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Cutting Edge Research from Scotland

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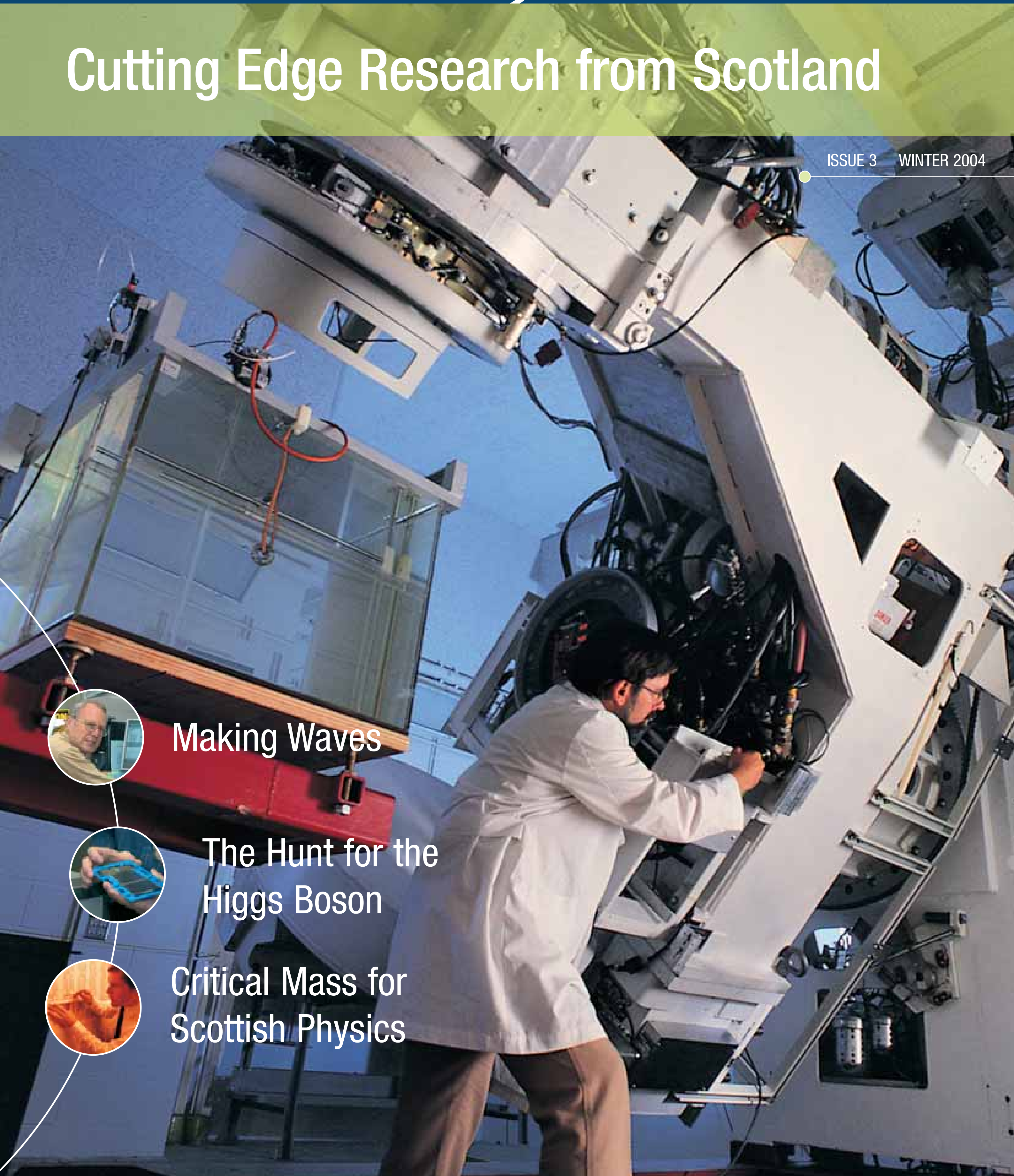

Making Waves

The Hunt for the Higgs Boson

Critical Mass for Scottish Physics

www.sciencescotland.org

Introduction

It gives me great pleasure to introduce the third issue of Science Scotland, a publication devoted to showcasing the creative talents of the nation's scientists, engineers and technologists. Scotland has a prolific legacy of discovery, invention and innovation. Its contribution to global science is not merely to be shelved in the archives of achievement, however. This spirit of pioneering research is very much alive and in evidence today amongst the outstanding scientists working in our leading universities, research institutes and high technology companies.

Scottish research is going from strength to strength. Innovative ideas are flourishing here, supported by initiatives like the Proof of Concept Fund, Enterprise Fellowships from Scottish Enterprise/RSE and the Scottish Co-investment fund. The energies of highly skilled scientists who are the future of our research base and in turn, our economy, are being nurtured and harnessed. The creation, by Scottish Enterprise, of three Intermediary Technology Institutes (ITIs) in Life Sciences, Energy and Techmedia seeks to stimulate and support new and existing high growth companies. From e-science and grid technologies, to life sciences, particle physics and photonics, today's Scotland can lay just claim to being an international competitor across significant sectors of science and technology. It's essential not to be complacent, however, and we are looking to the future.

We don't just talk about the value of collaboration here, we make it happen. Scotland's diverse research base recognises that the whole is greater than the sum of the parts and this is integral to the way we work. This means that connectivity is all important in Scotland. The result is a very positive and fertile environment for science. Internal collaboration is central to Scotland's success in science. International collaboration, as a global science community is a goal to which we are committed.

Science Scotland seeks to encourage debate and engagement with the scientific advances coming out of Scotland today. This issue captures a sense of some of the exciting, distinctively collaborative projects in which our eminent physicists are leading the way.

The work of the great Scottish scientific pioneer, James Clerk Maxwell, on electromagnetic radiation forms the cornerstone of communications in our modern world. In this, the 125th anniversary year of Clerk Maxwell's death, and the eve of The World Year of Physics in 2005, which celebrates the 100th anniversary of Einstein's "miraculous year", it is fitting that we focus in this edition on Physics. I hope you will be interested to read about: the physicists joining forces to create the critical mass of a 'superdepartment'; Scotland's key role in the largest ever scientific collaborative quest, seeking the "Holy Grail of Mass", the Higgs Boson; and the groundbreaking work on ultrashort pulses from lasers which, with potential to impact on medicine and communications is a beacon for interdisciplinary, research.

The accompanying website at **www.sciencescotland.org** contains additional news and links and this is being updated on a regular basis. I hope you enjoy this issue of Science Scotland. If you would like to follow up any of the stories please get in touch via the website.

Best wishes,

Professor John Coggins, FRSE
Vice President of the Royal Society of Edinburgh
Dean of the Faculty of Biomedical & Life Sciences
University of Glasgow

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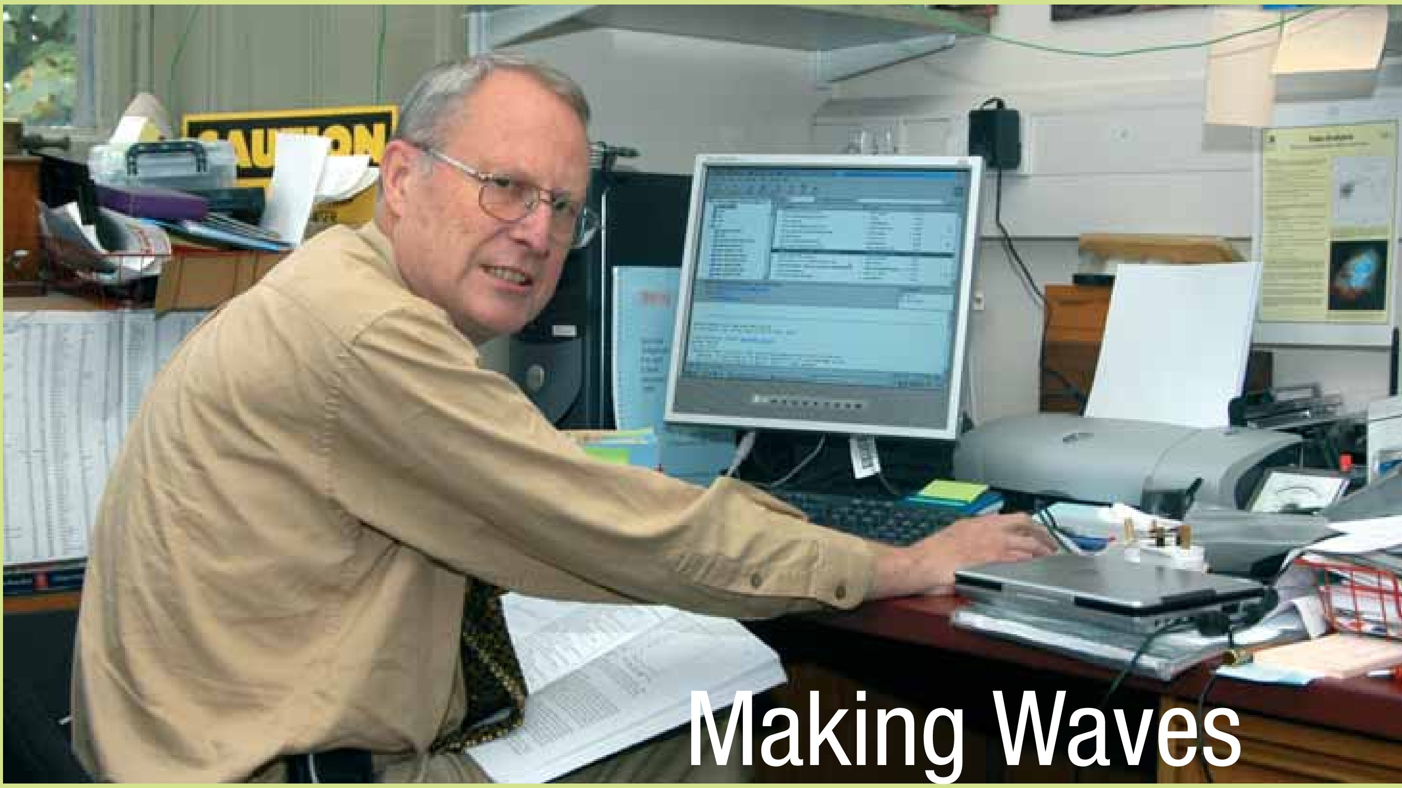


The Institute of Gravitational Research was set up four years ago and its current work is focused on the detection of gravitational waves. The work of the Institute is strongly supported by funding from PPARC, the Particle Physics and Astronomy Research Council, with £7.5m contributing directly to the Advanced LIGO project. PPARC is the UK's strategic science investment agency for particle physics and astronomy. By directing, coordinating and funding research, education and training in particle physics and astronomy, PPARC delivers world-class science. Other funding for the Institute comes from SHEFC, the Scottish Higher Education Funding Council. Working in Scotland, the research team forms a natural bridge between work being carried out in Europe and in the USA.

Jim Hough of the University of Glasgow is confident that Gravitational Waves will finally be detected within the next five years.

Einstein's General Theory of Relativity predicted the existence of gravitational waves as long ago as 1917 but these elusive ripples in the curvature of space-time have still to be directly detected. After 45 years when no-one showed any particular interest in proving their existence through experiment – and another 40 years of serious earth-based detective work with ever more sensitive equipment – the exploration is moving into space, with the intention of providing conclusive evidence that these tiny fluctuations caused by the acceleration of mass really do exist. However, Professor Jim Hough predicts the breakthrough will come in the next few years, even before the research goes space-side.

Professor Hough is Director of the Institute of Gravitational Research. This is a group based at Glasgow University that has been deeply involved in the development of earth based detection systems and is now playing an important role in the work on LISA, the Laser Interferometer Space Antenna. The research activities of this group, supported by PPARC funding, are currently focused on the development of detectors to search for gravitational waves from astrophysical sources.

Professor Hough explains, "Because the gravitational interaction is very weak, large masses and high accelerations are needed to produce gravitational waves that can be measured. Violent astrophysical events such as supernovae or coalescing binaries are the focus of our attention."

The existence of these wrinkles in relativity is no longer seriously questioned by scientists. The gradual changes in the orbit of a binary pulsar called PSR 1913 +16 (a pair of orbiting neutron stars, one of which is a pulsar emitting precisely timed radio pulses) can be explained only if angular momentum and energy is carried away from this system by gravitational waves.

"The reason why we have not directly detected gravitational waves over the years is because we have not had sufficiently sensitive equipment. With earth based detection there is also the challenge of interference from seismic activity and other environmental noise."

"In the early days, the search for gravitational waves was driven by an element of competition between scientists. Today however, the emphasis is on collaboration as researchers have recognised the scale of the project. Recent developments in precision measurement, lasers, optics and control systems have come together to bring the required sensitivity. The leading edge science that has resulted from our desire to detect gravitational waves also has wider applications in industry. The technological spin-off is high for our work on stable lasers, special reflective coatings and our extensions of a bonding technology-hydroxide-catalysis bonding – which exhibits very low mechanical loss."

As Principal Investigator for the UK on GEO 600, the Gravitational Wave Detector being developed by a German/British consortium, Prof Hough has played a significant role in developing technology that will now also be used at LIGO in the USA. GEO 600 and LIGO (Laser Interferometer Gravitational Wave Observatory) are long arm interferometers that offer the best chance of detecting gravitational waves from the ground. Hough's own work in developing very delicate suspensions for gravity wave detectors and his research into ultra-stable lasers have both played a significant role in increasing the sensitivity of the detection equipment. Between them, the team at Glasgow have expertise in precision interferometry techniques, the development of ultra-low light loss mirrors, the electronic measurement of signals, data analysis and the bonding of silicon carbide.

These optical and mechanical technologies are being transferred to the next generation of the US laser interferometer system LIGO, and the work originally carried out for GEO is playing a crucial role in the planning and development of Advanced LIGO. The new technologies will result in a ten-fold increase in the sensitivity of the detector.

The push to prove the existence of Gravitational Waves is not only driven by a desire to corroborate Einstein's theory. Hough explains, "The detection and study of gravitational radiation will actually be of great scientific importance. Think of it as a new branch of astronomy. It will open up a window on the universe through which may come unique information about a variety of astrophysical systems - supernova explosions, pulsars and coalescing compact binaries. It is also possible that totally unexpected discoveries will be made, in much the same way as has occurred in radio and x-ray astronomy."

Current branches of astronomy are largely restricted to observing and measuring the surfaces of objects in space. Gravitational Wave Astronomy will allow us to see right into the heart of objects such as black holes, develop our understanding of quasars and explore the mass distribution of the universe. It will also be possible to look back at events that took place early in the formation of the universe and learn more about the significance of objects such as cosmic strings.

The significance of the space project LISA may therefore be in pioneering research in gravitational wave astronomy rather than proving the existence of gravitational waves themselves. LISA is now not due to launch until 2013, well after the time when Professor Hough predicts we will have conclusive evidence of gravitational waves. LISA is jointly sponsored by the European Space Agency and NASA and is expected to detect waves generated by binaries within our galaxy and by massive black holes in distant galaxies. LISA will use an advanced system of laser interferometry and the most delicate measuring instruments ever made to directly detect gravitational waves.

As a system of three spacecraft, LISA will effectively have arms that are 5 million km in length, in contrast with the 4km arms of LIGO. This means that signals will be about a million times stronger and are therefore much easier to measure and interpret. In space, LISA won't be affected by the environmental noise that is such an issue for detectors on the Earth's surface. Because of seismographic activity and other vibrations, ground detectors can only make observations at frequencies above 1Hz, but LISA will be able to observe at much lower frequencies.

However, other environmental factors will have an impact on LISA. Such factors include the drift of the spacecraft and buffeting by the solar wind. Making these small disturbances negligible is a major technological challenge of the mission. The Glasgow team are directly involved in the LISA Pathfinder project, with optical bench development taking place in Glasgow.

While there seems to be little doubt that scientists are on the cusp of a major breakthrough in directly detecting gravitational waves, the excitement for Professor Hough and his colleagues lies not only in proving the existence of these enigmatic waves but also in the development of a new branch of astronomy. Projects such as Advanced LIGO and LISA are already poised to look deep into black holes and bring us new insights into how our universe began.

Gambling on Discovery

At a recent Institute of Physics conference, Photon 04, Professor Jim Hough revealed that he thinks high street bookmakers are crazy to be offering odds of 100-1 on whether Gravitational Waves will be discovered before 2010. He has placed a personal bet of £25 – the maximum Ladbrokes allowed him to stake. The available odds were quickly cut from an initial offering of 500-1, through 100-1 to 2-1.

Professor Jim Hough, from the University of Glasgow and one of the leaders of the UK search for Gravitational Waves, said: "I think the real odds are more like a favourite at 2-1 or 3-1, I'm almost certain we'll discover them in the very near future. I would have had much more money on at the odds they were offering but the maximum bet they allowed me to have was £25!"

Weak gravitational waves are probably passing through us all the time but are too faint to detect. Scientists are currently trying to detect the strongest waves, for example those created in violent events such as supernovae but none of the instruments looking for them have yet picked up a clear and definite signal. Improvements in the sensitivity of these instruments, resulting from the work on GEO 600 and LIGO should mean that scientists are very close.

The Hunt for the Higgs Boson

Professor David Saxon and Professor Tony Doyle of the University of Glasgow are contributing to the largest ever collaboration of scientists, driven by a need to understand the nature of mass.

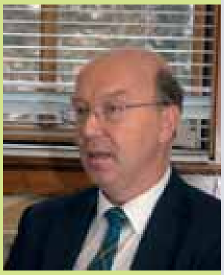
Along with over 1800 other scientists from around the world, Professor Saxon and Professor Doyle are working on the ATLAS project at the CERN installation in Switzerland. A 27km circular underground tunnel, located at the foot of the Jura mountains near Geneva will be the location for an experiment where protons will be made to collide with intense energy. LHC, the Large Hadron Collider, is the particle accelerator that will be used in the ATLAS experiment. Higher energy is the key to development in this area and the (LHC) provides the most powerful instrument ever built to investigate the fundamental properties of particles.

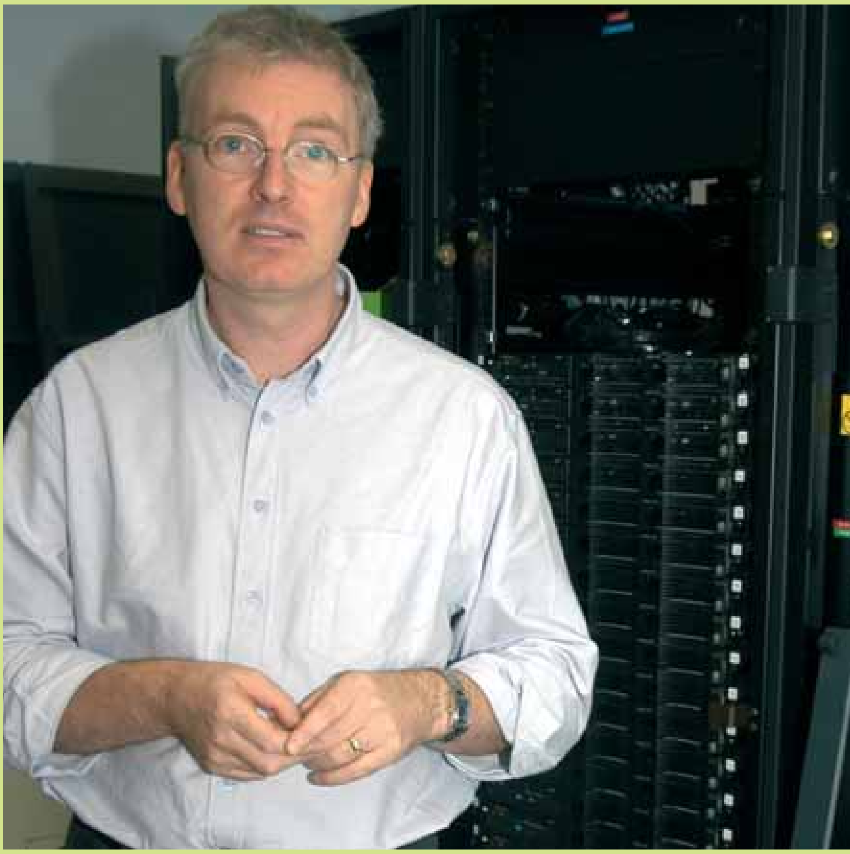
Just as important, however, are the detectors that will record what happens when the particles collide. ATLAS is one of four major detection projects that will use LHC. The sheer scale of the collaboration is an achievement in itself, with 1800 scientists participating from more than 150 universities and laboratories in over thirty countries. And the purpose of the experiment? To shed new light on the fundamental nature of matter and reach a new understanding of what mass is. By causing protons to collide at such high energy, it is anticipated that the existence of the Higgs particle may finally be proved.

About the Higgs Boson

The Higgs boson is named after Peter Higgs, the Edinburgh University physicist who predicted its existence as long ago as 1964. His work was not immediately recognised, leading him to comment to a colleague, "This summer I have discovered something totally useless." A now famous analogy was used by Prof David J. Miller of University College London, to explain the theory to William Waldegrave, the UK Science Minister in 1993.

"Imagine a cocktail party of political party workers who are uniformly distributed across the floor, all talking to their nearest neighbours. The ex-Prime-Minister enters and crosses the room. All of the workers in her neighbourhood are strongly attracted to her and cluster round her. As she moves she attracts the people she comes close to, while the ones she has left return to their even spacing. Because of the knot of people always clustered around her she acquires a greater mass than normal, that is, she has more momentum for the same speed of movement across the room. Once moving she is harder to stop, and once stopped she is harder to get moving again because the clustering process has to be restarted. In three dimensions, and with the complications of relativity, this is the Higgs mechanism."





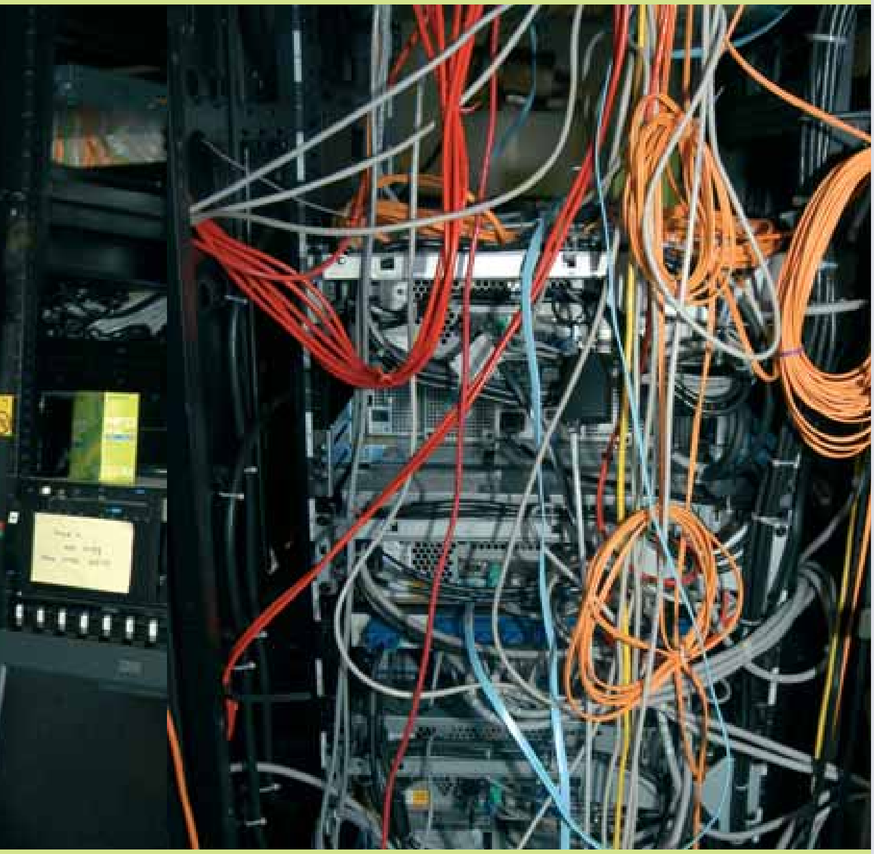
About CERN

CERN, the European Organization for Nuclear Research, is the world's largest particle physics research centre, located near Geneva, Switzerland. Technological development at CERN has given the world advances varying from contributions to medical imaging to the World Wide Web. Founded in 1954, the laboratory was one of Europe's first joint ventures and has become a shining example of international collaboration. From the original 12 signatories of the CERN convention, including the UK, membership has grown to the present 20 member states.

"The greatest unsolved mystery in Physics is that we do not know what mass is," says Professor David Saxon, who leads the Particle Physics Experimental Group in the Department of Physics and Astronomy at the University of Glasgow. Over the years, Professor Saxon has focused his work in the area of particle tracking. "Think of a jet trail left in the sky after the plane has gone," he says by way of analogy. "We can find out about the nature of the particles that make up protons from the trail that they leave." Professor Saxon designed the original layout concept for the ATLAS tracking detector and will also be involved in the analysis of data once the experimental stage is reached.

One of the main goals of the ATLAS program is to discover and study the Higgs particle. The Higgs boson or particle is of critical importance in particle theories and is directly related to the concept of particle mass and therefore to all masses.

"It is most likely that the Higgs boson remains only just undiscovered," says Saxon. "There are candidates, but at present no clinching evidence. Higgs events are so rare, it's like looking for a needle in a haystack…or would be if it were not for the incredibly sophisticated data analysis techniques that are being developed."



Professor Tony Doyle, also a member of the Particle Physics Experimental group in Glasgow, heads up the team that is responsible for delivering the computational power needed to make sense of the haystack of data created by the ATLAS experiments. The scale of this project, known as GridPP, means that Doyle and his team are operating at the edge of development in the area of data management and resource sharing.

CERN already lays claim to the World Wide Web as a spin-off invention. Around 1990, CERN, along with a few other particle physics labs, constituted the entire World Wide Web. At CERN the web provided the facilities required to exchange information between scientists working on different computers, perhaps at different sites.

The UK played a leading role in these developments and continues to operate at the forefront of the GridPP project. Where the web operates successfully on an anarchic basis, the Grid is a highly structured approach to managing data, organising the computational resources required and making them available to the huge number of people involved in over seventy institutes across the world. The Grid is concerned with the exchange of computer power, data storage, and access to large databases, without users having to search for these resources manually.

About LHC

LHC, The Large Hadron Collider is a particle accelerator, designed to cause collisions between protons and ions at higher energies than ever achieved before. This will allow scientists to penetrate still further into the structure of matter and recreate the conditions prevailing in the early universe, just after the "Big Bang". The LHC will be built underneath the Franco-Swiss border west of Geneva, at the foot of the Jura mountains.

The first particle collider was developed by Bruno Touschek, who was a PhD student at Glasgow University in the 1950's.
The technology used at LHC is a direct descendant.

About ATLAS

When LHC is switched on in 2007 the ATLAS project can get under way. The Glasgow group have responsibility within the UK-Valencia forward cluster for contributions to the construction (ultrasonic wire-bonding) and testing on the forward tracker silicon microstrip modules. Using this array of 1000 modules, ATLAS will detect and analyse debris from the proton collisions to reveal fundamental detail about the constituent particles. The energy density in these high-energy collisions is similar to the particle collision energy in the early universe less than a billionth of a second after the Big Bang.

About GridPP

GridPP is a six year, £33million project with additional associated funding from PPARC, HEFCE, SHEFC and The European Union. A collaboration of twenty UK Universities and research institutes and CERN, it will provide the UK's contribution to the Large Hadron Collider Computing Grid. Prof Tony Doyle of University of Glasgow is the project leader for GridPP, which has been running a UK Grid testbed for more than a year. The challenge is to scale up over the next three years to provide the equivalent of 10,000 desktop computers available to interpret the data from the ATLAS project.

More recently, as a PPARC Senior Research Fellow and member of the ATLAS Collaboration, he has been working on analysis methods to search for the Higgs boson at the LHC. This task requires significant data and computational resources and led to an interest in Grid Data Management as part of the EU DataGrid project.

To return to the particle at the centre of all this activity, the Higgs boson, if it exists, is reckoned to be the particle that will explain the mass of the other types of particles that make up the atom, and therefore provide an explanation for the mass of everything. The scale of the numbers in this project is astonishing. A proton is approx 10^{-15} metres in length, but in order to make it travel at near the speed of light, a tunnel 27km in length is required. During an experiment, one billion collisions will take place every second and a building that is 45m wide and 22m high is required to hold the detector that will be used to monitor the collisions of these sub-atomic particles. Then the equivalent of 10,000 PCs will be formed into a massive wide area network to deal with the data that is generated by the project. The 1800 scientists will need to collaborate closely at every stage in the process of constructing the experiment and analysing the data.

Even then, for the Higgs to appear, the "right kind" of collision needs to take place. Despite the billion collisions per second it could take many months for the type of incident that will reveal the evidence. "It does feel like trying to win the lottery," admits Professor Saxon, "but a £3bn international project does narrow the odds."

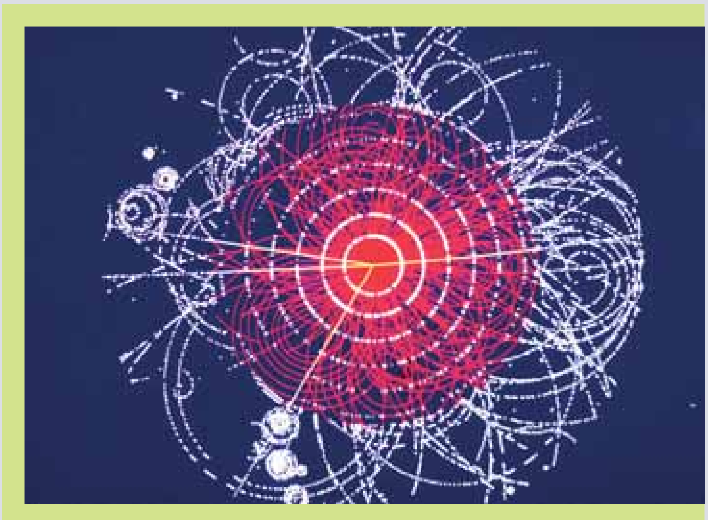


Image courtesy CERN

Critical Mass for Scottish Physics

Professor John Chapman of the University of Glasgow explains why an alliance between six Scottish physics departments is such a good idea.

"If we are going to continue to make an impact we need critical mass." That's the opinion of Professor John Chapman, Head of the Department of Physics and Astromony at the University of Glasgow, one of the six Scottish physics departments that are banding together as SUPA, the Scottish Universities Physics Alliance.

With a well established reputation for world class physics in Scotland, the Alliance will allow the Scottish Universities to compete with Oxford, Cambridge and Imperial College London at a time when funding policies favour large departments with high research ratings.

The super-department discussion involves Edinburgh, Glasgow, Heriot-Watt, Paisley, St Andrews and Strathclyde. As well as attracting funding to improve the overall quality of physics research in Scotland, the other main ambition is to set up a graduate school that will be open to all Scottish post-graduate students of physics.

Professor John Chapman is head of the Department of Physics & Astronomy at the University of Glasgow. His research centres around nanoscience, with particular emphasis on high spatial resolution characterisation and property modification using electron and ion beams.

Collaboration between the universities already demonstrates the health of physics in Scotland and SUPA will provide opportunities for more. "There is always a limited amount of money available, so it makes fine economic sense to share equipment, data, and resources across the universities."

"Initially we are not planning to branch out into new areas of expertise; rather SUPA will allow us to concentrate resources on five areas of physics where Scotland is already doing important work. It was necessary although not easy to focus in this way, as there is a wealth of excellent work going on across the board. Ultimately the themes picked themselves and the SUPA initiative has homed in on particle physics, astronomy and astrophysics, nuclear and plasma physics, condensed matter and materials physics, and photonics as the areas of strength."

The groundwork for collaboration is already in place and new links are planned. For example, Glasgow is the home of the Institute of Gravitional Research, where there is an interest in building advanced detection equipment. This interest is shared with the UK Astronomy Technology Centre (UK ATC), which is located at the Royal Observatory, Edinburgh. Within the first five years of its inception in 1998 the UK ATC delivered novel and state-of-the art instruments for the Gemini Observatory, the James Clerk Maxwell Telescope and the United Kingdom Infrared Telescope (all in Hawaii), and the William Herschel Telescope on La Palma. The Institute of Gravitational Research has contributed sensitive detection equipment to GEO 600, the Laser Interferometer Gravitational Wave Observatory in the USA. By working together the two organisations contribute different approaches and skills to a common area of interest and will open up opportunities for more detection equipment to be built here.

Another example of collaboration is in the area of photonics. Important applications in the area of biomedical innovation are resulting from work taking place between the Universities of Glasgow, Heriot-Watt, St Andrews and Strathclyde.

SUPA will receive £6.9 million from SHEFC (Scottish Higher Education Funding Council) over the four years, with further support coming from the universities themselves and the Office of Science and Technology. With the funding in place key appointments can be made to strengthen the work that is already developing. In addition, the plans for the combined Graduate School are designed to underpin the quality of research on a long-term basis. Formal training is becoming increasingly important for graduate students, and it will be possible to provide a programme that can be accessed by all Scottish post-grads. There are plans for graduate teaching rooms with broadband video links so that students can attend or participate at a distance. A distinguished visitor programme will build on the already successful physics summer schools that take place in Scotland.

With SHEFC having approved the pooling approach in principle, a distinguished international panel met in August to consider whether the new alliance was viable. The panel, which included the chief executive of PPARC (Particle Physics and Astronomy Research Council) and heads of laboratories around the world, offered strong support for SUPA. Final ratification then came from SHEFC at the end of November 2004.

SUPA will have a Chief Executive, an executive committee that is advised by an external advisory committee and will operate a single pan-Scottish Graduate School. Professor Chapman is looking forward to the well-conceived alliance plans being implemented early in 2005. "There is a lot of excitement about this project. It represents an opportunity to take physics in Scotland to a new level."

"SUPA will act as an effective shop window for physics at every level. As well as attracting key funding in the UK and expertise from around the world, it provides a focus for working with industry and for making physics more accessible to everyone."

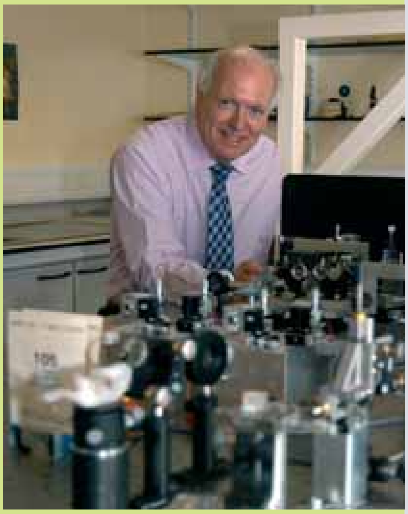
Lasers at the Cutting Edge

Professor Wilson Sibbett of the University of St Andrews is committed to a collaborative approach when it comes to finding exciting applications for his work with ultrashort pulse lasers and is convinced that the physical sciences can provide us with a new insight on the nature of disease.

Professor Sibbett heads up the W-Squad, a group of laser physicists in the Department of Physics and Astronomy at St Andrews, whose specialist interest is the generation, measurement and characterisation of ultrashort (picosecond and femtosecond second) pulses from a variety of laser sources and optical parametric oscillators. But their exploration is not taking place in a sterile environment. Cross-fertilisation with scientists of different disciplines is leading to important developments that will impact both medicine and data communications.

Professor Wilson Sibbett is Chairman of the Scottish Science Advisory Committee, established under the auspices of The Royal Society of Edinburgh to be a new and independent voice for Scottish science. He sees the value of physical and life scientists working together. "Critical mass is vital if we are to be commercially or scientifically viable. Working across the disciplines means there are more potential funding sources and excellent opportunities for knowledge transfer and innovation." The Scottish Science Advisory Committee was established in 2002 to provide independent advice to Scottish Executive Ministers on strategic scientific issues, including science strategy, science policy and science priorities.

The Committee membership represents a breadth of expertise and knowledge across a range of disciplines including education, business, engineering, technology, medicine, ethics, public engagement and public policy. "Think of the Committee as a catalyst that encourages people from different disciplines to interact. There was a great tradition of polymaths in previous generations. We've lost a lot of that and need to reintroduce the positive benefits of crossing the boundaries."



Ultrashort

A picoseconds is 10^{-12} second (a trillionth).

A femtosecond is 10^{-15} second (a quadrillionth).

Femtosecond pulses can be used to study some of the most fundamental processes of the universe, such as electrons moving between atoms and molecular bonds breaking or forming.

Kerr-lens mode-locking, discovered by Professor Sibbett and his research team at the University of St Andrews, is a key technique in producing ultra-short pulses that can be tuned over a broad frequency range at high power levels. The technique was quickly adopted by others working in the field and has become the standard approach to producing practical femtosecond-pulses in lasers.

"I've been at St Andrews for almost 20 years now and in that time have seen laser technology move out of the laboratory and into the arena of appliances. Barcode scanners in the supermarket and CD players in our living rooms are commonplace now." Sibbett and two of his colleagues developed a novel technique known as Kerr-lens mode-locking in 1989. This breakthrough in the production of ultrashort pulses led ultimately to the demonstration of 4.5 fs pulses from a Ti:sapphire laser which, in 1991, were the shortest ever pulses generated directly from a laser oscillator.

So how short is ultrashort? "We are talking about pulses of light that last a few femto-seconds (1fs=10^{-15} second) – the briefest of man-made events." It's difficult to grasp the scale of this number, but it may help to know that there are more than 10 times as many femtoseconds in a second than hours that have passed since the big bang!

Ultrashort pulses are especially important in medicine. The power is confined to such a short time that when a laser is used to vapourise tissue, the damage to the surrounding tissue is minimized.

"While the medical applications of lasers were recognised early on, development was plagued with impatience. There was a desire to see this exciting new laser technology in use. A process of refinement and development has been taking place that will lead to improved sophistication and performance, and most importantly bring us to the point where the ultra-short pulse laser is a small, useful tool that can be integrated as an element in other equipment. A vital part of this more mature approach is a deeper level of collaboration with scientists from different disciplines."

The St Andrews group are currently doing important work that includes the development of portable ultrafast blue lasers. These robust femtosecond lasers can provide a practical UV source for the photobiological study of the p53 cancer suppression gene. This application is being developed through close association with cancer research activities at the University of Dundee involving Sir Alfred Cucheiri of the Department of Surgery and Oncology. Professor Sibbett sees this as an essential element. "The work could not be carried out in isolation, as the requirements of the application must inform the developmental process. Collaboration across these usually separate disciplines encourages people to think out of the box. "

"I have always been excited about the possible applications for laser technology," says Professor Sibbett. "I imagine a doctor feeling in his pocket for the instrument he needs - something not much bigger than a pen, but one that incorporates a practical femtosecond laser. The lasers I worked with in the 70s and 80s were bulky and had to be switched on early in the morning and allowed to settle for hours before they could be used for anything - although one of our femtosecond dye lasers did make quite an impact shining through the late-afternoon St Andrews haar! The move to portable, battery-operated lasers is surprisingly important."

The latest generation of lasers are compact and versatile; hand held tools that can be powered by a few AA batteries. While the average power from such a laser is quite small, the extremely short duration of each pulse means that the peak instantaneous intensity is large. The practical applications of ultrashort pulse lasers for medicine and industry are only now being realised as more portable and reliable equipment becomes available.

While a pocket ultra-short pulse laser is still an instrument of the future, the current lasers have already been made so much more compact than their predecessors by reducing the pump power needed for mode-locked laser operation and using low-power diodes similar to those used in DVD players. Using sophisticated nonlinear optical phenomena, the new designs are not only small enough to incorporate into medical equipment or industrial tool-sets, they also have the reliability and accuracy needed for these demanding applications. The next level of downsizing will come when femtosecond pulses are available from special laser diodes - realising Professor Sibbett's vision.

In the meantime, ultra-short pulse lasers have become sufficiently compact and reliable to have many practical applications, one of which is biophotonics.

"Advances in the use of lasers in biophotonics will open the curtains on the nature of disease as three-dimensional images of living tissue can be produced with better clarity and definition than ever before," comments Professor Sibbett. Using a combination of short pulses and long wavelength light it is possible to observe what is happening at the core of diseased tissue or understand the impact of introducing a drug. Longer wavelength light penetrates tissue more efficiently, causing least damage to the surrounding cells, while the ultrashort pulses provide sufficient intensity even although the average power level remains low enough to avoid tissue damage. As well as studies involving the three spatial dimensions, the availability of time resolution in the picosecond and femtosecond timescales adds further to the capability offered by ultrafast lasers to quantitive investigations in photobiology and photomedicine.

In addition to the collaborative work in the medical sciences, ultrashort pulse lasers have an important role to play in taking high bandwidth data communication to a new level. Data communications could be revolutionised if femtosecond lasers are used to send hundreds of time-sequenced data channels through an optical fibre. This combination of time and wavelength multiplexing is particularly relevant to transferring complex imagery. Once more, this has an obvious application in medicine, where the facility to transfer high resolution medical images at speed around the globe could bring significant advances.

The applications for ultrafast lasers span physics, chemistry, biology, medicine and digital optical technology. As scientists continue to collaborate at the leading edges of these areas, Professor Sibbett believes the interactions across the disciplines will reinforce the position of Scotland as a world leader.

Piling on the Pressure

The Centre for Science at Extreme Conditions (CSEC) at the University of Edinburgh provides an ideal environment for pushing back the boundaries of our understanding of the structure and behaviour of materials, according to its Chairman, Professor Richard Nelmes.

A stunning new building is providing a home for a group of scientists from five different Schools at the University of Edinburgh. Their shared interest is in how materials react to the extremes of pressure and temperature and to high magnetic fields. It is anticipated that the collaborative work in CSEC over the next couple of decades will keep Edinburgh at the forefront of this dynamic area of science and could lead to the development of entirely novel materials and properties.

Of the extreme conditions on offer, Professor Richard Nelmes' own main interest is in the effects of pressure. High-pressure science was, for a long time, the preserve of geophysicists and mineralogists, but by bringing precision techniques into the arena, Nelmes has used neutron and synchrotron x-ray diffraction to discover fascinating complexity in the way many materials change when subjected to extremes of pressure. "This is not an esoteric pursuit", he observes. "Pressure provides a powerful probe of fundamental phenomena in condensed matter, and predicting high-pressure behaviour is a stringent test of theories and simulations. Moreover, more than 90% of the mass of our solar system exists at pressures above 100,000 atmospheres, so it is ambient pressure that is the unusual state!"

Professor Nelmes works closely with Dr John Loveday and Dr Malcolm McMahon, all members of the School of Physics at the University of Edinburgh. The group has been driven by the desire to understand the precise positioning and motion of atoms within materials, which presents the challenge of obtaining high-quality data from small samples under high pressure. In one approach, they have developed the use of high-pressure neutron diffraction to study ices, ice mixtures, hydrogen-bonded solids and other light-atom systems at high pressure. Neutron diffraction is particularly important and effective for the study of these and other important, common materials - like water, ammonia and methane - as it is the only technique for locating hydrogen atoms accurately.

Until 1990, neutron diffraction was limited to pressures below 30,000 atmospheres. This was a very low pressure limit when compared to other structural techniques like x-ray diffraction and light-scattering which at that time were already being used at pressures in excess of 1 million atmospheres. During the 1990s, a collaboration between the Edinburgh group and a group at Physique des Milieux Condensés, Université Pierre et Marie Curie in Paris increased the pressure range for neutron diffraction by a factor of ten with the development of a novel pressure cell and a dedicated experimental set-up. This represented a very significant step forward and the techniques developed have now been adopted around the world.

The most obvious example of a material that alters significantly under pressure is carbon. The super-hard form, diamond, can be synthesised from graphite at a pressure of 55,000 atmospheres and a temperature of 1400 degrees C. That pressure is equivalent to the Eiffel Tower (7000 metric tons) resting on a 5 inch plate.

The fundamental changes in the physical structures of material that occur under pressure are quite dramatic. Metals tend to have simple crystalline structures at ambient pressure. The structure of the same metal can become exceptionally complex under 100,000 – 200,000 atmospheres of pressure.

Under pressures of 170,000 atmospheres the metallic element rubidium (Rb) transforms to a so-called "hotel" structure. A 'host' framework made up of some Rb atoms has channels in which 1-dimensional chains of the remaining 'guest' Rb atoms form structures incommensurate with the host structure. It is expected that materials that form this particularly complex structure may prove to have interesting electrical or magnetic properties.

Hydrogen is…

Unusual because the nuclear spin state strongly affects the crystal structure.

Believed to become metallic at high pressure (millions of atmospheres). This has still to be observed experimentally under static conditions.

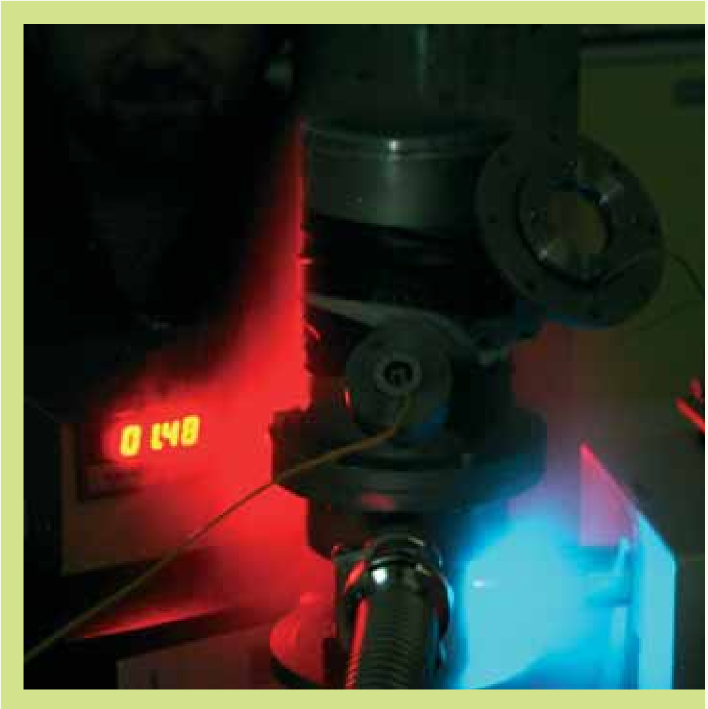
A very stringent test for computational modelling of solids – particularly models of how quantum effects are handled.

A major component of Jupiter and Saturn. Metallic hydrogen is likely to be vital to understanding their magnetic fields.

There is evidence that at very high pressures the melting temperature of hydrogen shows the unusual behaviour of reducing with pressure, and may be a fluid at all temperatures under these conditions. It has even been suggested that this fluid is a superconductor.

Dr Loveday comments, "There is great interest in understanding and modelling the behaviour of hydrogen -- in hydrogen itself as well as other hydrogen-containing materials -- and our structural data underpin this effort. For example, pressure quenches disorder arising from quantum effects in hydrogen, and there are several different theoretical predictions as to the quenched structure. Neutron diffraction will be able to settle this question." In another direction, Loveday's research into work on the behaviour of methane hydrate at high pressure has informed research into the interior structure of Saturn's moon Titan and the origin of methane in its atmosphere.
The trio of physicists is also involved in synchrotron x-ray studies. And here, too, they have developed experimental techniques that are now used worldwide for the precise determination of crystal structures at high pressure. Dr McMahon is particularly interested in how metallic elements respond to high pressure, and x-rays have been the most important way of studying these, as extremely high pressures are required. "At ambient temperatures, most metals have simple crystal structures. But pressure-induced changes in electronic energy levels lead to some exceptionally complex structures at high pressure. We have now found ten different elements that have particularly complex "incommensurate" structures under pressure. These are made up of two different interpenetrating components that are out of step with each other in such a way that the overall structure never exactly repeats. Theory is still only just getting to grips with this behaviour, but it seems likely that it is an intrinsically high-density – and thus high-pressure - phenomenon". Structures of this surprising, composite type were unknown in the elements before 1999. The next challenge is to explore the bulk physical properties of these exotic metals. Could it be that the complex, composite structure produces novel electrical or magnetic behaviour? The new facilities in CSEC will make it possible to address such questions.

This fundamental physics research by Professor Nelmes and his team makes extensive use of the neutron and synchrotron sources at the Rutherford Appleton Laboratory in Oxfordshire, the Daresbury Laboratory in Cheshire, and the European Synchrotron Radiation Facility in Grenoble, France, as well as the new facilities at CSEC for sample preparation and characterisation. Colleagues in CSEC are involved in many other projects that tap into the new equipment and resources. Diverse research interests at the Centre range from fundamental physics, chemistry and biology, through geoplanetary and materials science, to engineering and technology. The members of the Centre represent the Schools of Physics, Chemistry, GeoSciences, Engineering and Electronics, and Biological Sciences at the University of Edinburgh. However, the underlying philosophy at CSEC goes beyond sharing valuable instrumentation. The building has been designed to foster an atmosphere of collaboration, encouraging scientists from different disciplines to discuss their approaches and share their findings.



The core funding for the Centre comes from a Joint Infrastructure Fund (JIF) grant of £6.9m, awarded in December 2000. In addition, the Centre has attracted a major £2m award from the Leverhulme Trust. "This is bold funding," comments Nelmes, "as we've been commissioned to take a very fundamental approach and think long-term. The goal is to develop new materials for the 2020s and 2030s – perhaps a new generation of superconductors or super-hard materials. Better still, something no-one has yet thought of!"

"The JIF funding provided us with the infrastructure needed to create a unique multi-disciplinary approach to extreme conditions science across physics, chemistry, geoscience, engineering and biology. The very existence of CSEC opened up an exceptional opportunity for a new UK initiative in fundamental research on materials, but we were still short of special expertise in extreme-conditions materials synthesis. The generous Leverhulme funding provides exactly what we need in this area, funding a chair and several appointments across the disciplines. The prospects are very exciting."

CSEC

The Centre will use extremes of pressure and temperature, and high magnetic fields, to study a wide range of semiconductors, metals, molecular solids, polymers, ices, and bio-materials and engineering materials. The facilities will also be used for studies as diverse as the biology of organisms that live under the extreme conditions found on the ocean's floor and the behaviour of materials under the conditions found in the Earth's mantle and core, and in the interiors of planets. A future key aspect of the Centre's work will be the possibility of creating entirely new supermaterials under extreme conditions – like the naturally occurring example of diamond.

The Erskine Williamson Building was opened in April 2004 at the University of Edinburgh Kings Buildings as the home for the Centre for Science at Extreme Conditions. It was designed to create an environment in which there is close contact between researchers. The layout also encourages cross-use of techniques and facilities.

Erskine Douglas Williamson, who gives his name to the new CSEC building graduated from Edinburgh University in 1908. He earned an international reputation for outstanding and elegant experimental studies and theoretical calculations in high-pressure physics, physical chemistry, petrology, glass science and geodynamics. The famous Adams-Williamson equation laid the theoretical foundations for determining the interior structure of the Earth from seismic velocities, and remains widely known and used to this day.

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