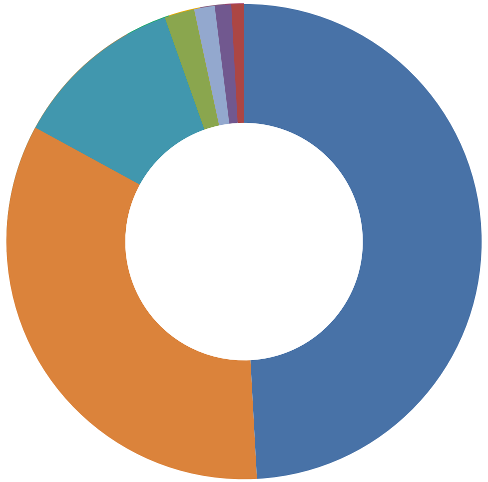
FINANCE 2018 -19

INCOME SOURCES

	£k
STFC ASTeC core	£10,405
STFC other funding	£182
EU	£432
International Laboratories	£236
Industry	£2,462
ESS	£7,162
Other (CI Grant and events)	£298
Total	**£21,176**

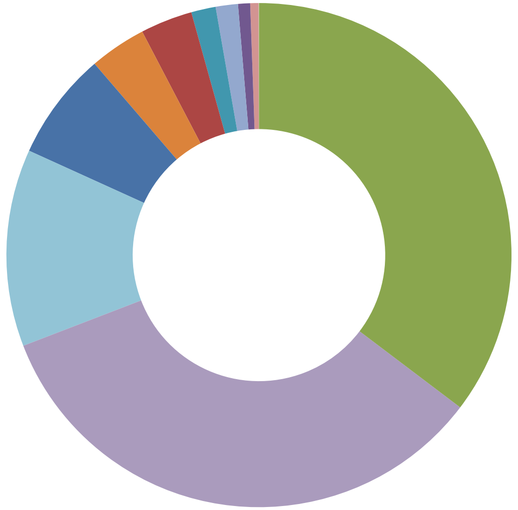


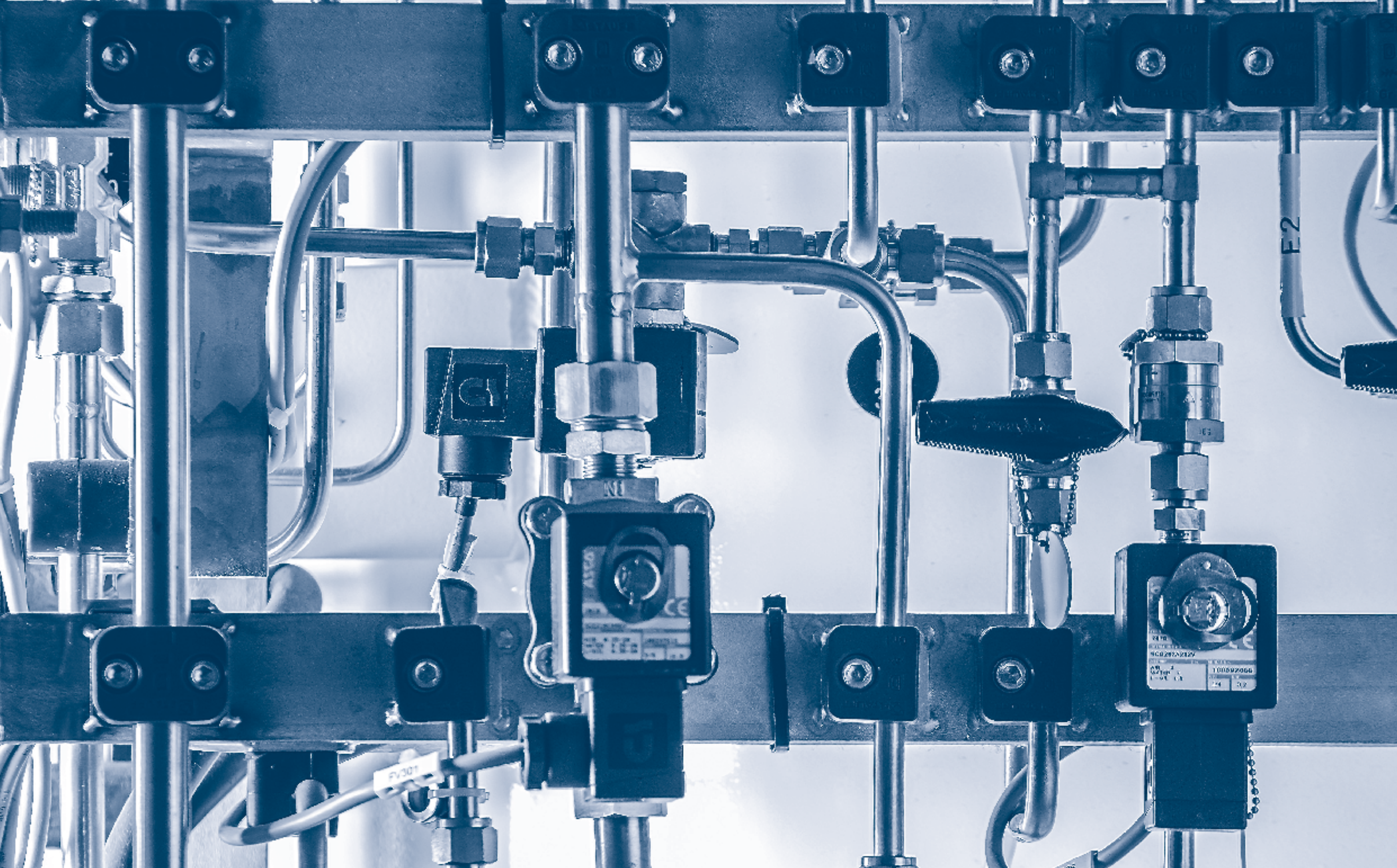
EXPENDITURE TYPE

	£K
Scientific & Engineering Staff Costs	£7,508
Cosumables	£10,476
Capital Expenditure	£3,192
Total	**£21,176**

EXPENDITURE BY PROGRAMME

	£k
High Brightness Electron Accelerators	£1,466
EU Programmes	£705
CLARA Project	£7,480
VELA Project	£163
Cockcroft Inst & New Initiatives	£332
Underpinning Research	£770
UK_NF Programme	£301
Photon Studies	£113
High Power Proton Accelerators	£5
ESS	£7,162
Other Repayment work	£2,679
Total	**£21,176**





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