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ASTeC

Accelerator Science and Technology Centre

ASTeC Annual Report
2004 – 2005

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Accelerator Science and Technology Centre

Annual Report

2004 – 2005

This report covers the work accomplished by the
Accelerator Science & Technology Centre
(ASTeC) for the financial year 2004 – 2005.

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with help from Joe Herbert and Carl Beard.

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Foreword

This third ASTeC Annual Report reflects a period both of consolidation and new initiatives, and a strong theme of collaboration, both national and international, can be clearly seen. Arising out of the 2002 Spending Review both CCLRC and PPARC received major resource increases earmarked for accelerator science and technology, in recognition of the importance of the subject in underpinning future scientific facilities, both in the UK and overseas. The two Research Councils have embarked on joint programmes that concentrate on the R&D needed to prepare for the next generation particle physics facilities: a linear collider and a neutrino factory. These programmes will continue up to 2007, by which time the UK will have re-established for itself a very strong position internationally on accelerator science and technology.

In addition CCLRC has a wider remit and has been able to direct significant extra funding to other accelerator research programmes. A substantial ASTeC input has been made to the advanced design activities for 4GLS, including the prototype project (ERLP), and details can be found in the report. A number of strong synergies have emerged already between this topic and the linear collider one, since both require a mastery of high brightness electron beam physics and technology, and this has been exploited by ASTeC staff. Similar synergies also exist in the other main ASTeC theme of high intensity proton beams, connecting developments on a possible neutrino factory to those required for a future high power neutron source. ASTeC continues to support much of this latter activity within the ISIS Department, including the construction of important accelerator test facilities.

The vital role of ASTeC in continuing to contribute to the design and construction of the DIAMOND Light Source must be highlighted. As construction proceeds to an advanced phase the supporting design activities do reduce, but important outstanding issues were addressed during the year. Furthermore senior ASTeC staff temporarily filled DLS Group Leader positions pending recruitment of their replacements. I am sure that the future success of DIAMOND will reflect well on its origins within ASTeC and CCLRC. This has certainly been the case for the SRS, and ASTeC has once again provided strong ongoing support both for the latest source developments and in resolving complex operational problems.

Once again I wish to pay tribute to the outstanding efforts of the ASTeC staff. This is our most valuable resource and they continue to be faced with many new and difficult challenges, as should be the case with any advanced research team, but they have always risen to meet them. Increasingly this is an environment of strong partnership with our university partners and with international collaborators.

Professor Mike Poole

Contents

Perfecting the Prototype

The reality of 4GLS grows ever closer, but there is still much work to do on the ERLP prototype in exploring beam dynamics issues and accelerator technology.

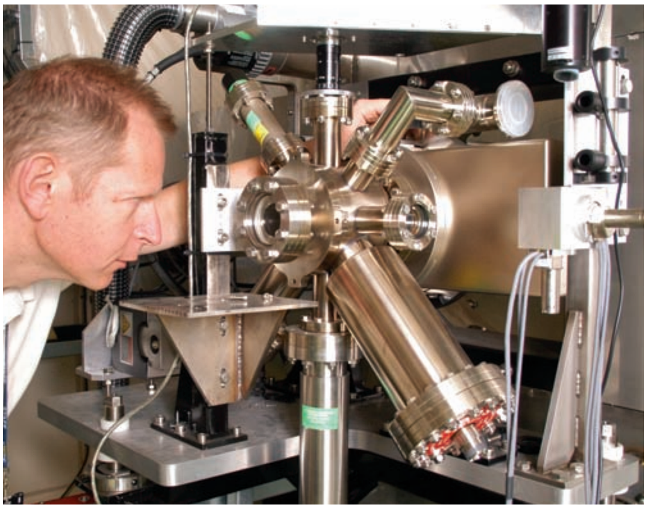
The Energy Recovery Linac Prototype (ERLP) being built at Daresbury Laboratory is an R&D facility for studying beam dynamics and accelerator technology important to the design and construction of 4GLS. The major objective of ERLP is to demonstrate energy recovery, particularly from a beam disrupted by a FEL – and ERLP's flexible optics design will allow for study of a range of beam dynamics issues important for optimising 4GLS design during 2006 and 2007.

Injector source built round DC photocathode gun

"The injector consists of a high-average current DC photocathode gun, booster and main linac transfer line," says David Holder, Senior Accelerator Physicist. "The gun will operate at a nominal accelerating voltage of 350 kV and bunch charge of 80 pC, and electrons generated at a GaAs photocathode will pass through two solenoids for transverse focusing and emittance compensation, as well as a normal-conducting single-cell buncher cavity to decrease bunch length." Electrons are accelerated to 8.35 MeV in the booster, which consists of two superconducting 9-cell TESLA-type cavities – and the cryomodule is based on the ELBE linac design. Injector electrons are accelerated to 35 MeV in the main linac (identical to the booster), and two 180° triple-bend achromat arcs recirculate the beam to the main linac, where electrons are decelerated to injection energy and dumped.

Design work concentrates on component specifications

A single four-dipole chicane provides bunch compression upstream of the wiggler and bypasses the upstream FEL mirror, and design work this year has concentrated on detailed component specifications like magnets and diagnostics. Before commissioning the whole machine, dedicated gun commissioning is planned and a diagnostic beam line (to be removed for machine commissioning) has been designed. This will allow for a full electron gun characterisation, transversely and longitudinally, and for comparison simulation results, particularly with the ASTRA code. The optimum focusing set-up for buncher and booster can also be determined in advance, for comparison with ASTRA simulation results. A combination of screens and a pepperpot mask will be used for emittance measurement, slits and a simple dipole spectrometer for measuring beam energy and energy spread – and a transverse kicker cavity from FZ Rossendorf will measure longitudinal characteristics.



Examination of the ERLP photocathode gun

START-TO-END SIMULATIONS

Advanced accelerator and free-electron laser modelling codes have been used to perform start-to-end ERLP simulations – the most complete way of predicting facility performance and confirming predictions made from analytic theory. Start-to-end simulations unite the whole facility's physics, allow ERLP section interdependencies to be examined, and model the complete electron bunch life-cycle from birth in the gun to beam dump death, each part of the cycle being modelled in an appropriate code.

ASTRA code chosen for electron gun modelling

The ASTRA code is chosen for electron gun modelling and bunch transport to the end of the booster linac. This is because ASTRA models space charge forces between electrons - and here, where electron bunch energy is low (<8.35 MeV), space charge forces play a significant role in determining beam dynamics. After the booster linac, sufficiently high electron bunch energy makes space charge effects less significant – and ASTRA output is converted into an input for the code Elegant, excluding space charge effects for faster transport modelling around bends. Elegant models electron bunch transport from the end of the booster, through main linac acceleration, around the first arc and through the bunch compressor to the free-electron laser. Here, interaction between electron bunch and optical field within the FEL cavity is modelled with the FEL code GENESIS 1.3, to help predict output radiation qualities and understand effects of FEL interaction on the electron beam. Predicted bunch energy profiles before and after FEL interaction agree well with theory. Finally the output from GENESIS 1.3 is converted back into an input for Elegant used to transport the bunch around the second arc, through linac deceleration to the beam dump. This is probably the first time a start-to-end simulation has modelled a complete ERL-based FEL as far as the beam dump, and results confirmed the beam transport system can deliver an electron bunch to the FEL, with required properties to allow lasing. Moreover, the disrupted bunch can be successfully transported around the second arc and decelerated into the beam dump with minimal losses.

CRYOGENIC ARCHITECTURE DESIGN

The ERLP currently under design will utilise TESLA-type superconducting accelerating (SCA) cavity technology requiring a sizable helium cryogenic liquefying plant, and the system's current transition from design to implementation is being assisted by ASTeC staff. The total ERLP SCA cooling power requirement is 180 W at 2 K, achieved by designing

Construction of the Energy Recovery Linac Prototype (ERLP) two sub-component plants. A liquid nitrogen pre-cooled Linde TCF50 Helium Refrigerator-Liquefier with a cooling capacity of 500 W at 4 K will make liquid helium – and at ambient pressure, it will be held in a 1500 litre buffer storage Dewar before entering the second stage of the process.

Second stage subatmospheric recuperator

Stage two will comprise a subatmospheric 2 K recuperator and distribution vessel operating at 30 mbar, requiring a large pumping station with exacting pumping volumes. A bypass valve feeding exhausted helium back into the pumping system will enable fine pressure adjustments, and recuperator pumping will be aided with a gas heater coil. Distribution of stable subatmospheric pressure 2 K helium to SCA applications occurs via liquid nitrogen and vacuum-shielded transfer conduits, whilst returning helium gas is recycled into the system to aid cooling of the forward-flow cryogenic cycle. Finally the helium gas at ambient temperatures is recovered into two 100 cubic metre gas storage vessels before being fed back into the TCF50 Helium Refrigerator, via a compressor, to re-commence the process.

LASER

The laser producing electron pulses from the ERLP photoinjector gun was specified in collaboration with CCLRC's Central Laser Facility, where it was set up before transfer to Daresbury in February 2005. A temperature-controlled RF-shielded room with two vibration-isolated tables had been prepared prior to its arrival. The laser system comprises an oscillator, with output amplified and converted to the correct wavelength for producing photoemission from the cathode. Short pulse trains are generated by chopping the continuous pulsed output of the laser to produce the correct electron bunch time structure from the cathode.

RF CONTROLS

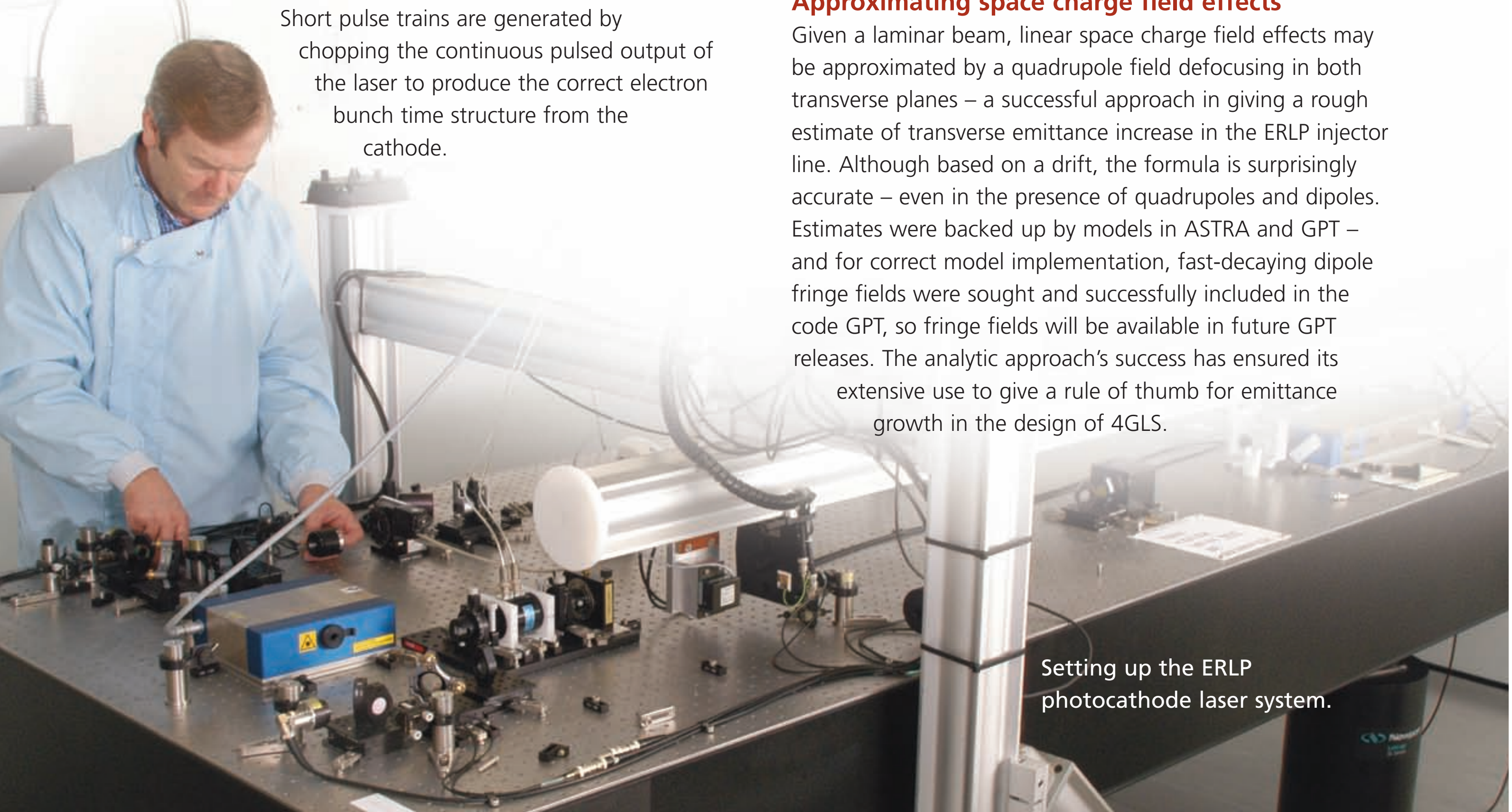
The former SRS Klystron power supply is being reinstated as an RF power supply for ERLP and RF test facilities. The RF for the ERLP will be from three 1.3 GHz 16 kW Inductive Output Tubes (IOTS) and the test facility RF will be from an IOT or a 500 MHz 250 kW klystron. A more suitable power supply control system will be required, delivering monitoring and control needed for successful commissioning and operation. The system will extend from the Siemens S7 300 PLC through to the EPICS interface device and to the local Human Machine Interface (HMI) operator. The system will not include high voltage a.c. equipment control, safety or high-voltage cubicle entry systems – control will be carried out by a separate failsafe PLC system.

SPACE CHARGE

A major factor in emittance degradation is space charge, particularly at low energies. Because of low beam energy (< 10 MeV) in the ERLP transfer line, estimation of space charge is important as it may hinder successful machine operation – which is why substantial time was devoted to finding a satisfactory solution. An analytical approach was extended from N. Vinokurov's work, assuming beam laminarity, i.e. if initial particle velocities depend linearly on initial coordinates, trajectories do not cross at any stage. This assumption means the average kinetic energy of beam transverse motion or temperature is much less than the electrostatic potential energy, though this would not be true immediately after the exit of the gun.

Approximating space charge field effects

Given a laminar beam, linear space charge field effects may be approximated by a quadrupole field defocusing in both transverse planes – a successful approach in giving a rough estimate of transverse emittance increase in the ERLP injector line. Although based on a drift, the formula is surprisingly accurate – even in the presence of quadrupoles and dipoles. Estimates were backed up by models in ASTRA and GPT – and for correct model implementation, fast-decaying dipole fringe fields were sought and successfully included in the code GPT, so fringe fields will be available in future GPT releases. The analytic approach's success has ensured its extensive use to give a rule of thumb for emittance growth in the design of 4GLS.

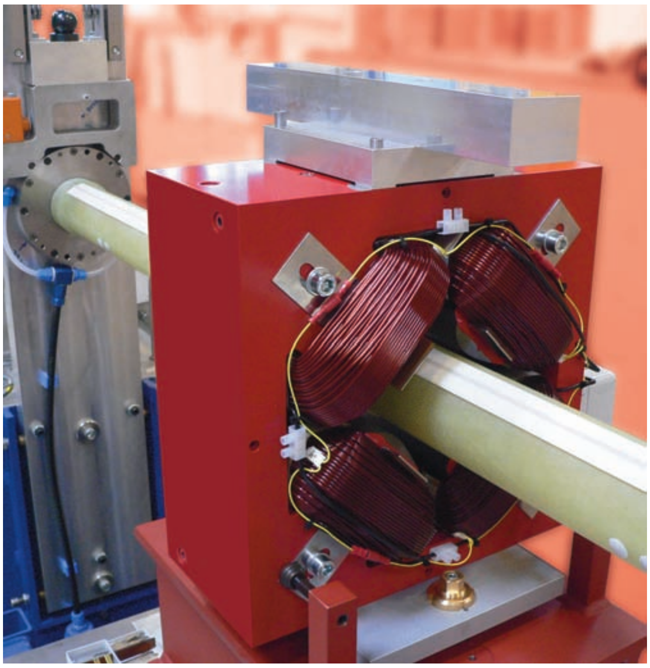


Setting up the ERLP photocathode laser system.

MAGNETS

JLAB Loan Magnets

Many ERLP transport magnets (along with the FEL wiggler) have been generously loaned by Jefferson Laboratory where they were used in the IR Demo free-electron laser, a machine with many similar parameters to ERLP. Before ERLP installation, magnets were tested to ensure they met tight project specification tolerances, and to provide a more detailed field map to fine-tune the computer model. Testing (in the Insertion Device Laboratory at Daresbury) comprised temperature tests and field mapping.



An ERLP quadrupole being measured on a Rotating Coil bench at the Danfysik premises near Copenhagen, Denmark.

Online field measurements

An accurate determination of the beam energy in the ERLP is important. To measure the beam energy the beam is deflected by a magnetic field. The field in several of the dipoles at key points around the machine will be directly measured as the machine is running, using specialised small Hall probes connected into the control system. The Hall probes are attached to the pole face of each magnet, and calibrated against the central field. Combined with readings from sensitive beam position monitors (BPMs), this will give highly accurate measurements of the beam energy as it is accelerated through the machine.

Procurement of New Magnets

Remaining magnets are being designed, manufactured and tested by Danfysik, and ASTeC carried out preliminary modelling using Finite Element Analysis (FEA) codes, producing a specification giving required magnetic field quality and maximum physical dimensions. Field quality specification is very demanding, with magnet apertures in the second arc being very large to allow a post-FEL electron beam with a large energy spread to be transported without losing electrons so as to maximise energy recovery. Aperture field variation must also be very small because a good FEL operation requires electron beam motion in the FEL to be limited to within 10% of beam radius. ASTeC staff have liaised closely with Danfysik to ensure tight specifications and aggressive delivery schedules are satisfied.

VACUUM SCIENCE

The design of ERLP vacuum systems was completed during 2005 and work began to focus on procurement, whilst finishing touches were made to the Beam Transport System (BTS) design, photoinjector systems, superconducting modules and the diagnostic beamline. Three particular challenges occurred during the year:

The photo-injector vacuum system requires a large ceramic insulating tube with knife-edge flanges sealed to a leak rate better than 1×10^{-11} mbar.l/s. Ceramic manufacture has been a real challenge, with the vacuum team involved in discussions with the tube manufacturers regarding cleaning, baking, handling and vacuum brazing. A satisfactory solution is being actively sought.

The superconducting linac and booster modules require very low operating pressures and clean, particle-free vacuum. By working with module manufacturers, a satisfactory vacuum acceptance and operating procedure has been agreed. Control procedures include use of sub-micron particle filters and implementation of carefully controlled pressure changes in modules during pump-down and let-up.

Superconducting accelerating modules and the ERLP photocathode are sensitive to particles, and two main methods have been used to minimise numbers of particles in ERLP vacuum systems:

- During the design phase, devices known to generate particles have been kept to a minimum.
- Procedures were required to flush out and prevent particle ingress into vacuum systems whilst being assembled and installed. Procedure detailing is well under way and will be completed in time for delivery of the first vacuum system parts.

Touching the Grail

For years, scientists have sought the holy grail of photon generation – an ultimate combination of sources delivering dynamic science to the low energy photon science community in the UK. And now 4GLS – the 4th Generation Light Source – is within reach, destined to outstrip current 2nd and 3rd generation sources and lead the world in advanced photon generation.

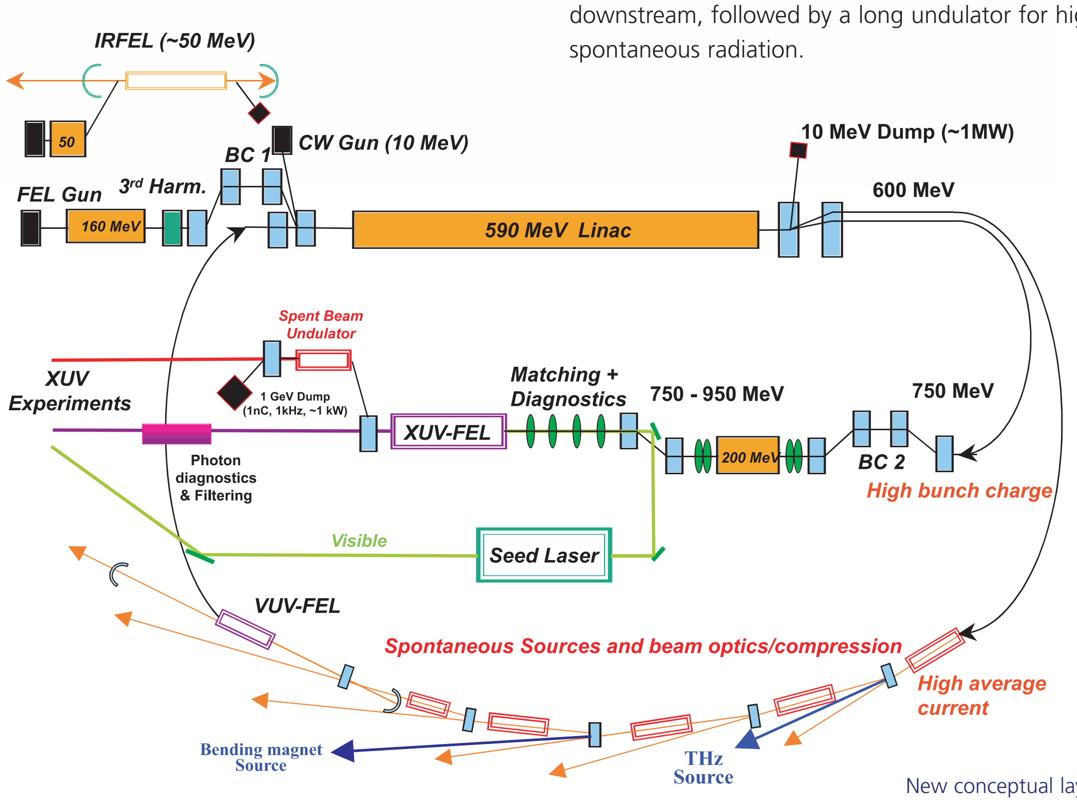
4GLS is a ground-breaking proposal for a UK national light source at Daresbury Laboratory, and is based on a superconducting energy recovery linac (ERL) with high average current photon sources (undulators and bending magnets) and high peak current free electron lasers. Key features include a seeded high gain FEL amplifier to generate XUV radiation – and the prospect of advanced research arising from unique combinations of sources with femtosecond pulse structure. This suite of sources must cover the whole range from THz to soft X-ray output and be synchronised for pump-probe and dynamic imaging studies.

4GLS - a realistic scheme capable of simulation

The proposed layout of 4GLS has moved on from its conceptual level to a realistic scheme capable of simulation, whilst matching users' scientific needs. The concept developed through early 2005, incorporating several important new features, a 10 MeV superconducting gun injects CW beam into a 590 MeV linac and whilst the 600 MeV output beam (at 100 mA) traverses the outer path via undulator sources and a VUV-FEL, before returning for energy recovery in a second pass. In parallel, a beam from a high-charge (1 nC) RF gun operating at 1 kHz can be accelerated to 160 MeV and then compressed before entering the high-energy linac.

Separating 750 MeV and 600 MeV beams

The emerging 750 MeV beam is separated from the 600 MeV beam by a fixed magnetic spreader and directed through an alternative arc to a further variable energy linac of final output of up to ~1 GeV. A seeded XUV-FEL is located downstream, followed by a long undulator for high-energy spontaneous radiation.



New conceptual layout of 4GLS.

The source portfolio is completed by an IRFEL fed from a separate 50 MeV linac synchronised to the high-energy linacs via their photocathode guns. At this stage, the baseline design assumes both the inner high bunch charge loops and outer high average current loops are based on three-bend magnetic cells. The CW loop scheme assumes control of the longitudinal bunch profile (through the undulators) can be achieved without using a lumped magnetic compressor. The control of the longitudinal dynamics would be achieved by balancing the linac-induced correlated energy spread and the energy-dependent path length of the particle trajectories through the three magnet cells. This would progressively develop the bunch profile through various undulators, optimising the profile to ensure efficient lasing in the VUV-FEL.

BEAM BREAKUP

Beam Break Up (BBU) occurs when the beam is kicked off course by Higher Order Modes (HOMs) contained within the accelerating cavities – a HOM is a resonant electromagnetic field with a higher frequency than the fundamental frequency used to accelerate the particles. If a particle passes through such a field off its usual axis, it will be kicked by the field and excite the field further. If the frequency of the field is a harmonic of the revolution frequency or the bunch frequency, the effect can accumulate until the kick is large enough for beam loss.

HOM growth rate dependant on beam current

HOM growth rate is also dependant on the beam current – since the larger the current, the greater the kick. This leads to a threshold below which the beam is stable and above which it is likely to break up. With its short linac and low current, BBU will not be a problem for the Energy Recovery Linac Prototype, and work is also being carried out to ensure that this will not be a problem for 4GLS, with two optical and two structural methods currently being investigated.

FREE ELECTRON LASERS

This year, the work began on developing the original concept FELs into complete designs – integrating closely with the design of the electron beam transport systems to ensure electron bunches delivered to the free-electron lasers have the low emittance and energy spread required for lasing.

Covering the wide wavelength range

The IR-FEL challenge is to cover the widest wavelength range whilst making allowance for optics materials and techniques appropriate for each part of the wavelength range.

Adopting the RAFEL concept

VUV-FEL design work has led to adoption of the Regenerative Amplifier FEL (RAFEL) concept, where optical gain over one pass is high enough to ensure the FEL reaches saturation in a few passes, rather than the typical several hundred passes necessary in a low-gain oscillator FEL. Because the gain is so high, it should be possible to use low-reflective metal mirrors offering high resistance to radiation damage, whilst being sufficiently reflective across the whole wavelength range of 3-10 eV. This contrasts with multilayer mirrors, which have a relatively narrow bandwidth. The low level of optical feedback provided by the optics is enough to significantly improve the quality of the photon output pulse when compared to that available from a SASE (self amplified spontaneous emission) FEL.

FEL seeding technique

The XUV FEL uses a seeding technique to improve photon pulse quality over SASE. The seed is generated by a High Harmonic Generation (HHG) source, where a high-power short-pulse IR laser is fired into a jet of inert gas. Electron ionisation and recombination with nuclei generates a high-intensity comb of harmonics, which can be filtered out for seeding the XUV FEL at its fundamental resonant frequency.

SPACECHARGE

Having learnt from the analysis of ERLP spacecharge effects, the analytical approximation (due to Vinokurov) was used for an estimate of transverse emittance growth for the 4GLS project. The formula was tested at different energies from those of the ERLP and also at different bunch charges - then a small program was written to give estimates for the 4GLS project. Detailed studies using GPT for both injector lines are still to be undertaken, whilst an in-depth assessment of longitudinal space charge is still ongoing. However, based on prior ERLP experience, this is not expected to be a serious issue.

Cross-border Co-operation

Work on the International Linear Collider (ILC) involves partnerships crossing national and global boundaries, to produce a formidable world partnership of scientific research – and ASTeC has made a strong showing on behalf of the UK through a range of pioneering projects.

RETURN OF THE DOUBLE HELIX

Most people associate the double helix with DNA - but this familiar three-dimensional shape recurs in a helical undulator-based positron source for the ILC.

"A major challenge facing the ILC is to efficiently produce the required positron intensity," says Duncan Scott, Physicist, "especially since the source must also be upgradeable so as to produce polarised positrons." To tackle this challenge, ASTeC is working internationally with SLAC, DESY, Cornell, Princeton and other centres of excellence on a proposed positron-producing system involving an undulator magnetic device.

The undulator - 200 metres long

The undulator would be around 200 metres long and radiation is created when the main electron beam passes through it. The radiation hits a target where electron and positron pairs are produced. The positrons can then be captured and accelerated down the main positron linac. Using polarised electron and positron beams in a future collider is a very attractive proposition to high energy physicists because the polarised beams will permit new physics, currently inaccessible with unpolarised beams to be studied as well as reducing the statistical error of the collected data.

The polarisation of electrons or positrons can be explained by their spin, which is a quantum mechanical property underlying all matter. Imagine the particle is a spinning sphere like the earth, with its spin simply the axis of rotation – though for electrons and positrons this axis of rotation can only be positive or negative. In a 100% polarised positron beam, all positron spins would be aligned the same way – and for the ILC, a positron polarisation of around 60% is required.

Measuring the magnetic field profile of the permanent magnet helical undulator prototype

The need for circularly polarised light

Creating a polarised positron beam requires left-or right-handed circularly polarised light, which can be produced by a helical undulator. The transverse magnetic fields of a helical undulator produce a helical electron trajectory through the device, emitting circularly polarised photons – and if you were to look head-on at the approaching electron, you'd see it moving in a circle, clockwise or anti-clockwise, i.e. left-handed or right-handed. ASTeC is a member of an international collective of institutes, working together to create a demonstration experiment of the idea and examining two different types of helical undulator; the first is a superconducting bi-filar geometry with two superconducting wires wrapped in a double helix around the vacuum vessel. When current is passed through the wires, the longitudinal components of the magnetic field cancel, leaving only the required transverse helical field on the axis.

Permanent magnet technology

The second helical undulator option is based on permanent magnet technology, where a dipole field is created by a ring of permanent magnet blocks, with the magnetisation vector of each block rotated around the ring. A number of rings are stacked together so that along a period, the dipole field is rotated by 360 degrees. To allow access to the vacuum vessel, the rings must be split to form top and bottom arrays.

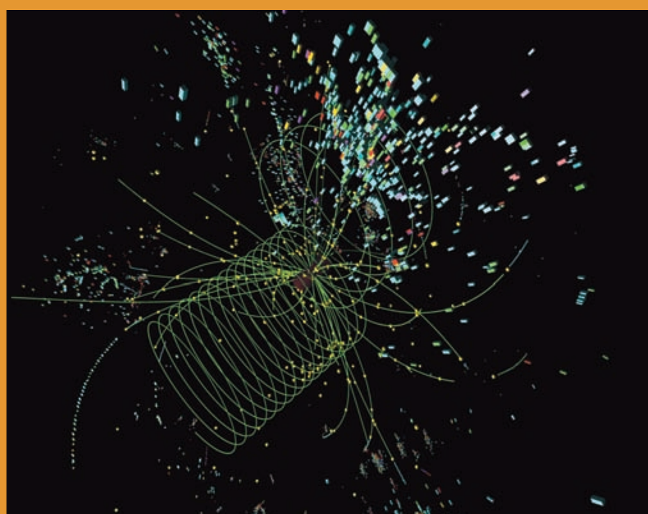
The chosen number of blocks per ring generates the desired field quality with the minimum magnetic force between the two arrays. Prototypes of each device have been made and are being assessed at Daresbury and RAL, with tests including measurement of magnetic field profiles.

The magnetic field of the superconducting device depends upon the amount of current flowing through the device – and, says Duncan, "the field only increases to a certain level before the magnet 'quenches' – in other words, it becomes non-superconducting." Measurements of when this occurs have proved valuable in verifying computer simulations, whilst determining the maximum possible field for the magnet.

A preferred technology recommendation

When the test results have been analysed, a preferred technology recommendation will be made, based on overall magnetic performance, capital costs and design flexibility – then a larger working prototype will be built. As well as the magnet design of the helical undulator, work has been done on vacuum vessel requirements – to create the highest possible field, the aperture of the magnet needs to be a small as possible. The limit for the electron beam is 4mm, though achieving a vacuum in such a long narrow gap magnet is no trivial matter.

Simulated event illustrating the associated production of a Higgs particle and a Z boson at a linear collider. (Credit: Norman Graf)



Simulated response of linear collider detector to the production of two Z bosons. Each of the Z bosons decays into a pair of jets. (Credit: Norman Graf)

EXTRACTION, COLLIMATION, CORRECTION - COLLABORATION

International collaboration underlines Accelerator Physics work for 2004-5, which includes the 2 mrad extraction line, collimation design for the linear collider and correction of local chromaticity, which forms the basis of the final focus design for the International Linear Collider.

In August 2004, the International Technology Recommendation Panel (ITRP) recommended using cold linac technology for the linear collider. The bunch structure of a cold linac allows a head-on beam collision, though the extraction of the highly disrupted beam poses a considerable challenge. ASTeC had been collaborating with French laboratories LAL, Orsay and CEA, Saclay on a possible solution to the head-on beam extraction for TESLA before the announcement of the technology decision. After the technology decision, it was clear that continuation of the work was urgently required.

Small crossing angle solution to save head on physics

To overcome the problems associated with the TESLA head-on scheme, two solutions had been suggested for TESLA – a small vertical crossing angle and a small horizontal crossing angle. The latter was preferred since it had major advantages which were head-on beam collision, it didn't require electrostatic separators, it required only minor crab crossing correction and it avoided septum irradiation problems. The first ILC workshop was held at KEK in November 2004, where the Beam Delivery working group recommended a 'Straw man' layout with two interaction regions – one with a 2 mrad crossing angle and one with a 20 mrad crossing angle. After the ILC workshop, the UK-France collaboration for 2 mrad crossing angle was extended to a USA-UK-France task force.

Collimation for the ILC

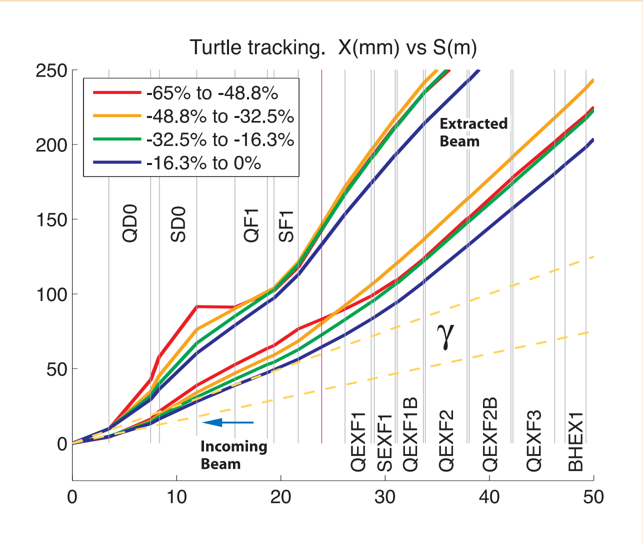
The beam 'halo' in particle collider experiments can be a serious source of background in the detector. The halo is the part of the beam that is spread out far from the beam centre. Using collimators along the length of the beam delivery system (BDS), the halo can be removed or reduced. The collimators are pieces of material with small gaps which allow the main beam to pass through, but stop the halo particles. However the narrow gaps can cause problems of their own, introducing strong wakefields to the beam in the BDS.

Developing Collimation Design

After the technology decision, international efforts began on developing the ILC collimation design. The NLC scheme was used as a starting point, since it had demonstrated good performance in previous studies. The design was changed to increase the beam sizes at the collimators and thereby allow survival of the system in case of direct hits by errant beams. In addition, the overall optics features of the BDS changed, necessitating re-evaluation of the collimation apertures.
The performance of the evolving collimation design is assessed by simulations which track the beam halo through the BDS. ASTeC has used the available simulation tools to estimate collimation efficiencies for current and past designs. In particular, the results of the 2002 collimation comparison studies have been reproduced using the codes MERLIN and STRUCT. ASTeC has also recomputed the collimation apertures, using tools developed within the TESLA collaboration.

Challenges for 2 mrad design

In the 2 mrad design, the large-bore superconducting quadrupole 'QD0', which is the closest magnet to the interaction point, is shared between the incoming and outgoing beams, whilst the next warm quadrupole 'QF1' is a pocket of field coil iron quadrupole, with the disrupted beam after collision going off-axis through the pocket of field. The sextupoles near the quadrupoles (used for compensating the chromaticity of the incoming beam) provide focussing to the outgoing low-energy particles, aiding beam extraction. The first few magnets in this design need complex designs to accommodate the incoming as well as the outgoing disrupted beam, which has a low energy tail. The downstream optics also needs to provide polarimeter and energy chicanes to diagnose the outgoing beam properties. This is currently being studied by the task force.



Beam tracking through 2 mrad crossing angle interaction region.

Collimator wakefields

The ILC collimators will probably have very narrow gaps, through which the high energy beam will pass. These narrow gaps induce strong wakefields which disturb the beam. Analysis of various collimator shapes is being carried out at ASTeC with other Linear Collider Accelerator and Beam Delivery (LC-ABD) collaborators to understand the possible effects of geometric or resistive wall wakefields. Several collimator designs are being considered to be tested at the SLAC End Station A (ESA).

Verification of wakefield tests

Numerical calculations are being undertaken by ASTeC with other LC-ABD collaborators to verify these wakefield tests, and the MAFIA simulations suite has a built-in function that allows the user to calculate the integrated wakefield as a function of the distance behind the source charge. This is then used to calculate the longitudinal long range wakefield produced by simulating a bunch through the structure. Once these structures are better understood, suitably designed spoilers will be recommended for the ILC.

Introducing a superconducting crab cavity

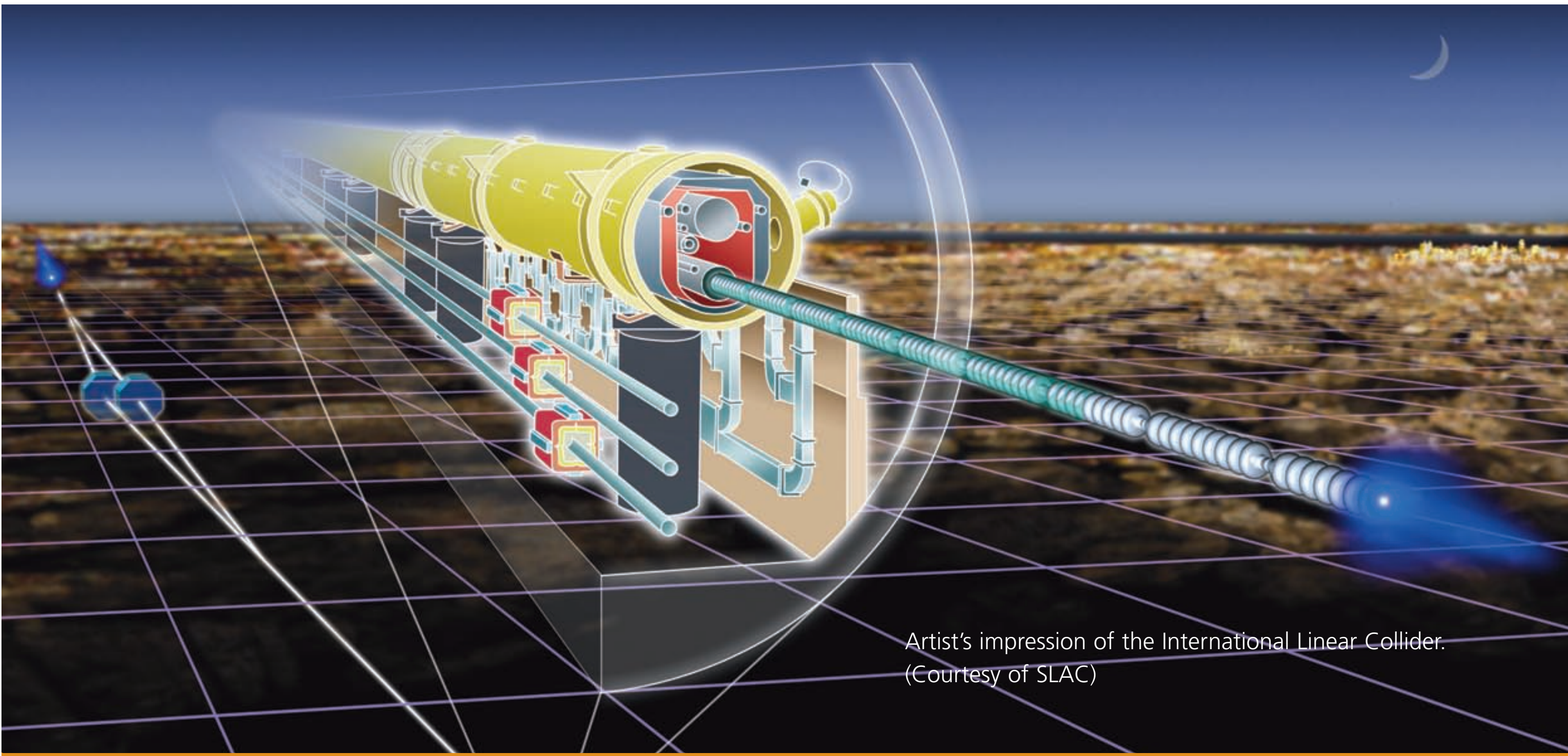
One of the interaction regions in the presently recommended ILC straw man configuration has a large crossing angle of 20 mrad. When bunches collide with a crossing angle, there is a loss of luminosity. Using crab cavities in the beam delivery system, bunches are rotated to collide head-on without loss of luminosity. ASTeC (with other LC-ABD collaborators) is designing a crab system that provides a sufficient kick with the necessary stability. The system is composed of a superconducting RF crab cavity resonating at the linac frequency or a higher harmonic, operating in the dipole mode. Stringent control of the crab cavity phase is vital to ensure that the bunches collide head-on.

SLAC End Station A test facility

Following the cold linac technology decision, international collaborations proposed to use ESA as a test facility for several ILC prototypes and experiments. Of particular interest to the UK LC-ABD project were collimation wakefield studies and material damage studies, with each experiment requiring different beam properties. ASTeC undertook the design of beam optics for these experiments.

ATF2 proposal for final focus test facility

The ILC final focus design is based on local chromaticity correction, where chromatic aberrations generated (due to the final doublet) are locally compensated by sextupoles near the final quadrupole magnets. This scheme is different from the classical method of dedicated chromaticity compensation sections, as designed and experimentally verified for the SLAC Linear Collider (SLC) and Final Focus Test Beam (FFTB). The proposal to extend the Accelerator Test Facility (ATF) at KEK to cover design and test the local chromaticity correction final focus (ATF2) was discussed during the first ILC workshop - the goal of ATF2 is to focus beams to a 35 nanometre vertical beam size whilst maintaining beam stability. ASTeC volunteered to study proposed optics designs, estimate tolerance requirements and develop tuning procedures for the scheme.



Artist's impression of the International Linear Collider. (Courtesy of SLAC)

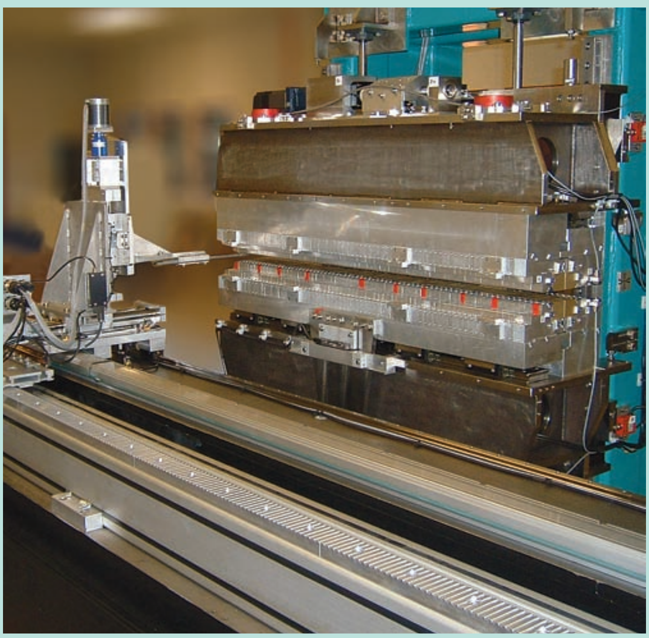
Crunch Time for Apple

After extensive work building the new HU56 APPLE II variable polarisation undulator, it was time for some extensive field tests to assess performance.

Built in early 2004, HU56 is the new permanent magnet-based helical undulator on Beamline 5 of the SRS. Following completion of the construction phase, both extensive field testing and shimming were carried out in the Insertion Device Laboratory at Daresbury. The undulator is an APPLE-II variable polarisation type with four permanent magnet arrays, two of which can be moved independently along the longitudinal direction. This allows for movement parallel to the beam in order to vary the direction of the field.The amount that the arrays move relative to one another (the undulator phase) determines the polarisation of the light produced by the electron beam travelling through the device and it can produce horizontal, vertical, linear, or circular polarised light, and any variation in between.

Hall probe used to generate field maps

Field maps were generated at different undulator gaps and phases using a scanning Hall probe. The resulting field map could then be used to assess the quality of the radiation output, together with the overall effect of the device on the electron beam. Since the undulator is installed in a straight section of the SRS storage ring, it must have no overall effect on the beam direction.



HU56 undergoing Hall probe testing

The magnet blocks are not all identical, with the remanent field strength and magnetisation direction varying minutely from block to block. These errors can add up over the length of the device, reducing the quality of the output radiation, whilst having a detrimental effect on the stored beam. The individual blocks are all magnetically tested before the device is built, then sorted into an order that will minimise such errors. However in a real device, some errors always remain and these should be corrected as far as possible. Field errors in the HU56 were corrected by swapping blocks within the device and by 'virtual shimming' – that is, moving the blocks up or down in small steps. There is also a small field error component that contributes to a disturbance of the stored beam, and this depends on the undulator's gap and phase. It can be corrected using trim coils, that produce a small horizontal or vertical magnetic field in addition to the undulator's field. The currents in these coils are automatically changed as the undulator's gap and phase are changed – and as a result, the gap and phase can be changed at any time, with minimal effect on the SRS stored beam.

Installation into the SRS storage ring

HU56 was installed into the SRS storage ring in October 2004 and the first measurement made was its effect on the beam without any correction. There was sufficient movement in the position of the beam to merit correction as the gap was closed but the effect was less than was anticipated.
The shift in the vertical tune (the rate of transverse oscillations within the beam) was minimal and did not require correction. Trim coil values were optimised for each setting of gap and phase, and the settings actually required were significantly less than the correction coils were capable of. The undulator gap and phase were then changed and the beam position was monitored with the trim coils switched on. The trim coils compensated well for the effect of the undulator on the beam, so that there was no significant movement.

RESTORING THE BALANCE

After an RF cavity loss, infrared beamlines showed low-frequency instability – but after a range of experiments, a solution was found to restore balance and order to beamline function.

LONGITUDINAL BEAM INSTABILITY

Following the loss of one of the four RF cavities due to a window failure, a low-frequency instability was observed on the infrared beamlines. As machine vacuum improved, this instability became so bad that the photon beam was unusable for certain experiments, so the accelerator physics group planned and carried out numerous experiments to characterise and control this instability, which was assumed to be longitudinal motion of the electrons in the RF bucket. It was suggested that the instability was triggered by the increase in the cavity voltage required to maintain the same forward RF power when operating with three instead of four cavities. It could also be due to the existence of the unpowered fourth cavity (with its tuning mechanism located at one end of its travel and disabled) in the beam.

This phenomenon had never been seen before in the twenty five year history of the SRS, due to changes in machine impedance (such as from the installation of the four narrow-gap insertion device vessels)

Damping the instability

Because it was not initially possible to change any of these factors, a mechanism was required that would damp the instability. Measurements were made of dependence of the instability amplitude and frequency on beam current, beam energy, fill structure, octupole field, operation of the superconducting wigglers and clearing electrode voltage. Deliberately induced small pressure rises were measured but no solution was forthcoming as to what could be used to damp the instability to an acceptable level. Finally, it was found that changing the position of the cavity tuner in the unpowered cavity (from one end of its travel to the other) acted as an on-off switch for the instability. Shortly after this was discovered, the SRS was returned to four-cavity operation – and since that time, there has been no sign of instability recurrence.

Commissioning the new APPLE II undulator

Diamond Transformation

As the Diamond light source facility evolves, it's transforming and enhancing the quality of work being undertaken – especially with regard to the booster synchrotron.

The booster synchrotron is a highly valued part of the machine, accelerating electrons from 100 MeV to their design energy of 3 GeV. "Designing the booster synchrotron to accelerate electrons without high losses ensures safe running of the machine," comments James Jones, Accelerator Physicist, "so we've undertaken extensive studies that involved simulating the injection of electrons into the booster so that we could observe their evolution over time." Errors were included on all booster magnets to mimic real conditions, and allowances were made for errors in other machine areas such as the linac, which feeds electrons to the booster - and the injection system, which is a complex arrangement of magnets taking electrons from the linac and inserting them into the booster.

Only a few percent electron losses

The final analysis showed we can usually expect the booster synchrotron to accept and accelerate electrons with only a few percent losses (mostly at known locations where we can contain them). "This is good news for implementing a top-up storage ring operation," says James. "It's a process in which the booster is used to regularly top up electrons circulating in the Storage Ring for the benefit of scientific users, since higher losses might mean too much radiation and a limitation to operations."

Lower electron loss inside storage ring

Although low booster losses are important, electron losses in the storage ring should be even lower. The 'Booster-to-Storage-Ring Transfer Line' is a ~40m beam transport section linking booster to storage ring. The line contains collimators impinging on the electron beam, removing stray electrons that would otherwise be lost in the storage ring. The collimators also provide a safety mechanism to stop electrons if anything goes wrong in the booster, protecting scientific users and storage ring equipment.

Effective modelling of transfer line collimator system

ASTeC physicists designed and modelled the transfer line collimator system, firstly arranging the other magnets so that collimators could be placed at locations where they would efficiently remove out-of-position or low-energy electrons. "The line was analysed under different likely error scenarios, including modelling of electron-collimator interaction," says James. "At the same time, though, we ensured that 'Secondary Electrons' (created when electrons collide with collimator surfaces), did not create a serious problem." The final design, and subsequent simulations, showed the collimation system was effective in protecting the storage ring from large electron losses – plus it could cope with unexpected failures in upstream systems such as the booster.

Further collimation design

The other transfer line, which links the linac and booster, was also designed with a collimator which can remove electrons with the wrong energy for successful injection into the booster. Again, magnets in this line were arranged so the collimator could function effectively. The engineering designs for both transfer lines were designed and approved so their components can now be manufactured.

Diamond installation work

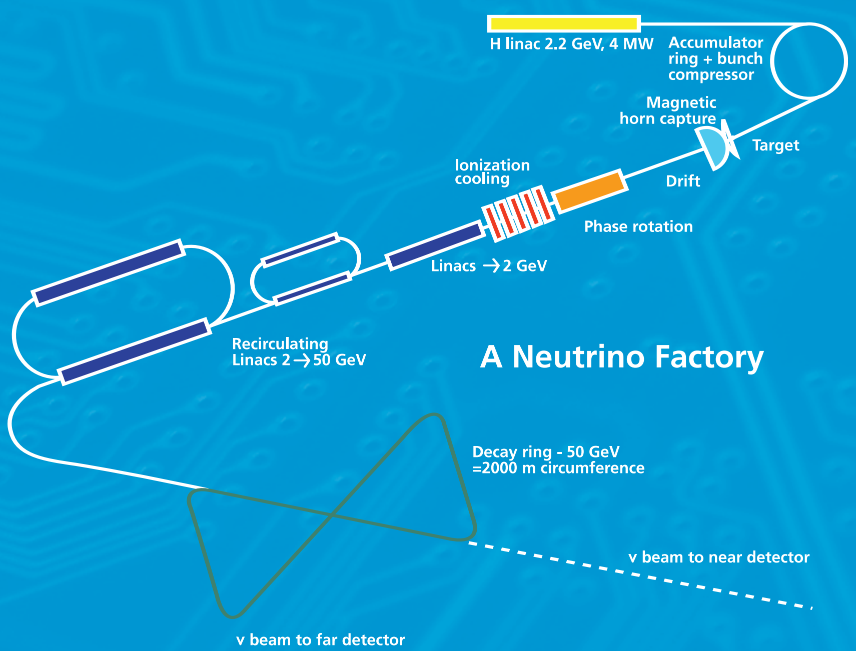
Of Mice and Men

The scientists working on MICE (Muon Ionisation Cooling Experiment) are intent on creating a future neutrino factory, using muon cooling to maximise the number of muons available for neutrino production.

Future Neutrino Factories will probably use muon cooling to maximise the number of muons available for acceleration, storage and neutrino production. Cooling involves reducing muon beam energy by passing through liquid hydrogen cells, with the beam re-accelerated longitudinally using RF cavities – so cooling removes energy and momentum in all spatial directions, with cavities replacing energy only longitudinally, for a beam with better emittance. More muons then enter the downstream accelerating structure's aperture and more neutrinos are produced.

MICE - testing the effectiveness of the concept

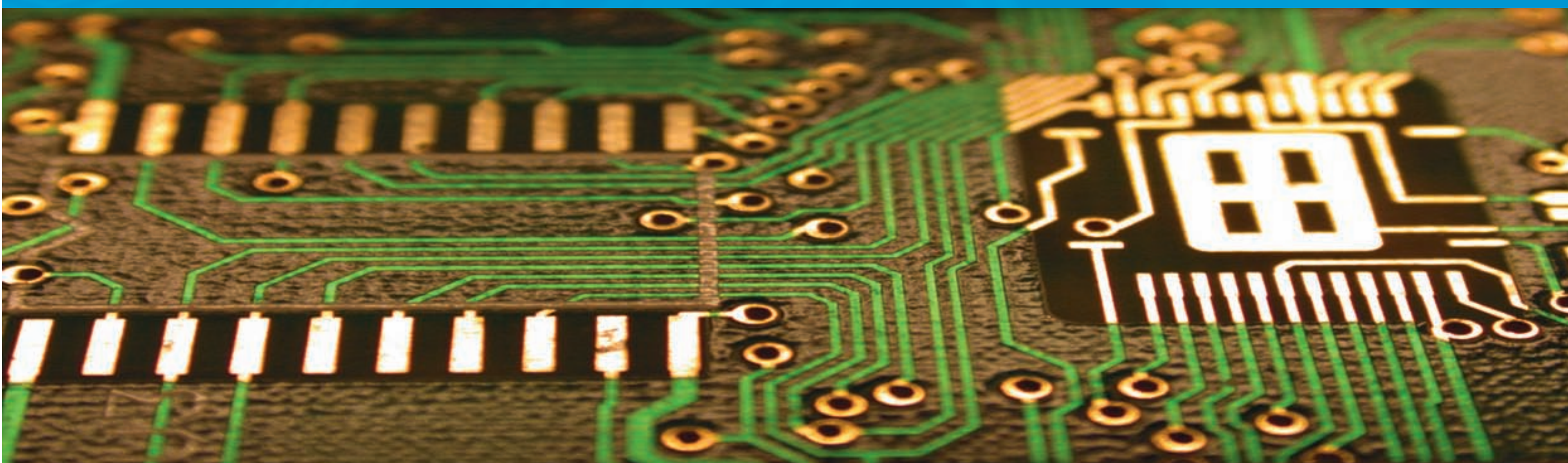
The purpose of MICE is to test the concept's effectiveness; a short length of cooling channel will be built and tested using ISIS-produced muons, with the radio frequency (RF) power requirement supplied using equipment from Daresbury Laboratory. Though MICE is a leading-edge experiment, the RF equipment required is not, comprising three 4616 tetrode circuits and two TH116 triode circuits.



Building an RF system with old equipment

Currently DL staff are procuring the HT and control racks for the 4616, a high power dummy load is being borrowed from CERN and the 4616 circuits are being refurbished.

The challenge of building an RF system using obsolete equipment (with no documentation) should not be underestimated – though this is a challenge which ASTeC is entirely capable of fulfilling.



Alpha Bet

For pioneering new work, ASTeC is always a good bet – as Alpha-X proves through its revolutionary laser plasma wakefield acceleration technology.

ALPHA-X is a four-year programme to develop the emerging technology of laser plasma wakefield acceleration – a revolutionary concept in accelerator science – and a collaboration between Strathclyde University, ASTeC and other UK research groups. In a plasma wakefield accelerator, a high-intensity laser pulse is focused in a plasma channel, into which a short bunch of electrons is injected. The consequent electrostatic wake produces high accelerating gradients for the electron beam – and the aim is to produce a 1 GeV electron beam, with a first step of 100 MeV to demonstrate the technology. The final beam will be injected into a pair of undulators to produce coherent FEL X-ray radiation.
The undulators have been designed by ASTeC and built at Daresbury Laboratory. They are a permanent magnet design, with 100 periods of 15 mm each, and a peak on-axis field of 0.7 T at the minimum gap of 5.5 mm. A slot cut into the centre of each block allows for focusing, with the beam confined in horizontal and vertical planes over the device's length.

Construction of an ALPHA-X undulator

Using a Hall Probe to obtain a field map

The construction of the undulators is complete, and data from the magnet block manufacturer was utilised to optimise the order in which they were placed in the undulators. The testing and shimming will take place in the Insertion Device test laboratory at Daresbury, and measurements will involve a Hall Effect probe to provide a detailed field map.

Modelling beam scattering through foil windows

ASTeC performed simulation studies for the ALPHA-X beamline design, in which the photo-injector is isolated from the plasma channel to ensure good vacuum conditions. A thin foil window between injector and plasma channel can achieve this, though beam scattering through the foil may have an adverse effect by increasing angular beam spread and beam size, making it more difficult (or impossible) to focus to the small spot size required at the plasma channel.

Investigations were undertaken into modelling beam scattering effects through the foil windows, which are particularly thin (a few microns or less), making straightforward multiple scattering calculations inappropriate. This is a 'plural scattering' phenomenon, with beam particles experiencing a small number of scatters in the foil, whilst some particles are not scattered at all. To calculate plural scattering requires detailed simulation using a statistical approach to estimate the number of scatters each particle experiences and the deflection angle of each scatter.

Using GEANT to undertake simulation

The GEANT (GEometry ANd Tracking) code (primarily used for high-energy particle physics studies) was used for the simulation, and routines to calculate plural scattering were extracted and interfaced to the existing accelerator physics code, MERLIN, at Daresbury Laboratory, allowing for study of the scattering effect of thin Beryllium windows (1 to 10 microns thick) on the 6 MeV ALPHA-X beam. As expected, the simulated angular distribution of scattered beams showed an unscattered portion and scattered 'tails' – with the thinnest windows producing the smallest tails.

Solving the Solvent Problem

Neutron absorption, vacuum gauge calibration – and finding a new cleaning solvent for vacuum component preparation – these are just some of the challenges facing the Vacuum Lab in the last twelve months.

"A key project completed this year was evaluating cleaning solvents for preparing vacuum components for UHV," reports Joe Herbert, Senior Vacuum Scientist. "We currently use trichloroethylene, but it'll be phased out by 2007 due to re-classification as a carcinogenic risk. "Work concentrated on chemical solvents, since aqueous cleaners were found to be unsuitable for preparing vacuum components for our applications – and a number of solvents (such as alcohols and n-propyl bromides) gave good results, though there are health and safety issues associated with using these solvents in a large-scale facility. "A range of solvents based on a hydrofluoroether (HFE) compound performed extremely well," says Joe. "In fact," he continues "they proved to be better than trichloroethylene, so we undertook extensive testing to ensure results were repeatable." HFE has now been recommended as a suitable replacement for trichloroethylene, and future work will concentrate on using HFE more cost-effectively, since it's expensive compared to trichloroethylene. The effectiveness of co-solvent cleaning techniques – a two-stage cleaning process using a cheap hydrocarbon-based solvent followed by HFE – will be assessed for similar (if not better) results than simple use of HFE.

Neutron Absorbers

Outgassing tests have been performed on Boron Carbide samples to be used as neutron absorbers for experiments at ISIS. Different samples were provided and their outgassing rates measured to determine which was most suitable. One particular Boron Carbide sample performed better than the others, and an internal report was submitted.

Calibration Facility

New funding has allowed the group to re-develop the vacuum gauge calibration facility, and the system has been redesigned to include a standard Fischer-Mommsen pumping speed dome with a common gas injection system. "Two extractor gauges were calibrated at national standards laboratories – NPL in the UK and PTB in Germany," says Keith Middleman, Vacuum Scientist, "and these were installed on the calibration system. Some time was spent commissioning the system and the facility established a good base pressure below 10^{-10} mbar."

Initial experiments monitored performance of calibrated gauges, generating some preliminary results – and in future, all total pressure gauges used in the vacuum science laboratory will be regularly checked against the two installed calibrated gauges, allowing the group to ensure the quality control of all total pressure gauge data. "This will be important for a number of vacuum science projects," says Keith and it'll provide the group with a more thorough understanding of the long-term behaviour of total pressure gauges – and later on, we're hoping to extend the programme to residual gas analysers."

GaAs Wafer Photocathode Preparation Facility

The photocathode gun is a particularly important item used in ERLP – and a key component is the GaAs photocathode, which requires careful preparation to ensure good quantum efficiency. A new facility in the vacuum science laboratory will study the key processes needed to prepare the GaAs wafer to emit electrons efficiently – and the system will also be used to develop and characterise these processes. This work will be reported more fully next year.

An XHV Vacum chamber

Speaking the Language That Unites the World

Collaboration and co-operation bring people together from across all geographical, cultural and linguistic boundaries – and ASTeC's collaborative projects over the past twelve months demonstrate the meeting of minds on a global scale.

VACUUM-PACKED

The Vacuum Science Group has packed plenty of valuable work into twelve months of intensive activity.

Increasingly, we're participating in collaborations in the UK and abroad," reports Keith Middleman, Vacuum Scientist of the Vacuum Science Group (VSG). "We're currently working with Manchester Metropolitan University (MMU)" continues Keith, "to study properties of alloy films deposited on vacuum chamber inside surfaces – and after heating to a modest temperature these alloy films act as a vacuum pump, so are useful in accelerators." Films are prepared at MMU with vacuum properties measured in the VSG laboratory. The redesigned measurement system simultaneously handles NEG-coated tubes and flanges – and, reports Keith, "Monte-Carlo system simulations have been carried out to extract sticking coefficients for injected gas. Measurements on coatings samples prepared commercially provide verification that the measurement technique used is suitable." Work will now focus on NEG-coated tubes produced by MMU, to understand parameters that affect NEG coating vacuum performance.

International Linear Collider

VSG is also involved in ILC design work, and a 200 m long helical undulator requires pumping along a 4 mm diameter beam tube irradiated by synchrotron radiation. "Room temperature and superconducting magnet designs are being considered," says Oleg Malyshev, Senior Vacuum Scientist, "and for the former, NEG coatings must be deposited inside the narrow tube." Techniques are being explored in collaboration with CERN and MMU. Implications of synchrotron radiation gas desorption on the design of the Damping Ring vacuum system are also being evaluated, as well as beam-induced electron multipacting in the vacuum chamber and ion-induced pressure instabilities.

KATRIN - measuring absolute neutrino mass

In Karlsruhe, Germany, KATRIN is an international experiment to measure the absolute mass of the neutrino. "It will feature a large vacuum system about 70 m long and we've made a substantial contribution to its design," says Ron Reid, VS Group Leader, "The experiment will measure the energy spectrum of electrons emitted in tritium β-decay from tritium gas injected into a tube at 10^{-3} mbar pressure, whilst the source is open to a large spectrometer which can only tolerate a partial tritium pressure of 10^{-20} mbar." This is achieved by differential pumping stages based on turbomolecular pumping, argon frost cryosorption and getter pumping, all requiring significant effort in Monte-Carlo modelling, analytical modelling of turbomolecular pumps in series and modelling of cryogenic and NEG- coated vacuum chambers. "The main spectrometer vessel is currently being manufactured in a former shipyard in Germany," says Ron. "It's around 23 metres long, with a 10 m diameter, operating at a total pressure less than 10^{-11} mbar, and we've been helping determine necessary vacuum procedures and processes." A suitable vacuum system has now been designed and accepted by the detector working group.

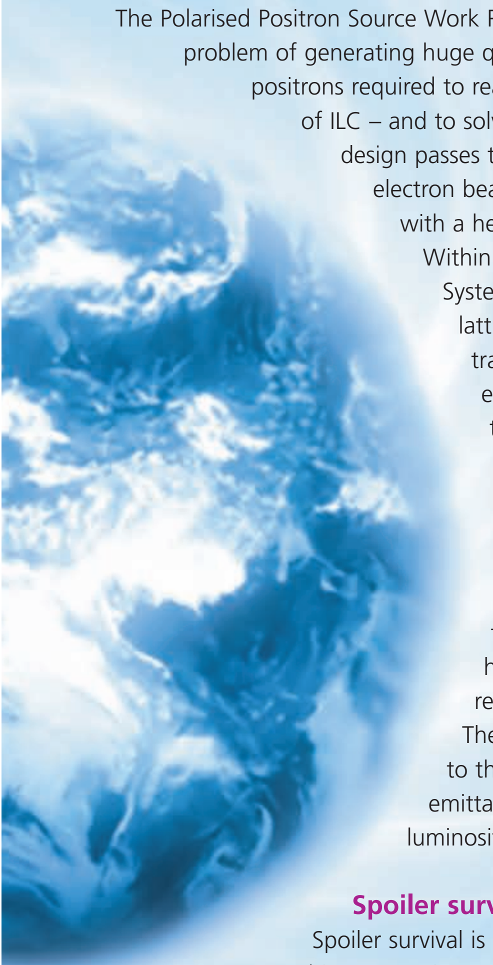
Beam-induced pressure instability

A collaboration between GSI, CERN, the Svedberg Laboratory and ASTeC is studying beam-induced pressure instability in heavy ion machines. Experimental work has been carried out at GSI as part of this collaboration, and the results were presented at the ICFA-HB2004 workshop at Bensheim. This work will continue as part of a new EU FP-6 programme.

EUROPEAN UNION

A remarkable union of scientific institutions across Europe is resulting in excellent collaborative work on EUROTeV and EUROFEL projects.

EUROTeV – A DESIGN STUDY FOR A TeV ENERGY RANGE LINEAR COLLIDER



EUROTeV is a collaboration of 28 European institutes working on a design study for a linear collider in the TeV energy range. The Polarised Positron Source Work Package addresses the problem of generating huge quantities of polarised positrons required to reach the design luminosity of ILC – and to solve this, the EUROTeV design passes the very high-energy electron beam through an undulator with a helical magnetic field. Within the Beam Delivery System Work Package, the lattice design includes beam transport design and extraction line designs to transport post-collision beams. To reduce the background in the detector requires a careful collimation design, and spoilers used for the collimation system have narrow gaps to remove halo particles. These offer large wakefields to the beam, diluting beam emittance and reducing luminosity.

Spoiler survival – a critical issue

Spoiler survival is a critical issue for machine protection, so different types of collimators will be tested for wakefields and damage studies at the SLAC End Station A test facility. When beams collide with crossing angles, crab cavities are required to rotate bunches to gain the loss of luminosity, so IP feedback is essential to ensure collision of nanometre-size beams and to maintain beam collision.

THE EUROPEAN FEL DESIGN STUDY (EUROFEL) PROJECT

EUROFEL is a €9M project funded by the EU's "Sixth Framework Programme" which commenced on 1st January 2005. It is a joint effort between sixteen European institutions to prepare for the construction of the next-generation of free-electron laser (FEL) light sources proposed in Europe.

The EUROFEL objectives :

- To develop proven designs for critical components such as the electron gun and the complete injection system, the optical system (to provide an optimum laser beam profile on the photocathode) and electron bunch compression.
- The improvement of the electron beam parameters to reach the hard X-ray region. This also benefits longer-wavelength FELs because it reduces the required undulator length and the electron beam energy.
- The development of seeding and harmonic generation techniques in order to ensure stable and well-defined output characteristics from the FEL sources. The synchronisation of all subsystems to better than 100 fs is a prerequisite for laser seeding as well as for high-resolution time-resolved experiments.
- Production of a flexible FEL pulse distribution in time in order to facilitate user experiments and enhance user access. This requires the qualification of the superconducting accelerator for high duty-cycle (CW) operation. It is expected that CW operation will also facilitate more precise synchronisation of the electron beam.
- To move from prototyping to industrial production of major components, in particular of complete superconducting accelerator modules. This is essential for the reliable and cost-effective construction of new facilities.

The ASTeC contribution

The work is split into 6 work packages: Photo-guns & injectors; beam dynamics; synchronisation; seeding and harmonic generation; superconducting cw and near-cw linacs; cryomodules technology transfer. CCLRC is leading the beam dynamics package and ASTeC are involved in all work packages.

SHRINKING THE WORLD

ASTeC has joined forces with institutes in the USA and Germany on a number of projects – and geographical distance has proved no barrier to major collaborative successes.

ASTeC continues to build relationships with leading global institutes, especially in relation to the ERLP project – and, reports Fay Hannon, Accelerator Physicist: "Those institutes contributing most are the Thomas Jefferson National Accelerator Facility (J-Lab) in Virginia, USA, Forschungszentrum Rossendorf (FZR) and DESY Hamburg in Germany. J-Lab has loaned the ERLP wiggler, as well as magnets no longer needed on their upgraded FEL project. J-Lab have also given their electron gun design (which has been slightly modified to produce the ELRP electron gun design) so we're particularly grateful for their input."

Learning from J-Lab, Virginia

Equally important has been J-Lab's assistance with accelerator physics and technology for the energy recovery-based light source, including transfer of key skills such as final preparation of electron gun parts and production of viable cathodes.

Components inside the electron gun are progressively polished to a final surface smoothness of 1 micron to minimise field emission – a technique perfected at J-Lab and passed on to Daresbury. "Similarly, procedures for cleaning, mounting and caesiating cathodes were devised at J-Lab", adds Fay, "so to acquire this technique, a team of us took the ERLP cathode to J-Lab last November. We then used our new expertise to devise our own cathode processing rig, which can also test performance of other cathodes when not being used for cleaning."

Major work with German laboratories

FZR Germany provided the buncher cavity and beam loss monitoring system design, supplied key components of the ERLP gun diagnostics beamline and tested various components of the RF system. In future, as part of the EUROFEL collaboration, ASTeC will be working with FZR on the design of superconducting RF guns and accelerating modules. Meanwhile, DESY Hamburg will allow ERLP to use its superconducting cavity test facilities – and as part of the TESLA collaboration, ASTeC staff have taken part in commissioning shifts on the TESLA Test Facility (now renamed VUV-FEL), helping with optimisation of the RF photo-gun and set-up of the FEL. ASTeC staff have also been involved in developing the code ASTRA (used for electron gun and beam transport modelling) with the original authors at DESY. The electron gun for the TESLA project was developed and tested at DESY Hamburg's sister laboratory, DESY Zeuthen in Berlin, where they have a Photo-Injector Test (PITZ) facility purely for gun and diagnostic development. As part of the PITZ collaboration, ASTeC has undertaken part of the commissioning of new accelerator components and diagnostics testing – and in future EUROFEL collaborations, ASTeC will design electron beam measurement diagnostics for PITZ.

Exciting developments at Brookhaven National Laboratory, USA

Improving the number of electrons emitted from a cathode for a given laser power is vitally important when a high-average current beam is required – and, reports Fay: "to massively multiply the number of electrons produced, Brookhaven National Laboratory, in Long Island, USA, is developing a new cathode using secondary emission from a thin diamond film mounted in front of the cathode. We're very keen to be involved with the further development of this novel idea, so we've already visited the laboratory to look at their progress, and are very impressed with the results."

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INCOME SOURCES 04/05	£K
PPARC	903
SR2002 SCIENCE BUDGET EARMARKED	930
OTHER CCLRC VOTE BUDGET	1636
EU	106
OTHER	475
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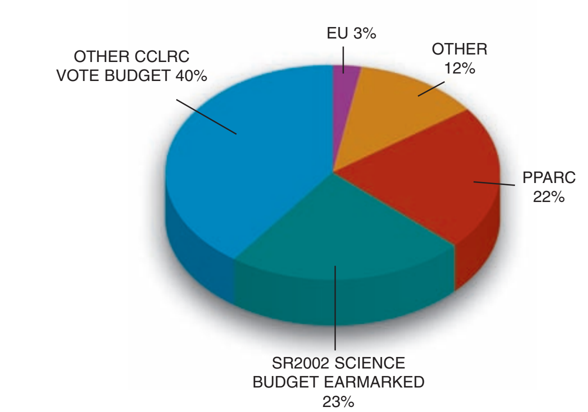
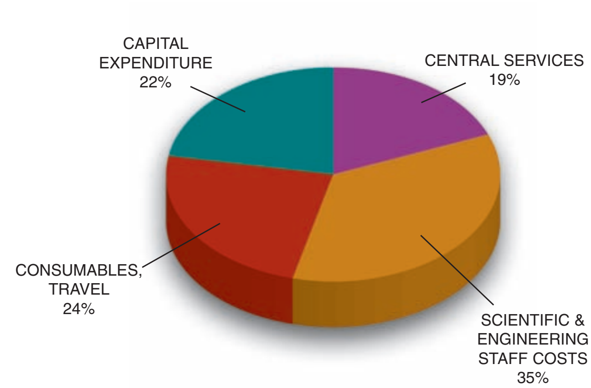


EXPENDITURE 04/05	£K
SCIENTIFIC & ENGINEERING STAFF COSTS	1378
CONSUMABLES, TRAVEL	977
CAPITAL EXPENDITURE	904
CENTRAL SERVICES	776
	4035



EXPENDITURE BY PROGRAMME 04/05	£K
PPARC/CCLRC LC-ABD PROGRAMME	747
PPARC/CCLRC UK-NF PROGRAMME	813
HIGH POWER PROTON ACCELERATORS	541
HIGH BRIGHTNESS ELECTRON ACCELERATORS	559
UNDERPINNING RESEARCH	494
OTHER PROFESSIONAL ACTIVITIES	469
EU AND REPAYMENT WORK	412
	4035