Accelerator Science and Technology Centre

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Annual Report

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Accelerator Science and Technology Centre

Annual Report
2006 – 2007

This report covers the work accomplished by the
Accelerator Science & Technology Centre
(ASTeC) for the financial year 2006 – 2007.

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Foreword

This has been a year in which ASTeC has continued to consolidate its leading position in UK accelerator R&D activities, whilst also having a growing impact internationally. These achievements have only been possible due to the efforts of all our staff, not only due to their many skills but also to their dedication to our many projects.

This year we moved into our new building to join up even more closely with our university colleagues in the Cockcroft Institute. This was more than a symbolic gesture as it has led to a deep integration of staff and beneficial cross-fertilisation of cultures. It is a unique venture even on the world scene and the success owes much to the founding CI Director, John Dainton, for his extraordinary vision. As I write we have a new Director, Swapan Chattopadhyay, who has brought his own enthusiasm and aptitude to the emerging challenges that face not only the Institute but the wider UK community. There is absolutely no doubt that ASTeC can face the future much the stronger for being a part of the evolving Cockcroft umbrella.

On the Daresbury site ASTeC has met many challenges in taking forward the ERLP project through design and construction to its commissioning phase, with first beam from the photoinjector already achieved by mid-2006. In parallel our staff had key roles in the design activities leading up to the publication of the 4GLS Conceptual Design Report and then in the subsequent cost optimisation process. This combination of experimental and theoretical challenges is exactly why ASTeC exists and on what it thrives. A new and exciting challenge now lies ahead with the confirmation of funding for EMMA, a revolutionary proof of principle accelerator with a range of possible applications. In support of the particle physics communities ASTeC has continued with its Linear Collider studies and has an increasingly high world profile, with our international partners offering us leadership in key areas. In parallel we provide the core of the conceptual design team developing the Neutrino Factory. In addition ASTeC promotes associated technology developments, especially in the areas of high intensity proton accelerators and high power targets, and these experimental developments underpin other important applications such as next generation spallation neutron source solutions.

Supplementing these specific project preparation schemes ASTeC pursues a programme of state-of-the-art underpinning technology. Not only does this advance the fields of magnetics, vacuum science and RF technology but it also sustains an important UK skill base together with the ability to contribute to other evolving programmes on a national and international level.

ASTeC was proud to co-host the 2006 European Particle Accelerator Conference, and to provide its Chairman and other support effort. Demonstrable international impact is one of our most important objectives and there have been many other workshops and meetings during the year. We are committed to such collaborations and all the stronger for them.

I believe that ASTeC has established its vital and leading role as a UK resource for accelerator science and technology. With the creation of a new merged Research Council there is an opportunity to consolidate its position but also better to exploit the synergies in advanced accelerator development in support of the wide variety of potential application areas. In all of this our most important resource will continue to be our staff and I thank them for all the efforts described in this Report.

Mike Poole

Contents

Progress on the Energy Recovery Linac Prototype

The Tower at Daresbury Laboratory is an obvious landmark. Once home to the world's highest energy Van de Graaff generator, the tower is continuing its cutting- edge role and now hosting one of the most exciting accelerator projects in the world.

Inside lies a colourful array of components, snaking their way around the base of the tower. This machine is the Energy Recovery Linac Prototype (ERLP) – a technology demonstrator for the 4th Generation Light Source (4GLS) or other advanced light sources.

Unlike more conventional particle accelerators, ERLP will be able to decelerate particles as well as accelerate them. This has never been done before in Europe. The deceleration process recovers energy from the particles, which can be used subsequently to accelerate new particles, dramatically decreasing the amount of power consumed by the accelerator and enabling higher-current electron beams to be used.

Primarily the purpose of ERLP is to study the beam dynamics and accelerator technology relevant to 4GLS. In particular scientists will be able to gain experience of operating a photoinjector gun and superconducting linacs, producing and maintaining high-brightness electron beams, achieving energy recovery and studying challenging synchronisation issues.

However, ERLP is not just a prototype for 4GLS: it will also be used as a test-bed for other new accelerator and photon science developments. An example is the EMMA project (*see report on page 16*), an electron model of a novel proton accelerator with many applications in radiotherapy and neutrino factories.

Key Milestones

Over the last year a number of significant milestones have been achieved:

- The first electrons have been obtained from the photoinjector electron gun.
- Most of the machine is now assembled and in place.
- High-power radio frequency tests have been carried out on the linac module and synchronisation of the radio frequency system with the photoinjector drive laser has been demonstrated.
- The cryogenic system has been installed and operated – cooling down the linac and booster to 2K.
- Last, but not least, a terawatt laser, to drive a Compton backscattering x-ray source and electro-optic longitudinal beam diagnostics, has been commissioned.

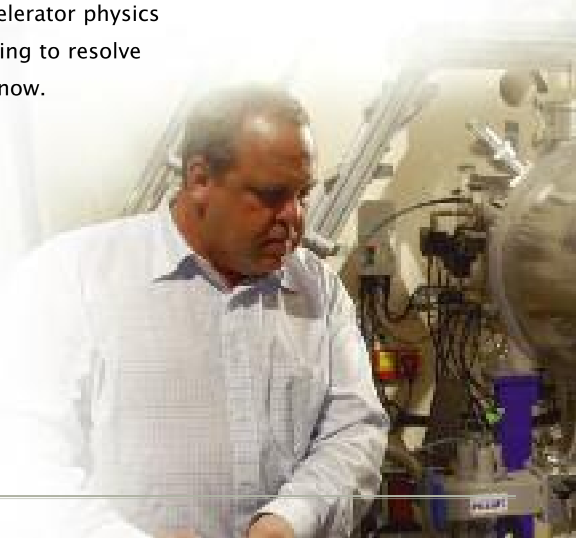
Firing the gun

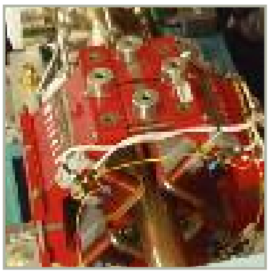
On August 16th 2006 the first electron beam was produced from the photoinjector electron gun. Using a dedicated gun diagnostic beamline the gun output has been characterised and compared to the properties predicted by simulation software. These measurements are very important for the design of the 4GLS electron guns, which have exacting performance requirements. Basic properties such as the energy, energy-spread and charge, and a crude measurement of beam size were obtained. The team still need to measure the emittance (a combination of the beam size and its divergence) and hope to do this later in 2007.

The photoinjector gun features a cathode that is designed to produce electrons in response to being illuminated by short pulses of laser light. The electrons are then accelerated immediately by a very high static electric field.

Pulses from the photoinjector laser have been synchronised with the machine radio frequency system, using a feedback control system provided by the laser manufacturer. Sub-picosecond timing jitter has been routinely achieved and the group are working to reduce this to the 100 femtosecond level.

Problems with the gun have been encountered in two key areas. Firstly, during the cathode activation process, the wanted photocurrent has been swamped by a significantly larger unwanted current, derived from caesium ionisation. This has made the activation process difficult. Secondly, contamination issues following cathode activation have impaired the ability of the gun to operate at the required voltage, and to maintain the XHV conditions required for workable cathode lifetime. The vacuum and accelerator physics groups are working to resolve these problems now.




Installation and commissioning work.

Under construction

Almost all of the machine has now been assembled and the relevant parts are under vacuum. One thing that isn't yet in place is the first linac module (the booster). This is because the gun is currently beaming into a dedicated gun diagnostic beamline. Once tests on the gun have been completed the first linac module will be moved into final position.

All of the ERLP beam transport system was assembled as individual modules on single girders in an ISO Class 100 clean-room, aligned and sealed with dry nitrogen gas. Temporary clean conditions were then established in the work area, prior to the joining of these modules. This was necessary to ensure the exceptionally low levels of particulate contamination required for the vacuum envelope.

Chilling out

In October 2006 the linac and booster modules were cooled down to 2K for the first time. However, the cryosystem (which produces the liquid helium used for cooling) did not have sufficient cooling capacity when the radio frequency power was going in. This has now been resolved and the system finally met its operational specification on 16th May 2007. It is now capable of cooling both modules to below 2K and maintaining this temperature under the dynamic load imposed by high-gradient operation of the linac system.

Progress on the Energy Recovery Linac Prototype continued

Let there be light

In addition to the mid-infrared output from ERLP's Free-Electron Laser (FEL), ERLP has two further state-of-the-art sources:

Inverse-Compton backscattering is a way of generating ultra-short x-ray pulses at a lower-energy accelerator. This will be useful for carrying out experiments in real-time and observing processes as they occur.

Hard x-rays, ranging from 15 keV to 30 keV, depending on the backscattering geometry, will be generated by the interaction of a terawatt laser beam with ERLP's electron beam, in either a head-on or side-on collision geometry. A highly accurate timing synchronisation scheme is being employed to minimise jitter in the x-rays generated. This is currently being constructed at Daresbury, including a commercial laser system which has been purchased and installed in the laser room, alongside the photoinjector laser. In addition this laser will be used for the development of an electro-optic longitudinal diagnostic.

Terahertz radiation will be extracted from the last bending magnet in the bunch compressor where the electron bunch is at its shortest. The radiation will then be transported through the labyrinth into the diagnostic room for measurements and then on to the Tissue Culture Laboratory for experiments aimed at understanding how terahertz radiation affects live cells.

Turning up the power

Rather than waiting for gun commissioning to finish it was decided to commission the booster linac in its temporary position, allowing further time for gun characterisation and keeping the entire programme moving.

High power radio frequency tests have now commenced with the main linac module. One of the cavities has now reached 12 MV/m and conditioning of the input coupler was clearly observed, resulting in a number of vacuum and arc events at greater than 10 MV/m.

However, mechanical failure of the tuner mechanism has temporarily halted progress. Once this has been fixed scientists intend to continue conditioning to higher gradients.

Useful applications

As well as using ERLP to prepare for 4GLS, there are plans to utilise ERLP for other exploitation work. One such project has been started on the Synchrotron Radiation Source (SRS), but will move over to the ERLP in the future.

Working in collaboration with the Photon Science Institute (PSI) of the University of Manchester, ASTeC scientists have developed a high power table-top femtosecond laser system. Currently they are working to synchronise this with pulses from the SRS.
A user group has been established, and several grant applications have followed. The science programme includes a wide-range of pump-probe experiments. For example, a collaboration between Imperial College and the University of Manchester aimed at designing new hybrid solar cells for rooftop microgeneration has recently been funded by EPSRC. In these experiments, ERLP and the SRS will be used with the femtosecond laser system to measure ultra-fast carrier transport in zinc-oxide nanorods.

In all cases, the planned studies provide the groundwork for a part of the future science programme envisaged for 4GLS.

A Diagnostic Screen Image of the First ERLP Electron Beam

The control room on the evening of the first beam

A team effort

Designing, constructing and testing ERLP has been a major team effort. The project is run by the Synchrotron Radiation Department at Daresbury Laboratory, with ASTeC, one of the collaborating departments, alongside Mechanical Engineering, Electrical Engineering, Health Physics, Controls and the Central Laser facility at RAL. Almost all of ASTeC's different groups have been involved. Many scientists have had to work on a shift basis, sacrificing family life to meet the challenging demands of constructing and testing this machine. Much of the most vital work, such as analysing data, writing up code and developing software, will be unseen when the machine is finished, but has been essential for the operation of ERLP.

Along the way the scientists have experienced a number of 'teething' problems and, although frustrating at the time, it is these hiccups that will help ensure the commissioning of the 4GLS goes smoothly. "We learn things by them not working," says David Holder, a member of the accelerator physics group. "It is much better to have these problems now on a simpler, smaller system like ERLP – it is what ERLP is for."

Very soon ERLP will be fully up and running. The Daresbury Tower will continue as a hive of activity, as scientists carry out experiments and test ideas for 4GLS and other future light sources and accelerator projects. From small accelerators, great ideas grow.

Photoinjector Research for ERLP and 4GLS

ASTeC scientists at Daresbury Laboratory have been working on the optimisation of photoinjector electron sources for ERLP and future light sources such as 4GLS.

Photoinjectors exploit laser-stimulated electron emission from a metal or semiconductor surface; in this instance, a type III-V semiconductor material – Gallium arsenide (GaAs). In the case of ERLP (and ultimately 4GLS), photoinjectors are the electron source of choice as they offer electron beams with good controllable time structure, high average current, high brightness and low emittance.

Over the past year scientists within ASTeC's Vacuum Science and Accelerator Physics groups have been familiarising themselves with electron emission from GaAs. After much experimentation they have devised a three-step process for activating the GaAs wafer and maximising the photocathode Quantum Efficiency for ERLP.

The process involved taking a GaAs wafer and cleaning it, by heating it to approximately 560ºC, thus removing the carbon and oxygen over-layers and re-ordering the surface. Once a 'clean' GaAs surface is obtained, alternate layers of caesium followed by either oxygen or nitrogen trifluoride are deposited. This procedure reduces the work function of the surface bringing it to the activated state, thus making the GaAs material emit electrons more efficiently.

To improve understanding of the activation process the photocathode has been studied using surface science techniques such as X-Ray Photoelectron Spectroscopy, Scanning Electron Microscopy, Rutherford Back-Scattering and Atomic Force Microscopy. Results detailing surface composition as a function of temperature and resulting Quantum Efficiency are currently being analysed. It is also planned to study the effect of atomic hydrogen cleaning on the carbon and oxygen over-layers to see if it improves the cleanliness of the GaAs surface.

Vacuum is critical to the lifetime of the GaAs photocathodes. Modern literature suggests that the presence of certain gas species can be detrimental and it is believed that partial pressures of less than 10^{-14} mbar of any oxygen-containing species are required to maximise cathode lifetime. As a result the Vacuum group are investing time and effort in learning how best to achieve these kinds of vacuum conditions. It is now specified that all oxygen-containing species must have partial pressures of three orders of magnitude (or more) below that of hydrogen at 250ºC before cool-down of the vacuum chamber begins. At this moment in time, it is not known how effective this new criteria is in practice, but it is believed that the photocathode lifetime will be extended from tens-of-hours to weeks.

The current Cs:GaAs photoinjector developed by the Vacuum group meets almost all the specifications for 4GLS. Its short pulses of high peak current and low emittance make it suitable for driving a Free Electron Laser (FEL). Meanwhile, its low timing jitter from the electron source meets one of the criteria for the High Average Current Loop (HACL) of the 4GLS. However, it is unable to produce a high average current – the other major criteria for the HACL. Nonetheless it is very effective in meeting the majority of the design criteria and represents a very good first attempt at producing such a highly specific electron source.

4GLS - A Future Light Source

The 4th Generation Light Source (4GLS) is designed to be a world-leading photon facility to enable internationally outstanding science in the UK. It will combine energy recovery linac (ERL) and free electron laser (FEL) technologies to deliver a suite of naturally synchronised state-of-the-art sources of synchrotron radiation and FEL radiation covering the terahertz (THz) to soft X-ray regimes.

In April 2006 the 4GLS Conceptual Design Report was published. The team immediately followed this report by a detailed costing for the machine. As part of this costing exercise a full value engineering study was made to try to optimise the design in terms of value for money without altering the scope or quality of the project. ASTeC scientists and engineers have played a major role in this value engineering program by first suggesting a number of possible alternative design configurations and then by assessing the most promising of those using a cost benefit analysis.

The biggest change that has been implemented has been to reduce the overall energy of the electron beams in both the High Average Current Loop (HACL) and the XUV-FEL (from 600 & 950 MeV to 550 & 750 MeV respectively). These energy reductions have had no impact on the scope of the project due to a clever redesign of the XUV-FEL into two shorter branches, rather than one long one. However, by reducing the electron energy a number of superconducting linac modules are no longer needed and that gives a considerable cost benefit to the project. In fact, since each linac module is 12m long the cost impact is even more beneficial since the building size, a major cost driver, can also be reduced significantly.

Another significant design advance has been to optimise the magnetic arrangement. To ensure that the timing of the electrons is perfect for energy recovery after they have passed around the HACL and then back into the linac with the opposite phase, ASTeC scientists have developed a novel path correction system. This consists of a collection of magnets that can move and rotate, altering their pull on the electrons and changing their path. “It is equivalent to being able to change the size of a Grand Prix racing chicane, while the cars are still going round,” says Jim Clarke, one of the scientists working on the 4GLS design.

In addition to carrying out the re-design of 4GLS, ASTeC scientists have been collaborating with colleagues at Stanford University, Cornell University and the Lawrence Berkeley National Laboratory, to design and build a linac more directly applicable to 4GLS. A short (3m) prototype is currently being built and it is hoped that this will be later tested on ERLP (Energy Recovery Linac Prototype).

As a result of the re-design 4GLS will now be incredibly efficient, but still able to answer some of the most tantalising and fundamental questions in science.

Synchrotron Radiation Source

ASTeC scientists have continued to provide support for the operation of the Synchrotron Radiation Source (SRS). This year the SRS had to have two unscheduled shutdowns, due to unforeseen problems – ASTeC scientists were able to spring into action and ensure that the problems were resolved as quickly and efficiently as possible.

The SRS at Daresbury Laboratory is a world-class facility offering a large mix of experimental facilities which deliver radiation with wavelengths extending from the infrared to hard X-rays. Scientists come from all over the world to use this facility.

ASTeC provides support for the SRS in a number of ways. Regular periods of beam studies are organised, which can help to start up the SRS after lengthy shutdowns. Operational issues (which limit the efficiency of the machine) are solved and data is taken, to improve the efficiency of the machine in the long term. Meanwhile, ASTeC's Radio Frequency group maintain the radio frequency systems.

During the last year two unexpected shutdowns have occurred. In August 2006 the electron gun on the injector linac klystron failed. There had been emission problems with the gun for a while and it gradually deteriorated until there was no emission. The SRS had to be shut down for several weeks over the summer while the klystron was replaced with a spare one.

In April 2007 the cathode which produces the electrons for the linac gun was due for replacement. Normally this is a routine procedure which takes a matter of hours, but on this occasion the new cathode failed to operate. After several more changes and a thorough cleaning of the gun area it was decided that the cathodes needed to be tested in isolation.

A high voltage test area facility had to be set up to verify which of the cathodes worked. The tests revealed that cathodes from a particular batch had a manufacturing fault and were all dead.

Having resolved this problem a cathode from a different batch was put into the SRS and the problem was resolved. Downtime for the problematic cathode change was two weeks.

Once the reliable cathode was installed scientists were able to confidently start a period of single bunch operations – a mode that the machine hadn't been run in for almost two years, and known to be difficult to set up.

Despite the unplanned hiccups with the SRS, it has been a successful year, with a number of interesting experiments carried out and plenty of satisfied users. Thanks to the ASTeC team disruptions have been kept to a minimum and the SRS is in good working order, ready to face the challenges of the next year.

Developments in the ASTeC Magnet Laboratory

The last year has been a busy one for the ASTeC magnet laboratory. As well as contributing to major projects like 4GLS, ELRP, ILC and CONFORM, scientists have started work on the new pulsed wire bench.

Pulsed wire benches are used to measure undulators. The measurement system consists of a wire stretched along the undulator gap. A short (delta-function) current pulse is sent down the wire. This pulse acts like a bunch of electrons, and as it passes through the insertion device's magnetic field a travelling wave is set up in the wire.

A laser is used to pick up the vibrations caused by the current. This signal is proportional to the magnetic field integral and can be differentiated to obtain the field map.

When a longer current pulse is used (a step-function), the signal is proportional to the second field integral and hence gives the trajectory of electrons through the undulator.

Pulsed wire benches can be used in-situ – with the insertion device still in the accelerator. Compared to a Hall probe where point by point measurements must be taken and the process takes hours, the pulsed wire bench is very quick and can measure the undulator in a matter of seconds.

Twenty years of fine service

Another project undertaken by the magnet lab this year has been to analyse an old undulator which has recently been removed from the SRS. U5 was installed into the SRS in 1984 and removed in 2004 to make way for an Apple-II undulator.

Because U5 was a permanent magnet undulator it was important to find out if the permanent magnet blocks had been damaged by synchrotron radiation in its 20 years of use. No other undulator has been in a machine for that long.

There are 80 magnets in U5. The kind of damage that the team were looking for was localised de-magnetisation – a possibility if radiation had been concentrated on one magnet.

Using a Hall probe and the flipping coil method the team measured the field through the middle of the undulator and compared the results to the measurements made by Poole and Walker in 1984, prior to the undulator's installation. In addition the measurements were compared to those predicted by a computer model.

Within the margins of error of the measurement no observable differences were found and it can be assumed that no significant damage had taken place – well done to U5! Now U5 will be used to test out the pulsed wire bench, once it has been constructed.

Development of Neutrino Factories

Neutrinos are some of the strangest particles around, yet understanding their behaviour could provide answers to profound questions in physics. ASTeC scientists are involved in international efforts to develop a 'Neutrino Factory', to enable physicists to study these mysterious particles.

Every second millions of neutrinos speed through your body. They do no harm and leave no trace, making them very difficult to detect. Nonetheless, neutrinos are thought to play an important role in our lives. It is possible they are equivalent in mass to all the stars in the Universe and may explain the origins of the building blocks of all atoms: neutrons, protons and electrons. So how can we find out more about neutrinos?

A neutrino production line

Rather than hanging around waiting for neutrinos to arrive, scientists have decided to try and take matters into their own hands. The Neutrino Factory is a groundbreaking project that will use accelerators to produce neutrino beams for physicists to study under laboratory conditions.

Neutrinos come in three different types: electron neutrinos, muon neutrinos and tau neutrinos. One of the main areas of interest for particle physicists is to understand how neutrinos oscillate between these forms. Another key question is to work out the neutrino's mass.

In August 2005 the Science and Technology Facilities Council (*then CCLRC*) set up the International Scoping Study (ISS) – an international review to find a workable design for future development of the Neutrino Factory. ASTeC scientists played a major role in the ISS. Chris Prior, leader of the ASTeC Intense Beams group, was appointed as one of the six members of the international council, while ASTeC scientists jointly led three of the five work packages. This year the ISS finished and plans are now in place for an International Design Study (IDS).

The ISS looked at ways of generating intense beams of neutrinos for particle physics research, from the decay of muons, using a system of particle accelerators. Every aspect of the Neutrino Factory was examined, from its high intensity proton driver, through the muon production and acceleration, to the design and orientation of the storage rings that will direct the neutrino beams through the earth to distant detectors.

Demanding requirements

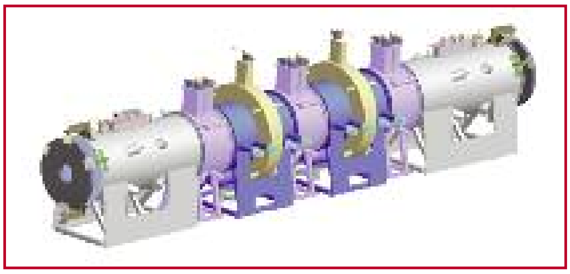
Working from the beginning, the proton driver has a role in setting the muon bunch structure that subsequently generates the neutrinos. In order to achieve the required specifications and produce 10^{21} neutrinos per year, the ISS concluded that the average beam power of the proton driver would need to be 4MW, with a pulse repetition frequency of 50Hz and a kinetic energy of 10 ± 5 GeV.

A number of target materials, including liquid mercury, carbon, copper and tungsten were considered during the ISS. By studying the different distributions of pions/muons emitted from each of these target materials, and the proton driver energies required, it was decided that liquid mercury was the most favourable target material.

As the pions are expelled from the target they need to be captured and controlled as they decay into muons. A system of solenoids with tapering fields is the suggested arrangement for the Neutrino Factory. ASTeC scientists have been investigating ways of reducing the energy spread of the beam and increasing its bunch length.

Once the muons have been captured then the beam undergoes ionisation cooling. It is then rapidly accelerated up to 20-50 GeV, probably with Fixed Field Alternating Gradient (FFAG) accelerators, before being stored in dedicated decay rings, where the muons decay in long straight sections, directed at distant detectors. The geometry of these rings is important and the ISS considered a few different shapes, including racetrack, triangular and bow-tie shaped μ^+ and μ^- rings. The racetrack ring appears to have the most flexibility and is the ISS preferred model.

The scientists involved in the ISS have been able to rule out a number of designs and materials for the Neutrino Factory and evaluate the advantages and disadvantages of the remaining options. A number of the ASTeC designed schemes are still in the running.



Experiments to test the theory

Complementing the theoretical work from the ISS, ASTeC scientists are involved in four ongoing research and development projects that are expected to provide valuable insights for the Neutrino Factory. The HIPPI (High Intensity Pulsed Proton Injectors) project is assisting the development of a proton driver front-end test stand (*see article on page 20*). Meanwhile, MERIT is an experiment at CERN to study liquid mercury jet targets. A parallel experiment at the Rutherford Appleton Laboratory is exploring thermal shock and lifetime in solid targets.

The MICE (Muon Ionisation Cooling Experiment) project is investigating ways of reducing the beam size. Muons will be passed through an absorber, reducing the momentum in all directions, longitudinal and transverse. Then, the longitudinal momentum will be put back by means of radio frequency cavities, restoring the muon energy but leaving them with reduced transverse momentum. "The cooling (absorbing and re-accelerating) reduces the beam size and makes it easier for the following accelerators," explains Prior. If MICE can help to achieve a smaller beam width then it will enable narrower beam pipes to be used, significantly reducing the overall cost of the project.

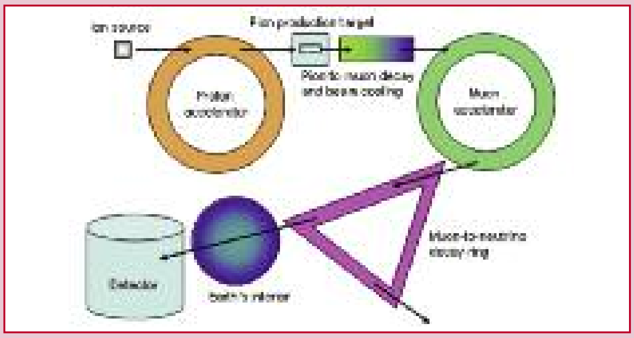
Finally the EMMA project is constructing an electron model to test beam dynamics in a non-scaling FFAG (*see article on page 16-17*).

Having carried out the ISS, the Neutrino Factory is a few steps closer to coming into existence and everyone is now eager to begin the next phase. The International Design Study is going to be launched later in 2007 at the annual Neutrino Factory Conference at Okayama in Japan. Will neutrinos hold the answer to some of the most tantalising questions in science? Hopefully in a few years we will know.

The Neutrino Factory ISS Concept

At the start is a high intensity proton accelerator, delivering 4 MW of pulsed beam power to a pion production target. The target is likely to be made of liquid mercury. Pions decay to muons in nanoseconds. Meanwhile, the muons, which have a mean lifetime at rest of 2.2 μs, will be captured in a high-field solenoid channel.

After this the muons must be accelerated very quickly, to ensure that relativistic time dilation can be used to get enough through to the final decay rings. Following initial acceleration in a re-circulating linac the beam goes into one or more fixed-field alternating-gradient (FFAG) accelerators, to be brought up to 20-50 GeV. Finally, the muons enter a storage ring, where they decay into neutrinos. The long straight sections of the storage ring point towards distant neutrino detectors, up to 7000 km away.



An Early Schematic of a Neutrino Factory, showing triangular decay rings

The EUROFEL Collaboration

Accelerator science continues to demand a wide range of skills and expertise. Currently, ASTeC scientists are participating in EUROFEL, a major European collaboration involving 16 partners, to prepare for the construction of the next generation of free-electron laser light sources.

Smaller and smaller

Free electron lasers (FELs) are seen as the next step in the evolution of short-wavelength light production because they produce intense pulses of light many orders of magnitude more intense than previous synchrotron light sources based on electron storage rings. Such pulses enable scientists to track the progress of things, such as observing reactions occurring in real time. The shorter the wavelength, the smaller the structures that can be observed; hence the drive to decrease the wavelength of FELs. The EUROFEL collaboration aims to address the technical challenges that must be overcome in order to operate at these wavelengths.

The EUROFEL (European free-electron laser) project is a design study to prepare for the construction of the next generation of pulsed, high-intensity, short wavelength light sources. Funded by the European Union's Sixth Framework Programme, this €9 million project is a three-year collaboration between 16 European institutions. This is the final year of the project and the scientists are preparing to present their results at the end of 2007.

In total the EUROFEL project consists of six work packages: photocathode guns and injectors; beam dynamics; sychronisation; seeding and harmonic generation; superconducting continuous-wave and near-continuous-wave linacs and cryomodule technology transfer.

ASTeC scientists are most heavily involved with the beam dynamics work package, which they lead. Over the last year they have continued their work in developing and using codes and models for the reliable simulation of high-quality electron beam transport. Studies of the beam break up threshold in superconducting accelerating cavities have been made, and alternative designs considered to increase this threshold.

Novel Solutions

ASTeC scientists, in collaboration with the University of Strathclyde, have also worked on novel methods of producing harmonic radiation in FELs, and new ideas for enhancing the quality of the output radiation, such as self-seeding schemes.

Many of the other work packages have also received significant contributions from ASTeC scientists. In particular, theoretical and practical studies of timing and synchronisation issues for accelerator-based light sources have been carried out using ERLP systems.

Working with scientists at Forschungszentrum Dresden (FZD), design studies of superconducting radio frequency photoinjectors have been carried out, and practical performance measurements of superconducting accelerating cavities have been made. The Radio Frequency and Diagnostics group at Daresbury have helped with an evaluation of the FZD SRF gun, assessing the design for high-average current operation.

The 2006 EUROFEL annual meeting at Daresbury

In November 2006 Daresbury Laboratory hosted the annual meeting for EUROFEL. Participants presented some exciting work and many fruitful discussions were had.

As the EUROFEL project draws to a close the participants are confident that they have increased the body of knowledge on free-electron lasers and that they are a number of steps closer to creating FELs with shorter wavelengths, able to resolve down to the atomic scale.

“The results will contribute to the whole body of knowledge for design of new accelerator-based light sources, such as 4GLS in the UK, XFEL and the BESSY FEL in Germany, SPARC and FERMI@Elettra in Italy and Arc-en-Ciel in France,” says David Holder, STFC’s project leader for its EUROFEL work.

The CONFORM Project – Developing Novel Compact Accelerators

Particle accelerators tend to be rather large, unwieldy objects, which require specialist knowledge to operate. But all this is about to change as scientists work towards creating a smaller, more user-friendly particle accelerator intended for medical and industrial applications as well as pure scientific research.

The most promising candidate accelerator for such purposes is the 'non-scaling fixed-field alternating gradient' (NS-FFAG) accelerator. NS-FFAG accelerators will be smaller, simpler and significantly cheaper than synchrotrons, and more flexible than cyclotrons. No one has ever built such a machine and the CONFORM (Construction of a NS-FFAG for Oncology, Research and Medicine) project is now in the process of developing the first one.

CONFORM is divided into three areas. EMMA (Electron Machine with Many Applications) will look to develop a prototype FFAG to be built at Daresbury Laboratory, while PAMELA is a design study for a proton NS-FFAG for medical applications. The third area will look at possible applications, from archaeology to zoology.

The research is being led by Professor Roger Barlow from The School of Physics and Astronomy at The University of Manchester, in collaboration with the Science and Technology Facilities Council at Daresbury Laboratory, The Cockcroft Institute (also based at Daresbury Laboratory), The John Adams Institute, Imperial College London, The University of Birmingham, The University of Surrey, The University of Leeds, The University of Glasgow and The Gray Cancer Institute.

CONFORM is sponsored by BASROC (British Accelerator Science and Radiation Oncology Consortium) and has been awarded a multi-million pound grant from the Research Councils UK Basic Technology programme to pursue this research.

ASTeC scientists have been heavily involved with the development of EMMA – a 20 MeV electron accelerator. One of the biggest challenges for the team of accelerator physicists working on the lattice design has been to predict how the beam will behave during acceleration.

Unlike conventional storage ring accelerators where the beam travels in a reference orbit and is accelerated on-axis through the RF cavities, the NS-FFAG beam will increase its orbit and move transversely across the RF accelerating structures. The beam will also not maintain a synchronous phase with the RF during its few turns of acceleration. An optimised RF cavity design has been developed by the Radio Frequency and Diagnostics group, and provides high acceleration efficiency for all 19 cavities employed on the 16.5m circumference ring. During commissioning the team will use extensive diagnostics to ensure that they can work out what the beam is doing at any moment in time during acceleration.

Meanwhile, over in the Magnetics and Radiation Sources (MaRS) group scientists have been grappling with the extremely demanding magnet designs for EMMA. The ring will consist of 84 magnets, which will act as quadrupoles and dipoles with the two field components being independently adjustable by a combination of position and strength changes.

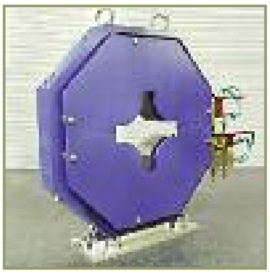
Unlike the magnets in most accelerators these magnets are exceedingly thin – between 65 and 85 mm. This makes the design extra challenging because three-dimensional end effects dominate the magnet.

Currently an order has been placed with Tesla Engineering Ltd, for two prototype magnets. One of these magnets will be horizontally focussing and the other will be vertically focussing. Delivery of these magnets is expected in September 2007.

In the meantime the MaRS group are working with finite element codes to define the geometry of the magnet and predict the magnetic field in three-dimensions. This will enable them to define the pole shapes.

When the EMMA ring has been constructed it will be installed in the same enclosure as ERLP in 2009: this will provide the beam of electrons for injection into EMMA. The experience gained in the development and operation of EMMA will inform the design and eventual construction of a prototype PAMELA.

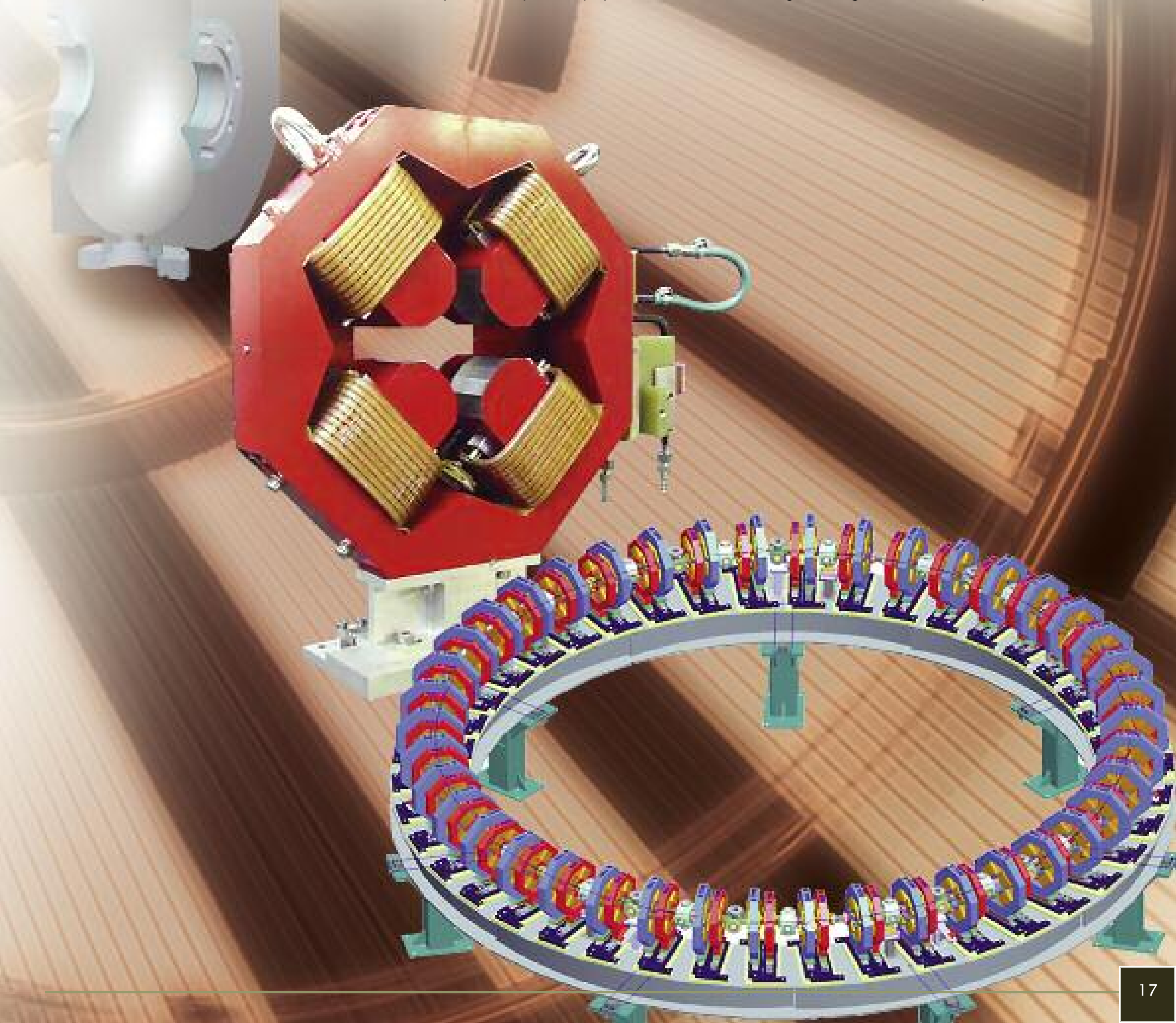
In terms of applications EMMA and PAMELA are expected to open up a host of new possibilities. The reduced size of the machines and their increased flexibility and reliability should lower the cost of ownership and enable them to be placed in a wide variety of environments.

Medical applications are of particular interest, with the potential for using charged particles in cancer therapy. Beams of protons or heavier particles such as carbon ions can deposit much more radiation directly in the cancer, while losing much less energy in the surrounding healthy tissue.

NS-FFAGs could also make significant changes to the way we generate power with the introduction of accelerator driven sub-critical reactors and waste transmutation. Potentially electricity could be generated without significant greenhouse gas emissions while the amount of long-lived nuclear waste produced would be reduced.

In pure science the machines could play a role in elementary particle physics. In addition they might provide a new generation of very intense sources of neutrons for studying the structure of materials and the dynamics of chemical reactions, of interest to physicists, chemists, biologists, engineers and many industries.



The International Linear Collider

Stretching out for a total of 31km, the International Linear Collider (ILC) will consist of two linear accelerators facing each other, hurling electrons and positrons towards the middle. Travelling at nearly the speed of light, the resulting collision will have a combined energy of 500 billion electronvolts (GeV).

These spectacular crashes will produce new particles, some of which may never have been seen before. Potentially the ILC holds the key to understanding our Universe.

Right now the ILC is at the planning and design stage. ASTeC scientists from Daresbury Laboratory are taking a prominent role within the LC-ABD collaboration in designing and costing various parts of this gigantic and ambitious machine.

In July 2006 the baseline design and its relative cost numbers were discussed at the Vancouver Linear Collider workshop. It was decided that the costs were too high and several changes were proposed to the baseline configuration of the ILC.

The Accelerator Physics group has continued to work on optimising the collimation optics for better performance, tuning procedures and optimising the alternative small crossing angle solutions for better performance at reduced costs. They have contributed to changes to the beam delivery configuration, with only one interaction region, with a 14mrad crossing angle. Two complementary detectors in a push-pull configuration will share the luminosity.

Meanwhile, the Magnetics and Radiation Sources group, in collaboration with members of the Technology Department at the Rutherford Appleton Laboratory (RAL), have built permanent magnet and superconducting prototypes for the positron source undulator and tested them in the lab. The superconducting magnet was selected as a result of these tests and since then five more superconducting prototypes have been built and tested.

The next step is to build a full scale 4m long prototype. This has now been designed and is under construction at RAL.

Over at the Radio Frequency and Diagnostics group, the team has been working on the crab cavity and collimation systems. A series of tests have been carried out on End Station A at the Stanford Linear Accelerator Centre to assess the suitability of various collimator designs for the ILC.

The team is also developing suitable superconducting crab cavity solutions and its phase control system to reach the ILC luminosity goals. A warm modular prototype cavity design has been fabricated to compare various wakefield simulation results.

Achieving the challenging requirements of very low pressures in a narrow vacuum chamber (of a very long undulator positron source) has been solved by the Vacuum Science group. The team is also dealing with the vacuum design of 6km damping rings, which need careful design solutions to avoid problems of electron cloud (in the positron ring) and fast ion instability (in the electron ring).

The international ILC design team produced the Reference Design Report and its draft version, including the cost of the ILC, was released in February 2007, at the Beijing International Committee for Future Accelerators meeting. Hard copies of this report are due to be published in summer 2007.

Superconducting RF Cavity Development

As the beam quality requirements of particle accelerators become more and more demanding, the technology must become more sophisticated. Superconducting Radio Frequency (SRF) cavities are crucial to this development, to couple the power into the particle beam of an accelerator.

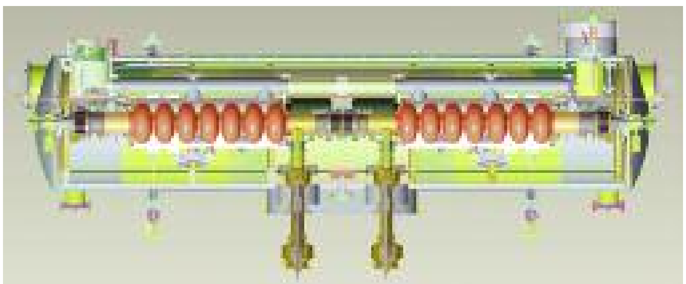
Scientists from the Radio Frequency and Diagnostics group have been designing RF cavities for two of the most ambitious accelerator designs to date: the 4th Generation Light Source (4GLS) and the International Linear Collider (ILC).

One of the key features of 4GLS will be its use of energy recovery, whereby electron bunches return their energy after being accelerated once around the loop. This recycling design improves the efficiency of providing power to the beam by one or two order of magnitude and therefore requires a fraction of the RF power compared to other accelerators.

However, energy recovery is a relatively new technology and creates some interesting challenges for the RF system designers. In particular the accelerated (and then decelerated) high current bunches must be synchronised to extremely tight tolerances to exploit the energy recovery principle. Meanwhile, the SRF cavity design itself must be able to damp the beam-induced Higher Order Mode (HOM) power which can drive instabilities in the beam, thereby limiting 4GLS's performance.

Currently the Daresbury team in collaboration with international partners (see page 9) is designing and building a prototype SRF cavity, which will be installed on the Energy Recovery Linac Prototype (ELRP) – the test-bed for 4GLS.

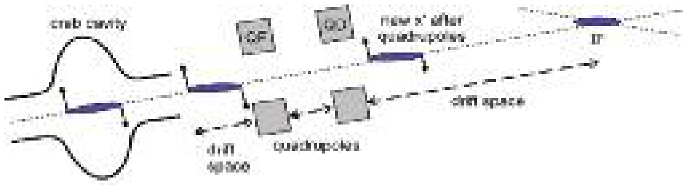
This prototype SRF cavity will act as a tool to address the many challenges facing the 4GLS SRF cavity design. The team hopes that they will be able to validate the cavity design at this early stage, ensuring that the solution is perfect for 4GLS.



Prototype SRF Cavity Cryomodule

Within the next few months they hope to start building the prototype, with the intention of installing it on ELRP later in 2008. After a year of testing they should be ready to develop and build the real thing for 4GLS.

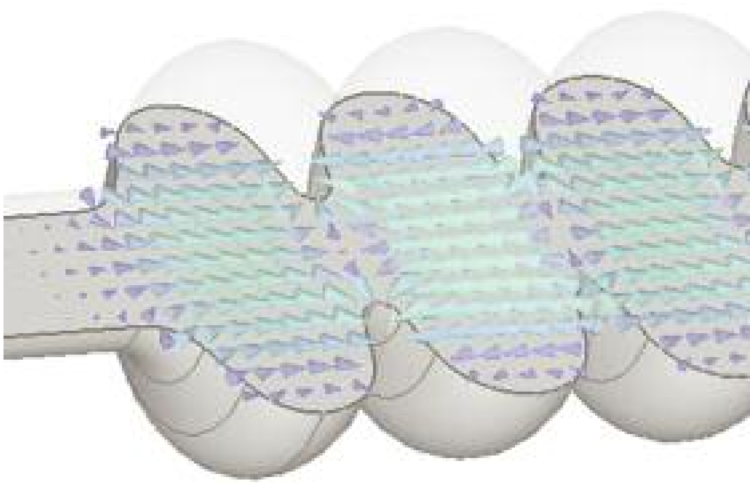
In addition to the 4GLS work, the Daresbury team in collaboration with FNAL and Lancaster University has been developing a crab cavity system for the International Linear Collider (ILC). This device is designed to maximise the collision efficiency of the two beams at the Interaction Point (IP) of the accelerator, by rotating each beam into the perfect orientation.



ILC Crab Cavity Bunch Rotation Prior to IP

Recently the RF labs have had an infrastructure overhaul, with a new SRF facility being set-up. There is now a substantial clean room, which can house SRF cavity assembly and shortly a high-pressure rinsing capability will be available. In addition a vertical test cryostat has been obtained, for the verification tests of TESLA 9-cell cavities and their like.

These state-of-the-art labs mean that the team are now well on the way to being able to process and test the R&D devices required for 4GLS – an exciting challenge for the future.



High Intensity Pulsed Proton Injectors

What happens to the atoms inside a material when they are squeezed to a higher pressure or heated to a higher temperature? In order to answer questions like these scientists need to be able to probe a material down to its atomic level and investigate changes in real time.

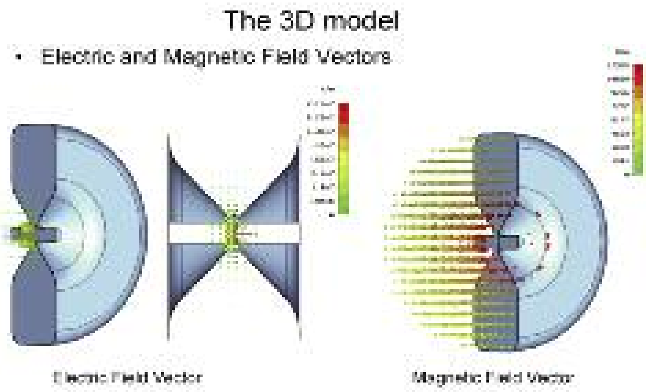
The best way to do this is to use intense secondary particle beams, such as pulsed neutron sources. And, to create these intense secondary particle beams, a high intensity proton machine with a linear accelerator (linac) is needed.

The HIPPI (High Intensity Pulsed Proton Injectors) project aims to foster the development of a common European technological base for the construction of just such a high intensity pulsed linear accelerator. Over the last ten years the majority of advances in this field have occurred in the USA and Japan, and Europe is lagging behind: the last advanced European proton linac was commissioned in 1988 and based on 1970s' technology.

Eight European partner institutions are involved in the project, including the Science and Technology Facilities Council's Rutherford Appleton Laboratory. Funded by the European Union under its Framework Programme 6, HIPPI is a programme running from 2004 to 2008.

The project consists of five work packages: administration and management of the project; a study of normal conducting accelerating architectures; a study of superconducting accelerating architectures; construction and testing with beam of fast beam choppers and comparison and development of computer modelling codes for linacs and development of diagnostic techniques.

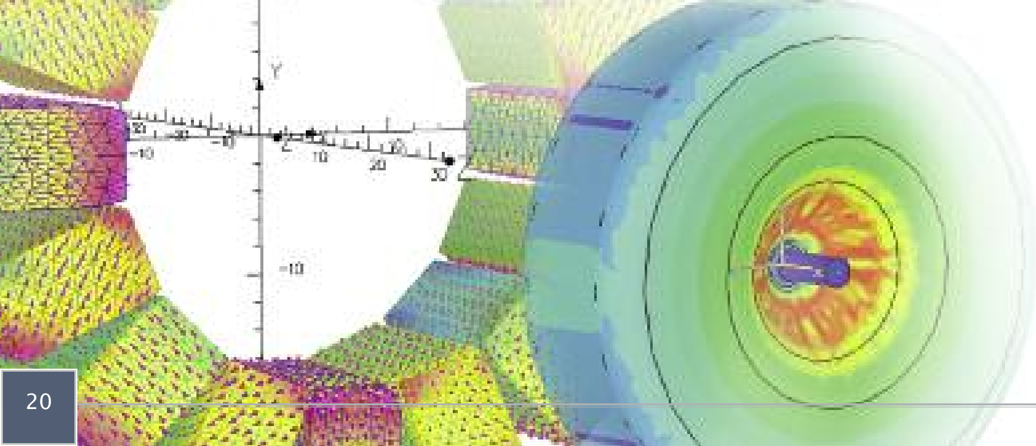
As a member of HIPPI, the ASTeC group at the Rutherford Appleton Laboratory is making a significant contribution to improving knowledge and understanding of underlying beam dynamics of normal conducting linear accelerators. In addition, emphasis is being placed on the design, construction and testing of a prototype chopper structure – an essential ingredient for any future high power pulsed proton accelerator.



Beam chopping is required to reduce beam loss. In most cases the beam from the linac is injected into a synchrotron or accumulator and then extracted. Considerable particle loss occurs unless suitable measures are taken to control the dynamics of the beam. To minimise beam loss at injection scientists have to ensure that no circulating beam coincides with the field ramping period of the extracting magnet. These demands can be met by selective elimination of sets of bunches in the low energy, early stages of the linac, by using a fast deflector, or 'beam chopper'.

In addition to the beam chopper research, ASTeC scientists are designing the linear accelerator structure to take the beam from the chopper system. Eventually this could be developed into a new linac to serve as the injector to ISIS in a future upgrade, or as the injector for a new stand-alone proton driver serving a neutron or neutrino facility.

So far work has been progressing well in all of the work packages that ASTeC is involved in. Thanks to HIPPI, Europe is catching up with the USA and Japan, and will soon be designing and building its own high intensity pulsed linear accelerators.



The Karlsruhe Tritium Neutrino Experiment – KATRIN

Every second 50 trillion solar neutrinos pass through your body. You'd expect to feel something, but these tiny particles are almost impossible to detect. Now an international scientific collaboration aims to pin this slippery particle down and measure its mass.

KATRIN, the Karlsruhe Tritium Neutrino Experiment, is designed to measure the mass of the electron neutrino. It will use the β decay of tritium directly, with unprecedented sensitivity of 0.2 eV. Currently around 100 scientists from European and North American institutions are involved in the experiment, which is situated at the Forschungszentrum Karlsruhe (FZK) in Germany.

The machine will consist of five major sections. First is a Windowless Gaseous Tritium Source (WGTS), in the middle of which tritium is injected - the main source of the electron neutrino from the β decay of tritium. Inside the transport section most of the tritium will be eliminated, while electrons from the β decay head towards the pre-spectrometer. Here the electrons are sifted, retaining only those with the highest energies and directing them to the main spectrometer. Finally the electrons are guided towards the detector.

ASTeC's Vacuum Science group has made substantial contributions in three key areas of the KATRIN project.

The first hurdle was the design and construction of KATRIN's main spectrometer. Needing to operate at pressures below 10^{-11} mbar, KATRIN required a gigantic vacuum vessel – 24 m long and 10 m in diameter – larger than the average house and not something that has ever been tackled before.

Using Monte Carlo modelling and their extensive knowledge of vacuum engineering techniques, the Vacuum Science group were able to rise to the challenge and provide expert advice for design, technology and manufacturing of a suitable vessel. After testing, the vessel was transported over 3000 miles to its final resting-place at FZK. En-route it had to squeeze between houses and weave along narrow streets, drawing quite a crowd of spectators.

To maintain the extremely low partial pressure inside the main spectrometer the tritium can only trickle in at an incredibly low flow rate – less than 10^{-14} mbar l/s. Normal inlet rate at WGTS is around 10^{-2} mbar l/s, so the Vacuum Science group had to devise a way of suppressing the flow rate by a factor of 10^{12}, between the tritium source and the entrance to the pre-spectrometer.

They have developed a tritium pumping system based on a combination of differential and cryogenic pumping sections. Using Monte Carlo simulations and analytic solutions they have proved that this flow suppression can be achieved.

Finally, the group has also been working on a suitable vacuum design for the detector. Budget restrictions have meant the design has had to be re-jigged over the last year, but a suitable and affordable design has now been agreed upon.

Because the detector is coupled directly to the main spectrometer the vacuum requirements are very stringent. Any gas loads generated in the detector may affect the performance of the main spectrometer. Modelling work indicates that the vacuum requirements can be met. Future work will aim to overcome some of the other technological challenges regarding magnetic field effects on vacuum equipment and cryosorbed layers on the detector surface.

KATRIN is going to be the ultimate set of weighing scales, finally enabling us to work out what these minuscule particles weigh.

The European Particle Accelerator Conference 2006

Over 1,000 scientists from around the world met in Edinburgh in June 2006 at the 10th European Particle Accelerator Conference (EPAC'06) to discuss the latest advances in particle accelerators.

Delegates discussed how CERN's new large hadron collider will unveil secrets of the Big Bang and possibly reveal the mysterious Higgs boson, how new cancer treatments are being developed using protons produced by particle accelerators, and revolutionary new approaches to designing intense light sources being developed in the UK.

According to Dr Chris Prior, chair of the Organising Committee and head of the ASTeC Intense Beams group, "The UK is a world leader in this vital field of science. Particle accelerators are a fundamental tool for modern research. They improve our quality of life by contributing to the development of new medicines and new materials. They help us understand what happened in the Big Bang and why the universe works the way it does. They benefit the economy, by forcing the pace of technology development and transferring skills and knowledge from universities to industry."

The conference was organised by the European Physical Society Accelerator Group (EPS-AG) and hosted by CCLRC. The Local Organising Committee (LOC) chaired by John Thomason, was made up from members of ASTeC and ISIS. The LOC reported to the EPS-AG. A sub committee of the EPS-AG, on which ASTeC had representation, decided on the scientific program.

Members of ASTeC took key roles to ensure the smooth running of the conference. Sue Waller was the Conference Secretary. Her job was to arrange local organising committee meetings, deal with students applying for grants, help delegates arrange their visas and deal with the many queries that arise during a conference of this size.

Hywel Owen was the Proceedings Editor responsible for processing hundreds of submitted papers to produce the published conference proceedings. Naomi Wyles looked after all aspects of registration for over a thousand delegates, Giulia Bellodi produced the conference web pages and Mike Dykes helped organise the Industrial Exhibition with Dan Faircloth from ISIS. Other roles on the LOC, including managing the poster sessions and giving computer support, were taken on by staff from ISIS.

Conference Reception

The Conference Reception was held at Edinburgh Castle on a beautiful June evening. The sun shone and much refreshment (and a few canapés) was served. Everyone got the chance to look around the castle at the exhibitions and the crown jewels.





Conference Banquet

The Conference Banquet was held at the Royal Museum of Scotland, Assembly Rooms and Merchants Hall. A traditional Scottish dinner which included haggis, Scottish salmon and whisky was served. A highlight of the evening was the pipers who 'beat the retreat' at the end of the night.

Chairman's reception

The Chairman's reception was held in the Scottish Parliament Building and was hosted by Nicol Stephens who was then Deputy First Minister.

The next conference in the EPAC series will be held in Genoa, Italy in June 2008.

The Cockcroft Institute

The Cockcroft Institute building was officially opened this year, and already ASTeC and university staff are taking advantage of the opportunities the new building provides for education and collaboration.

The Cockcroft Institute is a newly created international centre for Accelerator Science and Technology in the UK. It was proposed in September 2003 as a joint venture of Lancaster University, the University of Liverpool, the University of Manchester, the Council for the Central Laboratory of the Research Councils (CCLRC at the Daresbury and Rutherford Appleton Laboratories), the Particle Physics and Astronomy Research Council (PPARC) and the North West Development Agency (NWDA). The Institute is located in a purpose-built building on the Daresbury Science and Innovation Campus (DSIC), and in centres in each of the participating universities.

The Institute's aim is to provide the intellectual focus, educational infrastructure, and the essential scientific and technological facilities for Accelerator Science and Technology research and development, which will enable UK scientists and engineers to take a major role in accelerator design, construction, and operation for the foreseeable future. The Institute is named after the Nobel prizewinner Sir John Cockcroft FRS.

A new home for ASTeC

All the Daresbury-based ASTeC staff relocated in May 2006 to the new Cockcroft Institute building. A number of ASTeC staff were involved in sorting out the logistics for the move which took just over a week to complete. Fifty five people and their possessions were relocated from offices elsewhere on the DSIC to the Cockcroft Building, and other university staff who had not previously had an office at Daresbury also moved in.

The official opening

The Cockcroft Building was officially opened as part of the DSIC on 19th September 2006 by the Minister for Science and Innovation, Lord Sainsbury. He unveiled a plaque before representatives of all the universities and research councils involved in the Institute, as well as descendants of Sir John Cockcroft. Lord Sainsbury then spent time with some Institute staff discussing their work and viewing specially prepared demonstrations.

A place for learning

The Cockcroft Institute has been running an education program since September 2005 to teach newcomers the basics of particle accelerators and to educate more experienced staff on advanced accelerator topics. Lecture courses are provided by world experts, some of whom are already part of the Institute and some of whom visit from overseas.

Working together

An example of collaborative work being done within the Institute is the study of Higher Order Modes (HOMs) in superconducting RF cavities by ASTeC, Manchester and Lancaster. HOMs can cause emittance dilution so it is important to understand them. The team have modelled the 9-cell superconducting TESLA cavities found in ELBE (an accelerator at Rossendorf) to predict the HOMs and found that many of their predictions were verified by measurements. Similar cavities will be installed on ERLP at Daresbury Laboratory so this experience will be invaluable for the success of the project.

The ASTeC and Cockcroft Directorate have been working even more closely together in the last year. The two directors, their




PAs and other administrative staff are now all located together in the new building and this facilitates the close working between them.

The International Linear Collider (ILC) has yielded many collaborations between ASTeC and university staff. There are collaborations in the following areas:

- BDS Lattice Design and Simulations (ASTeC and Manchester University)
- BDS Collimation Simulations (ASTeC, Manchester University and Lancaster University + Royal Holloway, Birmingham University and RAL)
- BDS Crab System (ASTeC, Manchester University, Lancaster University)
- Positron Source (ASTeC and Liverpool University + Durham University and RAL)
- Damping Ring Low Emittance Tuning and Vacuum Design (ASTeC and Liverpool University)
- Electro-optics and Bunch Profiles (ASTeC + Dundee University)

The BDS Collimation Simulations collaboration involves staff from the widest variety of institutes. The aim of the project is to design optimal collimators for the ILC by specifying both the geometry and the material of the collimator jaws which will be used to remove the beam halo. The effects of transverse wakefields on the beam due to the collimators and the damage caused to the collimators due to interaction with the particle beams are also being considered.

And Finally...

ASTeC supports a wide range of activities, from education outreach to social events and team building. Here is a selection from this year.

Two Sandwich Students from Bath University spent a productive year with ASTeC. Lucy Hooper (*shown right*) spent much time in the magnet measurement laboratory taking measurements of a decommissioned SRS undulator and installing new equipment and Alison Birch (*shown left*) developed codes for the simulation of the ILC positron source helical undulator.

Keith Middleman (below left) finished second in the Daresbury Dash, a gruelling cross country race across the fields and woods around the laboratory.

ASTeC staff went on a team building exercise in Snowdonia for three days in March. Activities included climbing, orienteering and raft-making. Only one leg was broken.

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Financial Summary

ASTeC Activities 06/07

INCOME SOURCES 06/07	***£K***
PPARC	1800
ACC SCIENCE VOTE FUNDED COLLABORATION	550
OTHER CCLRC VOTE FUNDED ACTIVITIES	3671
EU	387
OTHER	375 deduct purchases for CI
	6783

EXPENDITURE 06/07	***£K***
SCIENTIFIC & ENGINEERING STAFF COSTS	2330
CONSUMABLES, TRAVEL	2756
CAPITAL EXPENDITURE	1115
SUPPORT AND SITE SERVICES	582
	6783

EXPENDITURE BY PROGRAMME 06/07	***£K***
PPARC/CCLRC LC-ABD PROGRAMME	1905
PPARC/CCLRC UK-NF PROGRAMME	523
HIGH POWER PROTON ACCELERATORS	844
HIGH BRIGHTNESS ELECTRON ACCELERATORS	483
UNDERPINNING RESEARCH	1307
NEW INITIATIVES	156
OTHER PROFESSIONAL ACTIVITIES	760
EU AND REPAYMENT WORK	805
	6783

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