Central Laser Facility

HIGHLIGHTS

Science & Technology Facilities Council

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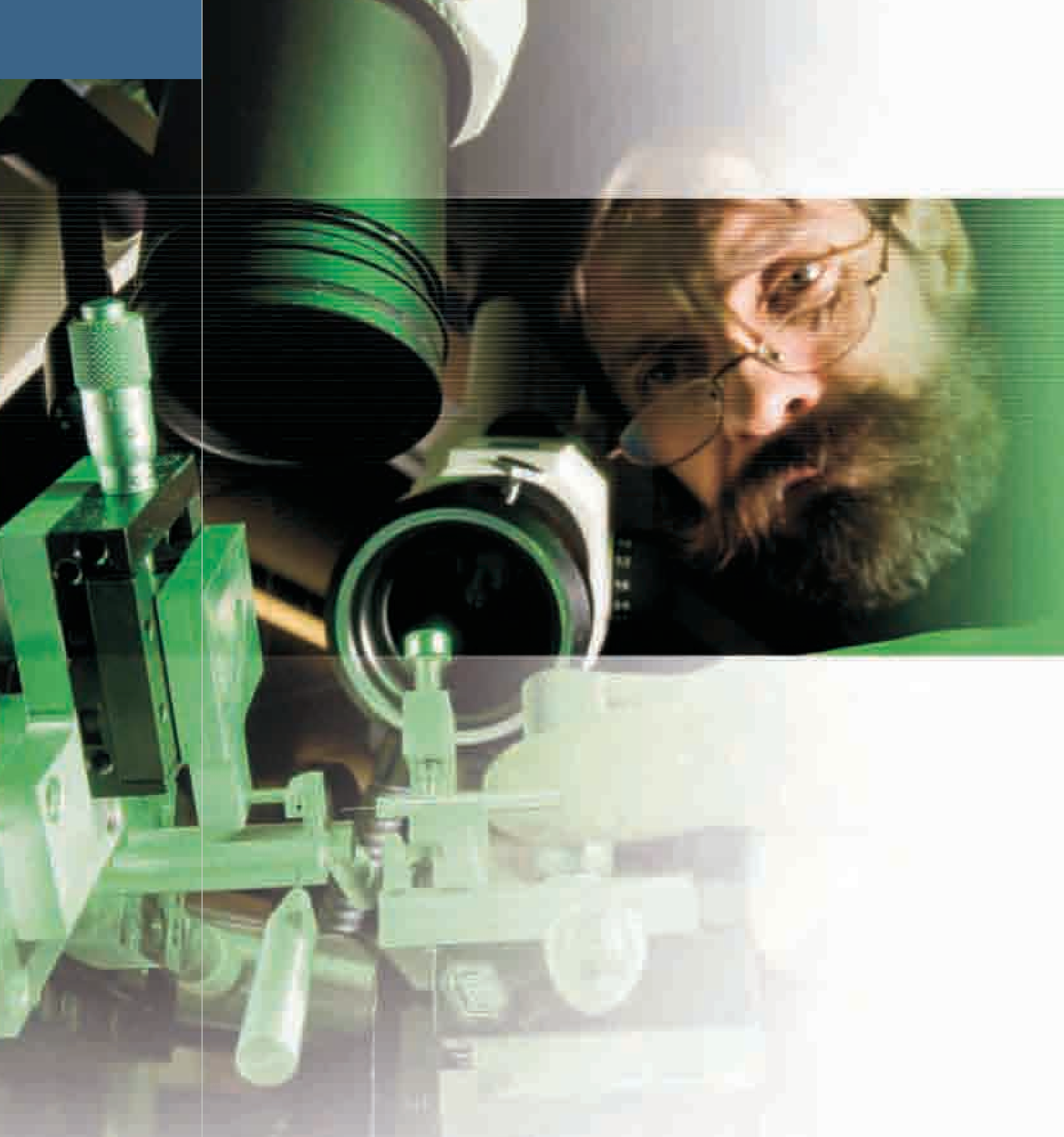


Contents

Foreword

Research at the Central Laser Facility (CLF) is a partnership between its staff and members of the UK and international scientific communities. The CLF offers world leading laser equipment, often developed in-house, that pushes the frontiers of extremely high power and intensity, ultra-short pulse length, and unsurpassed measurement sensitivity.

The research ranges from fundamental studies of physics, chemistry and biology, to applications that address the grand challenges facing our society: the production of abundant, secure, carbon-free energy, understanding and controlling disease, understanding our environment, and protecting our national security.

The CLF has delivered a range of major new facilities over the recent past to ensure its research communities can continue to operate at the forefront of their field. We have also laid out an internationally coordinated future development path to retain this leadership position and demonstrate the significant impact of this area of science.

I hope that the following pages provide a useful introduction to the exciting research currently underway, and illustrate the huge talent and creativity of our staff and academic and industrial partners.

Professor Mike Dunne
Director, Central Laser Facility

The Central Laser Facility

The Central Laser Facility (CLF) is one of the world's leading laser science institutes, giving researchers from across the UK and around the world access to an unparalleled suite of state-of-the-art laser light sources

The CLF's facilities are used for activities as diverse as subatomic particle acceleration, probing chemical reactions on the shortest timescales, and studying bioscience processes critical to life itself. From advanced, compact, tuneable lasers, which can reveal intricate detail on a microscopic scale, to high-power installations that recreate the conditions inside stars and point the way to new carbon-free energy sources, the CLF's facilities span the whole range of ultra short pulse capability. The CLF's lasers are available to academic and industrial groups – anyone who can devise the most exciting experiment!

The largest systems are Vulcan and Astra Gemini. Vulcan is a very high energy laser with a footprint bigger than six tennis courts. A single Vulcan shot can involve irradiating a sophisticated target with several beams and monitoring the resulting extreme plasmas using multiple diagnostic instruments. At the peak of a pulse Vulcan delivers a power of one petawatt (a thousand million million watts).

Astra Gemini is designed to match Vulcan's power in shorter, lower energy pulses. It drives similar areas of plasma research but its design allows it to fire shots much more quickly than Vulcan can – up to three per minute compared with Vulcan's few per hour.

The CLF's Artemis laser operates at a higher pulse rate still – 1 kHz – with the shortest pulses (below ten femtoseconds). Another difference from the larger systems is that Artemis can be tuned across a wide spectral range. These features allow it to carry out the most advanced experiments in, for example, materials science and gas-phase chemistry.

The Lasers for Science Facility is home to the CLF's Molecular Structural Dynamics and Functional Biosystems Imaging groups. The 10 kHz ULTRA laser is one of the world's best instruments for infrared-visible-ultraviolet spectroscopy and the scientists using it have an international reputation in the dynamics field. The OCTOPUS cluster of lasers enables real time imaging in complex physical and biological systems, integrating a very wide range of techniques. A multi-skilled team works on problems ranging from fundamental biochemical pathway analysis and optical manipulation of micro- and nano scale objects through to the development of predictive methods for healthcare applications.

Harwell Science and Innovation Campus

The CLF is based at the STFC Rutherford Appleton Laboratory, on the Harwell Science and Innovation Campus in the heart of Oxfordshire. The site hosts many other facilities and institutes, including:

- ISIS – the world's leading pulsed neutron and muon source;
- The ESA International Space Innovation Centre, alongside Europe's biggest space science and technology department;
- The Diamond Light Source – the UK's national synchrotron radiation facility and the country's largest scientific investment in 40 years;
- Laboratories of the Medical Research Council, the UK Atomic Energy Authority and the Health Protection Agency.

In addition, a growing number of high tech businesses are based on the campus, several of which have been spun out from the laboratories themselves.

APPLICATIONS OF CLF LASERS

- Fusion energy
- Molecular biology
- Compact particle accelerators
- Microscopy
- Cancer therapy
- Astrophysics
- Diagnosis of disease
- Drug development
- Atmospheric physics and environment
- Planetary studies
- New materials
- Chemical manufacturing

Laser light is not like normal light. It is produced through an amplification process which works at the atomic level (see p 6) and which gives it very particular properties. It can travel a long distance without expanding (for example, from a laser pointer or in a laser light show). It can also be compressed in time to produce very short bursts of light (currently less than 10^{-16} seconds) or to create very high powers (over 10^{15} watts). And it can be focused to very small spots to act as a high resolution microscope, or to create extreme temperatures.

Having evolved in a few decades from an exotic scientific concept, lasers are now found everywhere, from supermarket checkouts and CD players to hospitals and the factory floor. They also power the whole global communications network. Depending on the application, they can be tiny semiconductor devices, table-top instruments or huge laboratory installations. Many hundreds of different kinds of laser exist, designed to emit radiation over a wide range of wavelengths from microwaves to X-rays.

Lasers remain a major scientific research tool because they interact with all kinds of matter in very specific ways. They can, when required, dramatically change its state and they can also reveal detailed information about its atomic, molecular and structural properties. They are among the most versatile and useful laboratory instruments available.

The largest lasers can be used, for example, to recreate the extreme conditions found in stars. High-power laser pulses are focused down to a tiny spot where the temperature reaches millions of degrees and the pressure rises to billions of atmospheres. Under these conditions, atoms and molecules are blasted into a gaseous soup of charged particles called a plasma. By analysing the content of such plasmas and observing their behaviour, scientists can learn about the fundamental properties of matter. They can also develop practical schemes such as the harnessing of nuclear fusion as a source of abundant, safe energy.

Ultra-short pulsed lasers can follow transient changes in atoms and molecules, even tracking the subtle and complex reactions of biomolecular species in living cells. Understanding these processes is important, *economically*, for example in sensing and chemical engineering, *environmentally*, since climate is affected so strongly by atmospheric chemistry and physics, and *medically*, since the prevention

Lasers
and their applications

Lasers are powerful tools for ground-breaking research in and treatment of disease often involves managing processes at the cellular level. Their extreme selectivity and their ability to resolve detail down to the microscopic scale are also making lasers an increasingly important tool in biomedical imaging.

The CLF provides laser systems to enable all of these studies. The systems all have the same general form, consisting of three principal components:

- One or more oscillators, where the initial pulses of light are produced
- Amplifiers, where energy is pumped into the pulses
- An experimental area, where the laser pulses emerge and are delivered to the sample being studied. This area also includes all of the diagnostic instruments used to gather the experimental results.

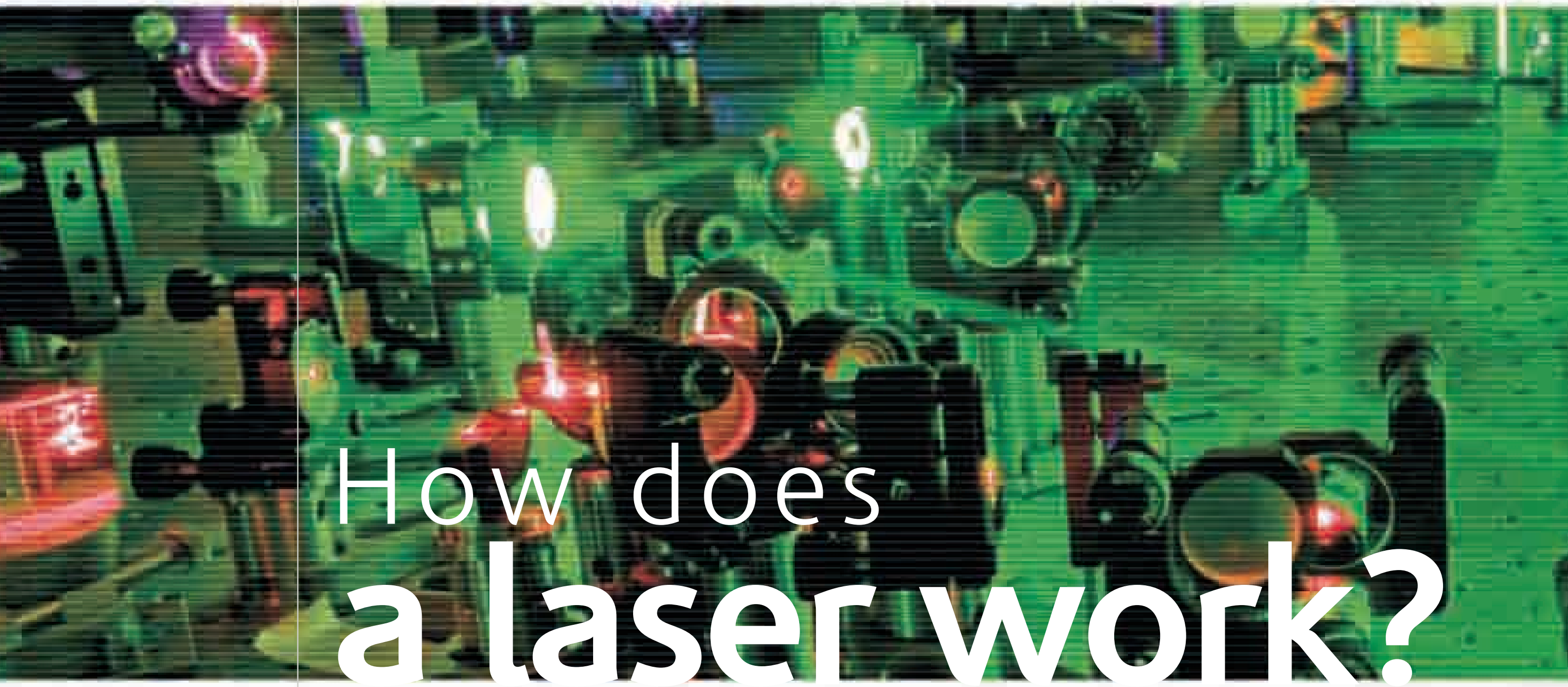
An unusual characteristic of the CLF's lasers is their great versatility. Each is run by a team of experts who work closely with the end users, configuring the laser itself and the experimental area to deliver exactly what each research group needs. Indeed their familiarity with the systems is so complete that the setup can even be changed while an experiment is taking place, allowing novel phenomena to be followed up as soon as they appear. The combination of design flexibility and expert operation means that the lasers in the CLF are very much more productive than they would be if each was limited to just one task. The best equipment in the world is, inevitably, expensive and this approach ensures that the country gets the maximum value from its investment.

science, health and technology

By 1917 a lot was already known about how light (radiation) interacts with atoms and molecules (matter). Quantum theory explained that electrons in matter are restricted to certain well-defined 'energy levels'. An atom with an electron in a high energy level and a space in a lower one is said to be 'excited', and excited atoms relax by letting the electron drop down from the higher level to the lower one. This process emits a packet of light – called a photon – to carry away the excess energy. The amount of energy determines the colour of the light (photons from the blue end of the spectrum carry more energy than ones from the red end). This process seemed to need no encouragement, so it was called 'spontaneous emission'. It produces almost all the light we see.

It was also known by 1917 that if a photon of the right energy (colour) is shone onto an atom then it can make an electron in a low energy level jump up to a higher one. In this case the photon is absorbed. Einstein's insight was to ask what happened when light was shone onto excited atoms. He theorised that one photon from the light beam might stimulate the atom to relax and to emit a second photon. When he added this new idea into the theoretical equations which already described spontaneous emission and absorption, he discovered that it neatly explained why the broad spectrum of light from hot bodies like the Sun is the shape that it is. So stimulated emission meets the most important test of any theoretical idea – it explains the experimental facts. An important feature of the process is that the second, stimulated photon is identical to the first – it has the same energy, travels in the same direction and is 'coherent' i.e. the two photons' waves are in step. This is why laser light is single coloured, travels in tight beams and can be focused to tiny spots.

For a laser to work, stimulated emission has to occur more often than absorption, otherwise the device consumes light rather than produces it. This means



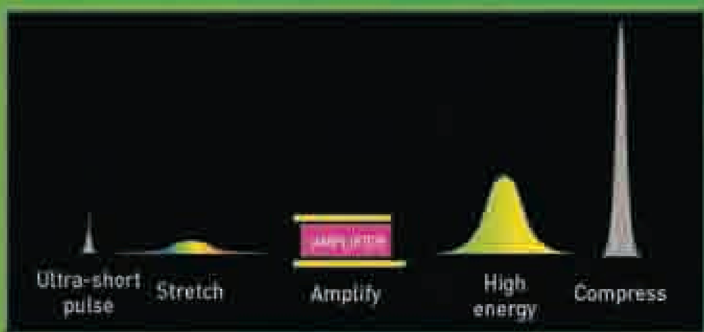
How does a laser work?

The word LASER stands for 'Light Amplification by Stimulated Emission of Radiation' – a process predicted by Einstein in 1917 and first demonstrated in 1960 that a photon must be more likely to encounter an excited atom than an unexcited one, which in turn means that excited atoms need to outnumber unexcited ones. The stimulated emission process can then cascade, with each new photon likely to generate an additional one, adding to the light beam until it becomes very bright indeed. The excited atoms are produced by using a power source to 'pump' electrons up into the higher level. This is easier to do with some atoms than others, so the choice of laser material is important. The CLF's lasers are based on materials like neodymium in glass and titanium in sapphire.

As well as a power source for pumping and some material in which stimulated emission can occur, a laser needs one more thing – a set of optics (mirrors, lenses etc) to control the properties of the light beam. Without these the laser will amplify every photon it can, producing a poor quality beam which spreads out quickly in space and fluctuates unpredictably in time.

The CLF's lasers are almost all pulsed. They are pumped for a relatively long time, building up a store of energy in the population of excited atoms, then a very short pulse of light is sent in to stimulate the emission of all the stored energy. This can lead to an enormous increase in power (energy divided by time) since in Vulcan, for example, the energy is stored over a millisecond but extracted in a nanosecond. So the power emitted in the laser beam can be a million times higher than the power absorbed from the pump source. Handling such high powers requires very special techniques to avoid distorting the laser beam and damaging the laser itself (see box on Chirped Pulse Amplification).

Chirped Pulse Amplification



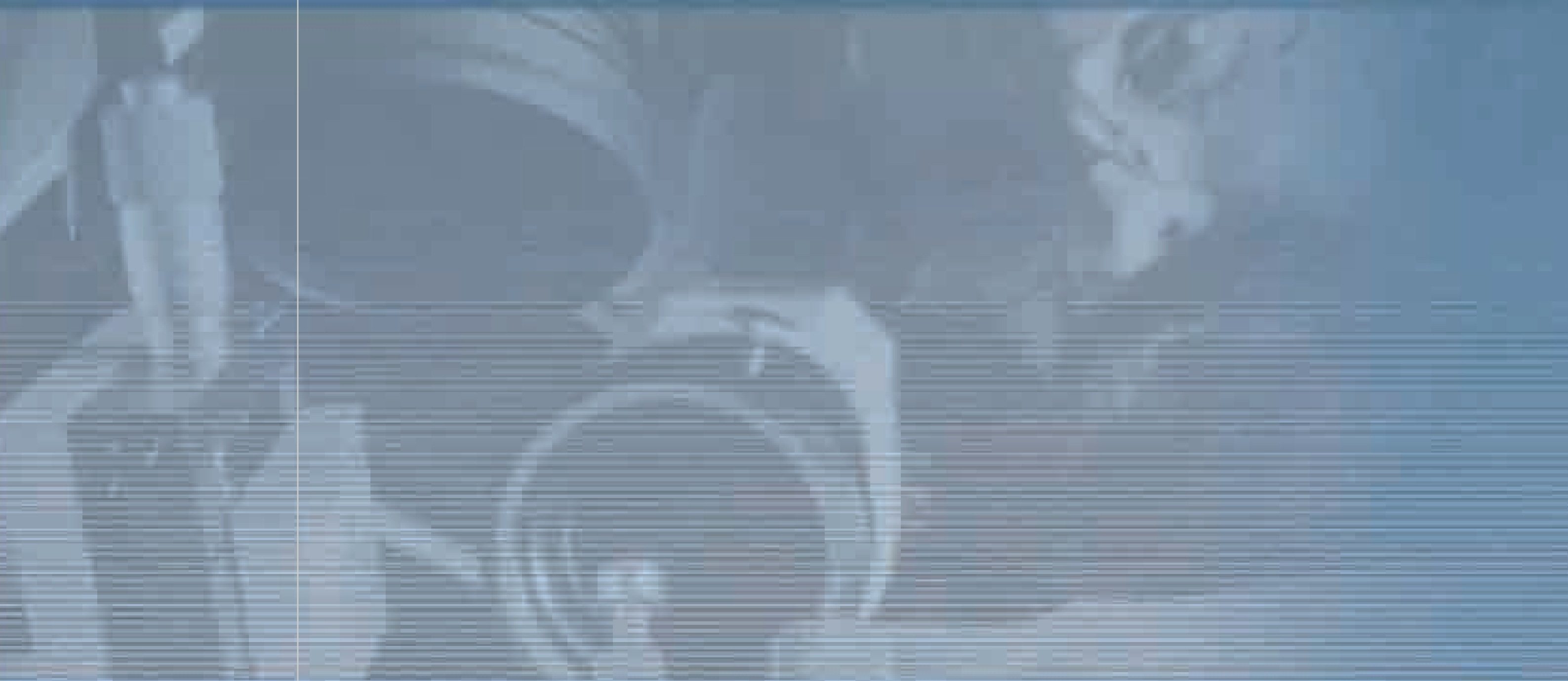
The CLF produces some of the world's most powerful light beams – so powerful that they can even cause problems for the lasers themselves. High power light can change the properties of the material it passes through. This, in turn, can act back on the beam, degrading its spectrum and, at worst, focusing it down so tightly that it does permanent damage. This limited the growth of lasers through the 1970s and 80s until a solution was found. The solution is a technique called Chirped Pulse Amplification (CPA).

Power is energy divided by pulse length, so the power can be reduced to a safe level if the pulse can be stretched out in time. Of course the highest power is precisely what the facility's users want, so this technique will only be useful if the stretching can be reversed after the beam has left the laser.

A CPA laser achieves this by first stretching a low power laser pulse in time, then amplifying it, then compressing it to recreate the original short pulse length, but now with much higher power.

Chirped pulse amplification makes use of the fact that short pulses of light contain a range of different colours. An optical component called a diffraction grating is used to separate the colours out (called 'chirping') and send them in slightly different directions. The different colours spread out in space, and thus in time. The spread in time will typically be less than a nanosecond. This is still a very short duration but it can easily be thousands of times longer than the original laser pulse.

The resulting drop in beam power can reduce the effects in the laser material from catastrophic to negligible. And the beauty of the scheme is that a second pair of gratings, arranged to delay the colours in the opposite order can, after the pulse has been amplified, recompress it back to its original very short length.



Science

Recent research at the Central Laser Facility

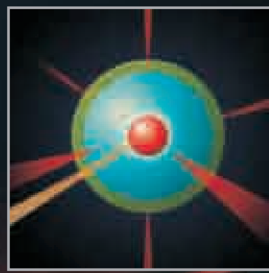
Experiments with the Vulcan Petawatt laser system are revealing the potential of a new laser-driven fusion scheme for abundant, environmentally friendly energy generation

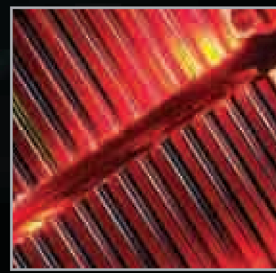
Fusion energy

For 60 years scientists have been exploring how to generate energy by harnessing the nuclear fusion reactions which power the Sun. The fusion of the two heavier isotopes of hydrogen, deuterium and tritium, at temperatures of 100 million degrees, to produce helium and energy-carrying neutrons would provide a safe, controllable, carbon-free power source with security of supply to all nations, readily manageable waste and at a scale to power our civilisation for millennia.

The advent of high-power laser systems has allowed researchers to study a fusion scheme in which a spherical pinhead-sized pellet containing the hydrogen fuel is compressed by several laser pulses. The resulting implosion heats up the deuterium-tritium mixture, creating a plasma that is hot and dense enough to cause 'ignition' marking the start of self-sustaining nuclear fusion reactions. This Inertial Fusion Energy (IFE) scheme is to be demonstrated on the US National Ignition Facility. This scheme requires the delivery of a huge amount of laser energy into the pellet in a very balanced symmetrical way, and so is not easy to achieve. Now, another route is being studied, called fast ignition, which should require much smaller lasers and offer a cheaper, more practical route to a commercial fusion reactor.

Fast ignition involves two steps. A laser first compresses the fuel to high densities, then a second high-power beam delivers a single, ultra-short pulse which heats it up enough to start fusion. The principle is analogous to a petrol engine, in which the fuel is first compressed and then ignited with a spark. The fuel pellet is typically mounted around the tip of a hollow gold cone and the short pulse is injected into the base of the cone towards the tip. The laser pulse interacts with the gold to form a beam of accelerated electrons. These electrons then travel into the compressed fuel where they deposit their energy to ignite the fuel.





UK research teams are using the Vulcan Petawatt laser system to study the electron acceleration process, which is not yet well understood. They are examining how the electrons are produced, then move in a solid, or high density plasma, and deposit their energy. One of the most important issues is that the paths of the electrons tend to spread out, whereas they need to be confined in a narrow beam (collimated) in order to create a hotspot in the dense plasma. Researchers are devising methods to control and collimate the electron beams using magnetic fields, either intrinsic to the plasma itself or created artificially. One approach is to generate two successive electron beams, the first of which provides the magnetic field to collimate the second, main beam. Another method is to create guiding magnetic fields at the interface of two metals with different resistivities.

The experiments on fast ignition are at the stage of testing and diagnosing the physics of the various steps. They are preparing the ground for the work that will be carried out at the proposed European High Power laser Energy Research Facility (HiPER), which will be dedicated to demonstrating the feasibility of laser-driven fusion as a practical energy source.

The Earth's climate is deeply influenced by factors affecting cloud formation. Clouds are responsible for both absorbing and reflecting heat transferred through the atmosphere and so have an important role in global warming.

The formation and growth of water droplets in clouds is thought to be affected by pollutants such as organic compounds produced when fossil fuels are burnt. These can react with volatile organic products of biological origin that are adsorbed onto the droplets. Subsequent chemical and physical changes in the droplets can also affect how they interact with sunlight, and thus affect global temperature.

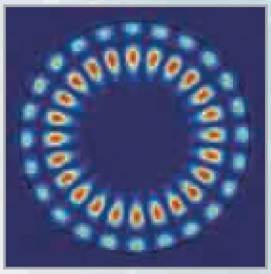
These processes need to be studied in the atmosphere, in model 'cloud chambers', and at the individual droplet level. The latter approach can be achieved using the intense light field of a laser to trap and hold the droplet, as if in a pair of tweezers. Laser optical tweezers offer a powerful method for manipulating minute objects, from molecules to living cells. In recent years, researchers from Royal Holloway University of London, Birkbeck University of London and the CLF have been applying the approach to study model chemical reactions of the type that could occur on the surfaces of droplets in the atmosphere.

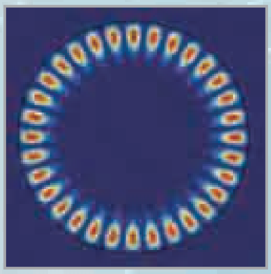
The experiments typically involve spraying a mist of particles into a cell on a microscope stage, while the microscope tightly focuses a laser beam which passes into the cell. One of the droplets eventually finds its way into the centre of the laser beam where it is levitated and held in position by light pressure. By analysing the characteristic wavelengths of laser light scattered by the droplet (Raman spectroscopy), the researchers can follow changes in the chemical composition of the droplet surface over time. Experiments carried out include monitoring the uptake of ozone and its reaction with organic molecules in salty droplets simulating sea water. The presence of organic coatings is thought to affect the formation of cloud droplets around sea-salt particles thrown up into the atmosphere. The results showed that oxidation by ozone increased the size of the

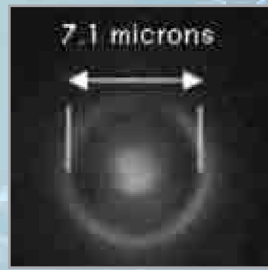
Capturing

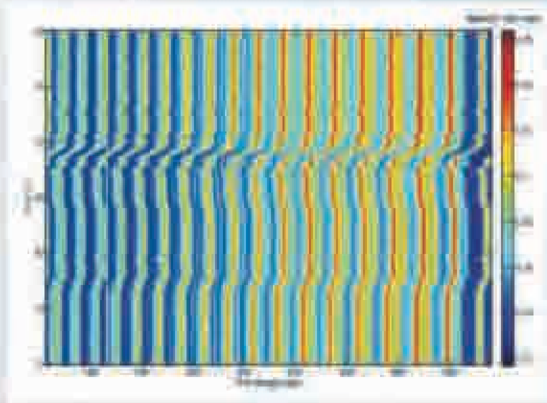
droplets, which could be significant for cloud growth, cloud reflectivity and the onset of rain.

More recently, the CLF team has extended the technique to exploit the droplets as tiny optical cavities. White light, with its broad spectrum, is allowed to bounce around the internal walls. When a particular wavelength of light matches a resonance mode of the cavity, two counter-propagating waves form a resonant standing wave around the droplet, producing a distinctive scattering signal, rather like the amplified sound in a circular whispering gallery. Recording the resonance scattering modes gives a very accurate measure of the droplet size and also its refractive index. Changes due to evaporation and heating can also be monitored over very short times, as well as shape changes and coalescence. The researchers can use the resonance scattering signals to monitor the build-up of layers of molecules on the droplets, as a method of following surface reactions relevant to cloud chemistry on a faster timescale. This information on single droplet behaviour will be used to guide atmospheric models of whole clouds.



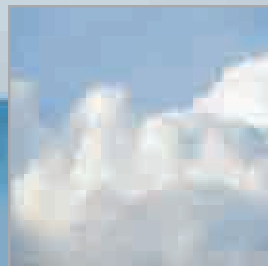


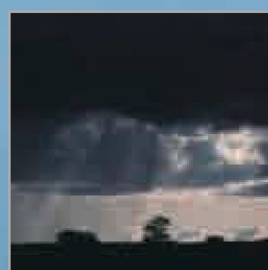




cloud chemistry on a droplet

Scattered light from droplets trapped by optical tweezers is providing clues about factors affecting climate change





Electrons

take a quick hop across proteins

Laser studies of how energy flows through large biological structures are guiding the next generation of solar cells

Life depends on biochemical processes which harness and transport energy. One of the key elements is the transfer of electric charge across an assembly of proteins and associated small molecules.

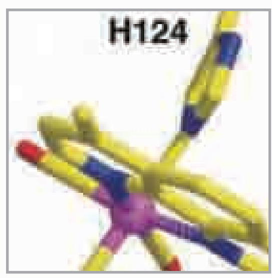
This requires a flow of electrons similar to that in a battery or a household electronic device. Researchers interested in solar-energy conversion, for example, have looked to nature to copy the mechanisms employed in photosynthesis, which is extremely efficient at the molecular level. Electrons are often transferred over distances of a few nanometres, a long way in molecular terms, in a fraction of a microsecond. Theoretical modelling suggests that this is optimally achieved in short hops via molecules that act as ‘relay elements’ between electron donor and acceptor cofactors attached on either side of the protein matrix.

To test this idea, researchers at the California Institute of Technology and Queen Mary University of London (QMUL) designed and investigated, spectroscopically, a model system consisting of azurin, a copper-containing protein involved in electron-transfer in bacteria, linked via the amino acid histidine to a rhenium-containing complex acting as the electron acceptor. The distance between the copper electron-donor and the rhenium electron-acceptor was 1.9 nanometres. Then a tryptophan group was placed alongside the rhenium. Tryptophan is known to behave as an electron-shuttle in certain biochemical reactions, allowing electron transfer to happen many thousands of times faster than would be expected if it were a single-step process.

Using the PIRATE instrument of the CLF Ultrafast Spectroscopy Laboratory, the QMUL team, with the CLF scientists, set up a series of experiments to measure the speed of electron transfer in the azurin/metal-complex system. A short laser pulse was used to raise the rhenium complex into an excited state so as to trigger the electron-transfer process. The system was then monitored over time with a tuneable infrared laser. This detects how the system’s characteristic spectrum of molecular vibrations is affected by the subtle electronic and structural changes associated with electron hopping. The measurements allowed the researchers to detect independently when the electron left the copper donor site and when it arrived at the rhenium acceptor site, and calculate the speed of electron

hopping. They were able to produce a two-dimensional map showing the energy changes driving the two-step electron-hopping process, and show that the ~2 nanometres transfer from copper to rhenium started with an ultrafast hop from the tryptophan to the rhenium site followed by a somewhat slower hop from the copper site. Overall, the experiments revealed that when tryptophan was incorporated in the structure, the rate of electron transfer in the resulting two-stage process was more than 300 times faster than when, without the tryptophan, it had to occur in a single step.

These kinds of detailed spectroscopic experiments not only help biologists to understand fast electron transfer in living systems, they also provide a test bed for developing novel protein-based devices. Using bacteria to make selected protein variants, the molecular system's electronic behaviour can be optimised for specific technologies. A long-term goal of the researchers is to synthesise modified protein complexes to carry out tasks requiring very efficient electron transfer – such as catalysis (mediating a chemical reaction), molecular signalling (used in bio-sensors), imaging (in electronically-sensitive pigments), information storage and light-energy conversion.



DNA damage limitation

Protecting the instructions for life

Infrared laser science can reveal how DNA protects itself from damage and how that protection can sometimes fail

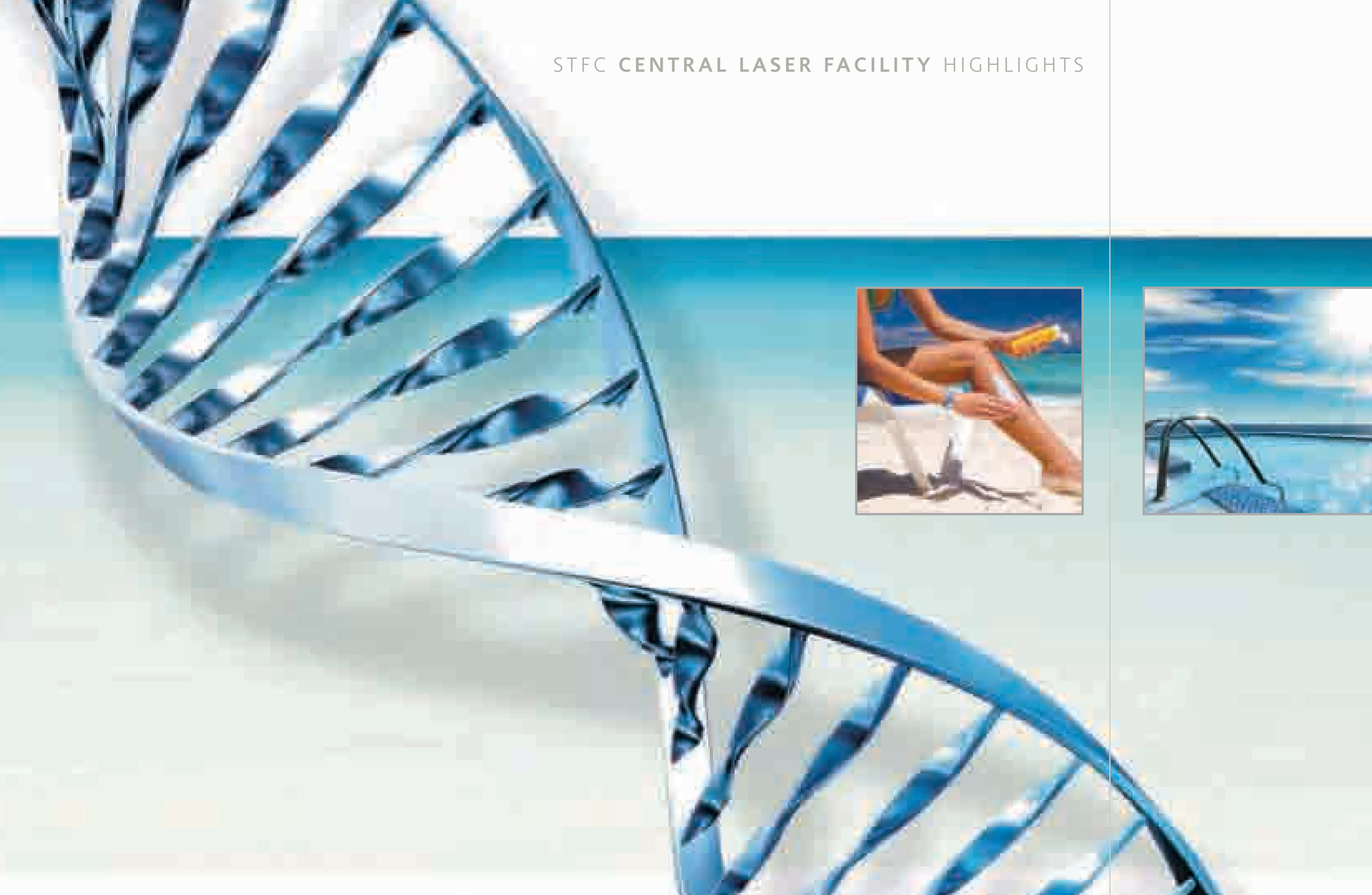
The processes involved in making and operating a human being are controlled by a set of detailed instructions written, in the form of genetic code, along our DNA. The instructions are complex, so DNA molecules are large - each and every cell in our bodies contains about two metres of DNA, twisted into a double helix then coiled up again and again until it is small enough to fit into the cell's nucleus. Not only is the code itself critically important, but the details of the coiling also strongly affect the way the molecule works.

Our DNA is under constant attack, by other chemicals inside the cell and by external factors such as natural background radiation and the ultraviolet component of sunlight. It is estimated that the DNA in each cell is damaged 10,000 times every day! Given its size and complexity, and the constant assaults on it, it is remarkable that it survives at all. But in fact it is extremely robust and can be very long-lived indeed. The genetic code is passed from generation to generation with relatively few mutations and DNA from ancient mummies and even from Neanderthal burials has been reliably extracted and sequenced. So how come it survives for so long?

It turns out that the damage which does occur is handled in several different ways. In living cells repair processes have evolved and these are largely successful at correcting the coding errors which arise. If the damage repair fails then the cell usually either dies or, at the least, doesn't produce viable offspring. These are benign outcomes too, since the body doesn't miss a few cells. But very occasionally the damaged DNA is not repaired, yet the cell still goes on to divide. In some cases this division is uncontrolled and a large number of defective cells appear. This is cancer.

Research is under way to attack cancer at every stage of its development. Surgery, drugs and radiotherapy are used both on cancers themselves and on pre-cancerous conditions detected by screening. Improved understanding of DNA damage repair and of the ways that nature has of eliminating damaged cells may help us to target cancers at the point where they start. At the most fundamental level, however, it is also important to understand how the DNA itself resists damage in the first place. If this resistance can be supported, by changes in diet or lifestyle for example, then the problems might never occur at all.

Consider the damage caused by ultraviolet light. When DNA absorbs an ultraviolet photon the immediate effect is that a very small part of the molecule acquires a large amount of energy – enough to break chemical bonds or initiate dangerous chemical reactions. The chances of such a bad result are lowered if the DNA can dissipate the incoming energy as quickly as possible, either to its



environment or by spreading it out over a larger region of the molecule. Researchers in the CLF's Molecular Structure and Dynamics Group are working to understand how, exactly, it does this.

Unfortunately DNA is a difficult molecule to study. Its complexity means that there are many processes going on simultaneously and these can be specific to a particular part of the molecule and also to a particular way in which it might be coiled up. The very nature of fast dissipation means that things change quickly, so the tools used to observe it must be capable of ultrafast temporal resolution. And, perhaps most importantly, while one part of the molecule is attempting to shed energy, other parts may be changing in ways that enhance or inhibit its ability to do so. This dynamic element in the environment can complicate experimental measurements significantly.

Many of the conventional analytical approaches make some headway in these conditions but are eventually limited by their lack of discrimination. This is where the strength of the CLF's technique – picosecond time-resolved infrared spectroscopy (ps TRIR) – comes to the fore. The infrared is rich in spectral features which relate to particular parts of a molecule or to particular ways (modes) in which it behaves. The times over which these features grow and decay reveal how individual sub processes progress and which ones are related to one another, allowing the details of a complex reaction to be unravelled.

An example of this relates to the behaviour of cytosine, which is one of the four coding substances (the so called 'bases') that occur in DNA. Cytosine can be studied more easily by looking at a simpler molecule – poly(dG dC)$_2$. This has the same double-helical structure as DNA but it contains only two of the bases, cytosine and guanine. Like DNA, the poly(dG dC)$_2$ helix can have either a right handed or a left handed twist, with the detailed molecular structure being quite different. When ultraviolet light is shone onto either form ps TRIR reveals that the absorbed energy is not always dissipated quickly. Instead it can create a state which lasts for 10-20 ps. The details of the ps TRIR spectrum, including the fact that the lifetime doesn't depend strongly on the handedness of the molecule, indicate that the energy is localised quite close to the cytosine base. It may be that this long-lived state leads to a type of damage called a cytosine dimer, which is implicated in the development of skin cancer. Learning the secrets of its formation is a first step towards understanding how to minimise it.

A new compound that fluoresces in laser light over microseconds radically extends the power of microscopy in studying the cellular processes that cause disease

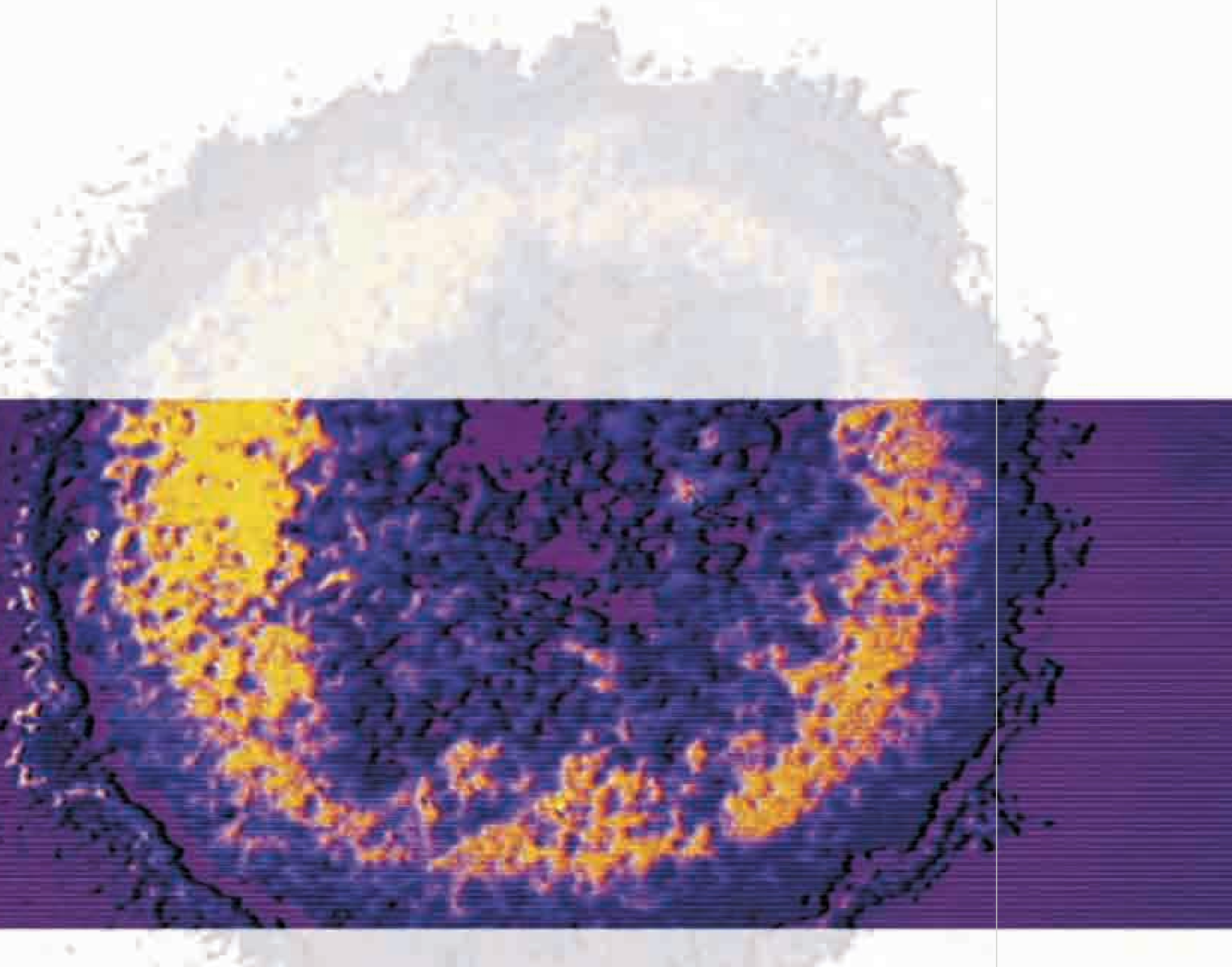
A platinum probe lights up live cells for longer

Fluorescence microscopy has become a standard way of imaging biological cells

Selected cellular components can be labelled with a compound (a fluorophore) that emits light by fluorescence when a laser of the right wavelength is shone on it. Using a powerful microscope, biologists can then pick out the structures of interest and monitor processes in the cell, for example those associated with disease. Several types of microscopy have evolved, including ones in which the fluorescence lifetime is measured. Changes in the lifetime provide information about changes in the chemical and physical environment close to the fluorophore.

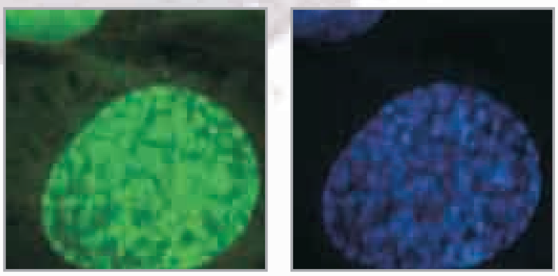
However, researchers are always on the look-out for new fluorophores which are more stable and fluoresce for longer. Last year, a team from the Universities of Durham and Sheffield and the CLF identified a new fluorescent platinum-based compound which allows them to image and map live cells over timescales much, much longer than before. The platinum complex, a flat ring-like organic molecule, is non-toxic and electrically neutral. It readily diffuses into cells in just a few minutes, attaching itself to the DNA in the nucleus – and possibly the RNA as well – without disrupting the cell's functions.

Experiments with a pulsed laser have shown that the green-yellow fluorescence lasts several microseconds, which is orders of magnitude longer than for other fluorophores. The light emission is also very strong. This means that the natural 'autofluorescence' from the indigenous molecules in the cell, which dies away very quickly, no longer swamps the more persistent target signal. This combination of attributes takes fluorescence microscopy into a new regime, whereby



cells can be imaged over time and cellular processes followed in vivo. Because the complex is stable, so-called two photon microscopy can be used, in which the fluorescence is excited by a near-infrared laser emitting light of half the energy and twice the wavelength normally needed, but over a longer period. This lower-energy light is much less likely to damage the cell.

The time it takes for fluorescence to decay has been measured in different cell types, including human skin cells, cancer cells and animal cells often used in genetic studies. The lifetimes were longer in the cells than in solutions of the compound exposed to air, which is probably due to the fact that binding with large molecules such as DNA in the cell protects the fluorophore from active oxygen-containing molecules which tend to quench the fluorescence. This lower oxygen environment is common in cancer tissues where the blood supply is less than in normal tissue.



The platinum complexes are chemically versatile, and the researchers are hoping to make versions – tagged with an antibody, for example – designed to bind to specific target proteins in the cell. In this way, time-resolved emission microscopy could be used to follow a wide range of intracellular processes. Because the lifetime is affected by the presence of small, highly-reactive oxygen species such as oxygen radicals and nitric oxide, the new fluorophores could shed light on oxidative stress in cells, which is related to ageing and diseases such as cancer as well as neurodegenerative disorders.

Living organisms depend on complex arrangements of molecules within their cells to harness, store and utilise their sources of energy. The molecular process can be very efficient, and scientists would dearly love to understand the underlying mechanisms well enough to exploit them in the design of much-needed new energy technologies.

Take photosynthesis: sunlight is captured and harnessed in green plants via large molecular assemblies composed of units such as chlorophyll, which contain chemical bonds rich in electrons. It is these electrons that convert the light into electrical energy, transferring it across the assembly to trigger various biochemical reactions. Chemists have already designed simple photochemical systems that mimic this electronic process for use in solar-energy conversion – but they are much less efficient than the processes that have evolved in green plants.

To make further progress requires a deeper understanding of the energy-transfer processes – which means building up a picture, right at the quantum level, of not only localised electronic behaviour but also the subtle interactions between electrons in different parts of the assembly. The electrons absorb and release energy by jumping between lower and higher quantum energy levels, and laser pulses with the right range of energies (which depends on the colour, or wavelength) offer the ideal tool for probing these transitions. By using timed pulses, the relationship between electronic transitions across the system can be followed.

Laser experiments on laboratory samples have shown that the electrons mediating the energy flow appear to be closely coupled – they are coherent. However, multiple measurements were required, which took several hours and tended to degrade the sample.

Capturing photosynthesis in action

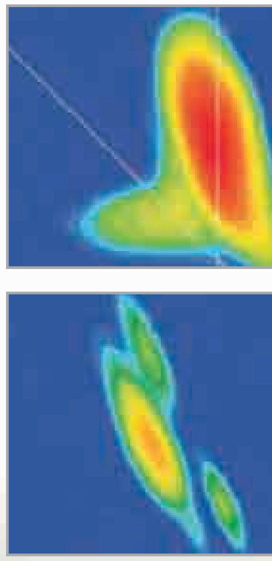
How plants turn sunlight into energy is caught on camera, thanks to a novel laser method

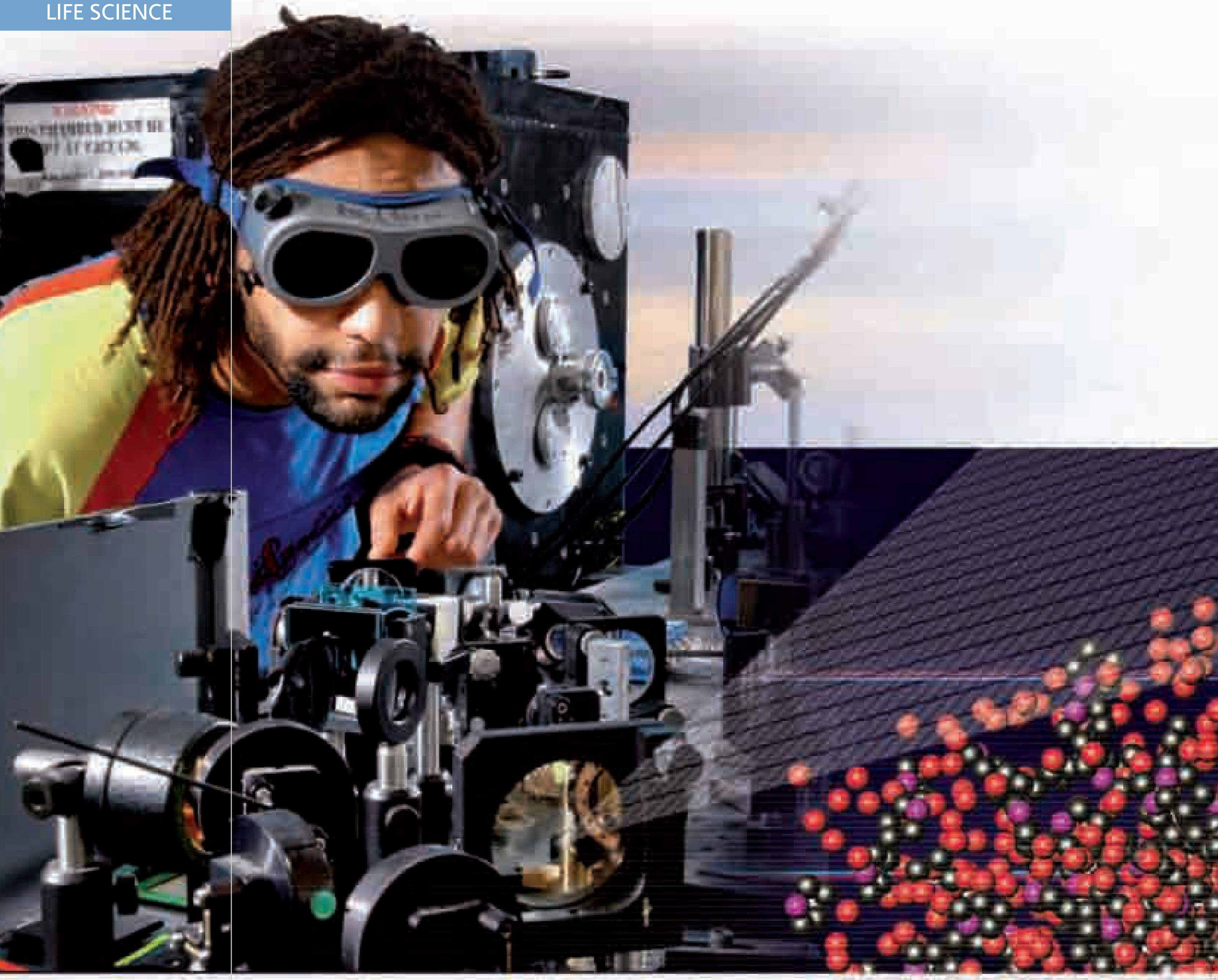
Recently, however, a group of chemists and physicists from University College Dublin and Imperial College London working with Artemis (p 68) have developed a way of mapping this 'Mexican-wave' energy flow in a single snapshot using a new technique called angle-resolved coherent (ARC) wave mixing. Working on test samples of photosynthetic proteins from purple algae, they were able to gather all the information in just a fraction of second.

Many lasers make light work

The method involves splitting a femtosecond laser beam with a diffraction grating into three further beams. The beams enter the sample from different directions, while being precisely overlapped in time, to produce a fourth, output beam. The timing of the pulses is engineered via a controllable delay. An essential feature of the experiment is that the laser pulses are first fed into a long hollow fibre filled with inert gas, which spreads them out into a wide band of colours that encompass all the crucial energy transitions in the photosynthetic material. The output beam is then collected as a series of bright spots on a CCD camera. The angle made by each spot depends on the wavelength and thus energy of the emitted light, which in turn carries a direct 'fingerprint' of electronic behaviour in the sample – to give a global map of the coupled electronic transitions and energy transfers across the photosynthetic system.

The researchers plan to take the technique further to study biological systems in their real environments, for example in cell membranes, and to pick apart the structural chemistry that could eventually be the basis of a cheap, efficient solar cell.





Atoms form molecules by binding together via the electrons in their outer orbitals. These atomic orbitals overlap to form a stable molecular orbital in which the coupled electrons sit – a chemical bond. This tried-and-tested quantum description of electronic behaviour underpins our understanding of chemical structure and reactivity, including that of large biological molecules important for life.

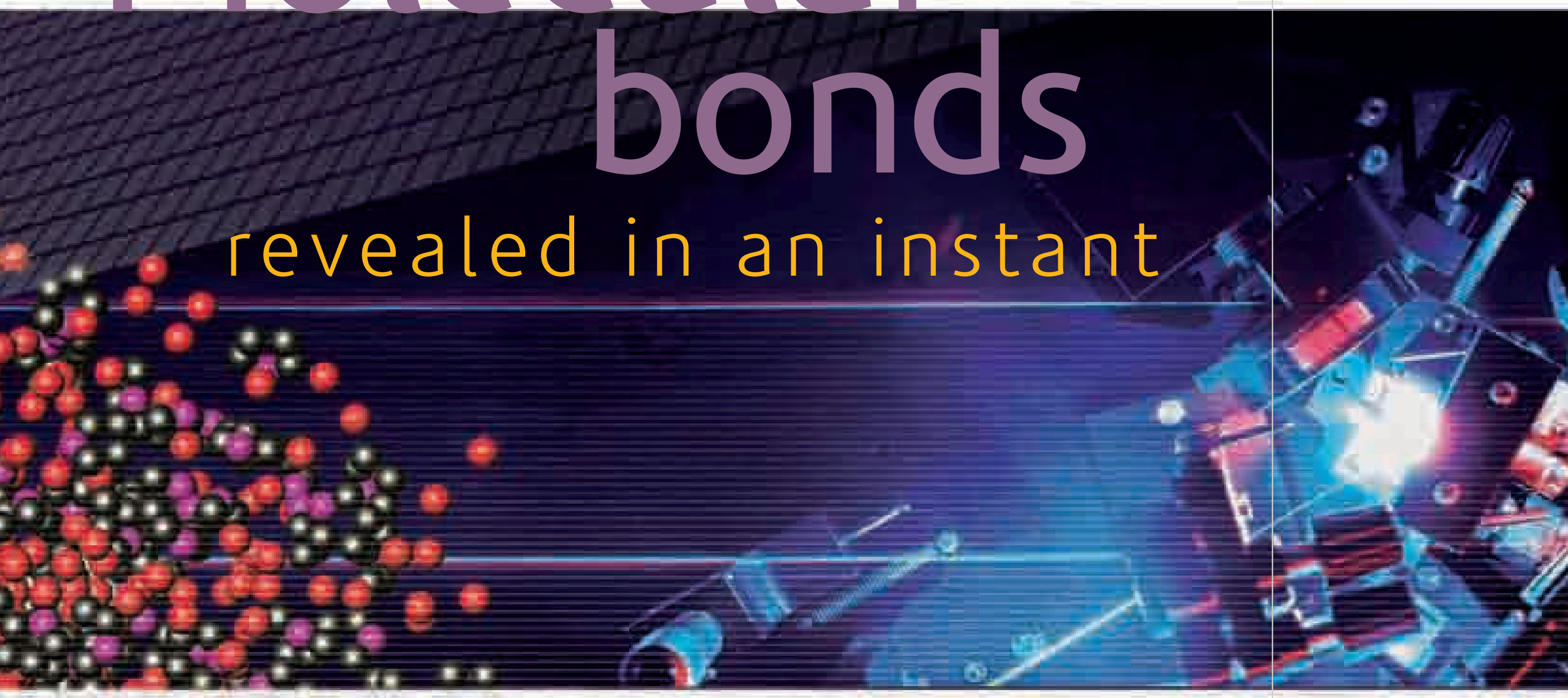
Chemists and physicists have a range of techniques to probe chemical bonding, many of which use pulsed lasers.

Recently, a new type of laser-based measurement has excited great interest. It has the potential to map molecular orbitals and even track detailed changes in electronic structure on ultra-short, attosecond timescales not accessed before. The method is based on the subtle interaction of an intense, ultra-fast infrared pulse with bonding electrons. When the pulse hits the electrons, they are shaken loose from the atom or molecule and accelerated. The electrons are then pulled back (like stretching and releasing an elastic band), collide with their parent atom and recombine. In doing so, the energy acquired by the electron is converted into extreme ultraviolet radiation, which is emitted over a range of multiple, harmonic frequencies (high harmonic generation, see p 50). Because electrons are quantum particles, they also behave as waves, which interfere with each other during the recombination process in a way that depends on the structure of the molecular orbitals. This diffraction modulates the strength and phase of

A new laser technique based on high harmonic generation can image the fine electronic details of molecular structure

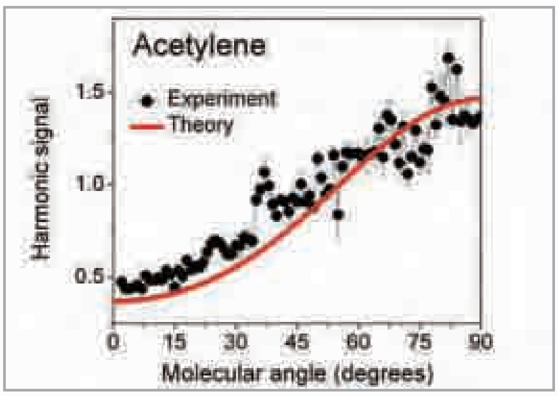
Molecular bonds

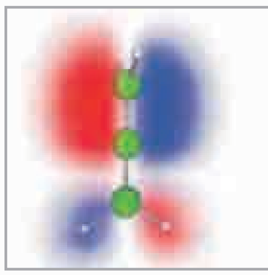
revealed in an instant



the harmonics, which therefore encode information about electronic structure.

High harmonic spectra have been measured in gases of simple molecules such as nitrogen (N_2) and oxygen (O_2). Recently, a research group at Imperial College London, working with staff from the CLF's Artemis laser, extended studies of the effect to more complex linear molecules acetylene (C_2H_2) and allene (C_3H_4). Both molecules have multiple carbon-carbon bonds involving a type of molecular orbital found in many organic molecules called a pi-bond. To obtain the maximum amount of information, the researchers used two carefully-timed laser pulses, which were fired into jets of the gases released in a vacuum chamber: the first pulse was designed to push the molecules so that they all lined up in the same direction, while the second pulse drove the high harmonic generation mechanism. The results showed that the amount of harmonic generation depended on the angle in which the molecules were lying in relation to the polarisation (orientation of the light waves) of the driving laser field. This reflected the shape of the molecular orbitals: the maximum





harmonic generation occurred when the acetylene was lying perpendicular to the laser field, as had been predicted by theoretical calculations on pi-bonds.

The expectation is that this technique will be extended to provide a complete mapping of orbitals and to follow electron dynamics in molecules. With the new ultra-fast X-ray sources now being developed, high harmonic generation could then provide a powerful tool for the biological and materials sciences.

Serotonin mapping in living cells

Two photons are better than one for imaging the neurotransmitter serotonin in cells

Serotonin is an important natural chemical in the body, involved in functions ranging from brain activities to blood flow. Levels of serotonin present in the cerebrospinal fluid, which surrounds the brain, are linked to mood, anxiety, arousal, aggression, impulse control, and cognitive abilities.

In the UK chronic depression is associated with 20,000 suicides per annum. Changes in serotonin concentrations are not only responsible for many depressive behaviours but also play a role in neurological diseases such as Alzheimer's and Parkinson's. From a medical perspective a major strategy for the treatment of a range of psychiatric ailments is to develop drugs that target serotonin-induced pathways. An improved understanding of the chemical's distribution and function could significantly benefit this research.

Serotonin is synthesised in the body from the naturally occurring amino acid tryptophan through an intermediate compound, 5-hydroxytryptophan. It is stored in specialised 'enterochromaffin' cells and released to the bloodstream where it is taken up over a period of time into blood platelets. A team led by Professor Roger Bisby (University of Salford) and Dr Stan Botchway (CLF) is working to develop analytical methods that can track its location and activity in live cells using novel imaging technologies. The serotonin is identified by the characteristic light, called fluorescence, that it emits when it is illuminated with short-wavelength UV light. Not only does an image of this emission show where the serotonin is, but its lifetime (i.e. the time for which it continues to fluoresce after the UV stimulus is switched off) varies with the local environmental conditions. So mapping out the fluorescence lifetime across an image of cells and their surroundings reveals information about the serotonin's local environment and activity.

Serotonin is structurally similar to other chemicals in the cell, including its precursors, and unfortunately its fluorescence spectrum is also rather similar to theirs. This makes it difficult in practice to distinguish it from, for example, tryptophan. Despite this, fluorescence microscopy is still an important tool in this area of research since it gives good spatial resolution and tremendous sensitivity – down to the single molecule level in some circumstances. The search is on, therefore, for ways to improve the technique's selectivity.

The Salford/CLF team is pursuing two approaches to separating the serotonin signal from the background. The first is to drive the fluorescence not with one

315 nm wavelength UV photon, but with two 630 nm red ones. This two photon pumping only becomes strong when a very large number of red photons strike the serotonin together. So it needs the light to be concentrated in space, at the focus of a lens, and in time, in a very short pulse. The CLF's femtosecond laser microscopy setup is the perfect tool for this, and the use of two photon excitation has resulted in a one hundred fold signal contrast between serotonin and tryptophan.

The second approach is to identify the characteristic fluorescence lifetimes of serotonin and to separate these components from the overall fluorescence decay curve, which includes the fluorescence from all of the background species. The timescales are very fast, with measurements using state-of-the-art equipment taking place in nanoseconds. It has been found that serotonin has three distinctive lifetimes. When it floats free in solution its fluorescence lasts for 3.8 ns. This is reduced to 2.5 ns as soon as the serotonin is taken inside a cell. And when it is put into storage for future use by the body the lifetime drops further – to 2.0 ns.

The combination of two photon excitation and fluorescence lifetime imaging is proving to be a powerful tool for the detection and imaging of serotonin in live cells. The same techniques can also be extended to other important biomolecules, using either their own fluorescence or that from a molecular tag (p 18). In the case of serotonin the next step will be to apply the technology to study the transport of the molecule and the effects of drugs being developed to treat depression.

Using laser microscopy to highlight complex molecular interactions in cells could revolutionise the treatment of disease

Towards personalised medicine

Imagine going to the doctor and being prescribed a drug or therapy that is designed specifically for you; it is guaranteed to work and will have no side effects. This is one of the current aims of biomedical research, and depends on having a deep understanding of the complex molecular processes that go on in living cells.

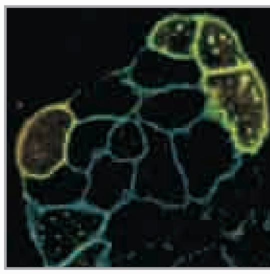
The modern way to develop new drugs is to identify a protein, such as an enzyme or receptor, known to mediate a specific biomolecular interaction associated with a particular disease. A drug molecule can then be designed to lock onto the protein and block that process, so bringing the disease under control. In reality, the accompanying molecular changes in a cell make things much more complicated. The behaviour of the target protein, and thus the drug, may affect a whole cascade of interconnecting molecular interactions. Since these complex systems are also influenced by an individual's genetics and environmental history, the final therapeutic outcome is less than certain. There may be side-effects and the drug therapies may be less effective than expected. For example, chemotherapy works in just a minority of cancer patients.

Unravelling all the possible molecular interactions in a cell might seem a hopeless task, but over the past few years physicists, computer scientists and biologists have been working together to develop a 'systems' approach to understanding cell biology. The idea is to combine powerful physical techniques that probe the detailed structure and behaviour at the molecular level with advanced laser microscopy which can now image single molecules (p 36). The data gathered are then processed and interpreted using powerful computer-based analysis.

Researchers at the CLF and King's College London, have started a new project based on STFC's version of this technology, called 'Lab in a Cell', to test and develop the concept in a real cell environment. Using the facility's suite of advanced laser microscopes, they will image different sets of molecules simultaneously with the aim of pinning down the interactions between them. Each molecule, or component in a molecular assembly, is colour-coded with a different fluorescent dye so that it glows when excited by laser light of the right wavelength. The molecule is revealed under the microscope as a luminous dot. Any molecular interactions cause a change in the fluorescence, which can then be measured. The laser light is also polarised to give further information about molecular orientation. This is important because subtle changes in shape are often a key

aspect of crucial biological processes such as cell signalling.

Recently, the team has been using this approach to study interactions and conformation changes associated with a family of signalling receptor proteins called ErbB. These proteins sit in the cell membrane and regulate different signalling pathways by binding with partner molecules. Deficient ErbB signalling is associated with neuro-degenerative diseases such as multiple sclerosis and Alzheimer's, while excessive signalling is linked to tumour growth. The idea is to use cell cultures and patient tissue biopsies to measure the effects of drugs binding to the receptors, by imaging different combinations of molecules involved in the signalling pathways. In this way, the researchers can build a network model encompassing hundreds of interactions that represents how chemical communication between cells actually happens.



Quantitative high-throughput screening based on the Lab in a Cell methodology could ultimately be used to classify patients according to the characteristics of the protein interactions in their own cells. In this way, treatment protocols could be adapted to meet the needs of specific patient groups.

BBSRC

Nanoprobes

sense tiny forces

How hard does a virus have to work to force its way into a cell? A sophisticated tool being developed at the Rutherford Appleton Laboratory may be just what's needed to find out

The measurement of force on a human scale is something that we are all familiar with. We measure the weight of things, which is just the force that gravity imposes, by balancing it with an equal force from the spring inside our weighing scales, and we detect this force by measuring how far the end of the spring has moved.

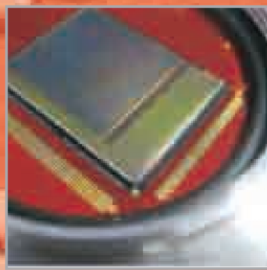
But what if we want to measure forces on the molecular scale – the force between a single DNA strand and an enzyme which binds to it, or between the individual actin and myosin molecules which, in enormous numbers, make our muscles work? These forces are tiny. The weight of an apple is a few newtons, but the actin-myosin force is in the piconewton (10^{-12} newtons) range. However it turns out that they can both be measured in essentially the same way.

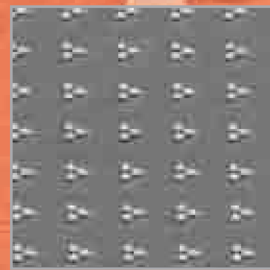
For some time now intense lasers have been focused down to hold tiny objects in 'optical tweezers' (p 12). If a small force is then applied to the object it will be pushed or pulled away from the laser focus. The size of the force can be measured by measuring how far the object moves and multiplying the result by the 'spring constant' of the tweezers. This technique can be extremely sensitive and it has been used to measure how strongly algae swim and how much force is needed to unzip the DNA double-helix. But there are limitations – some objects are vulnerable to damage by a powerful laser and others simply perturb the focused beam, which changes the spring constant and makes the force measurement inaccurate.

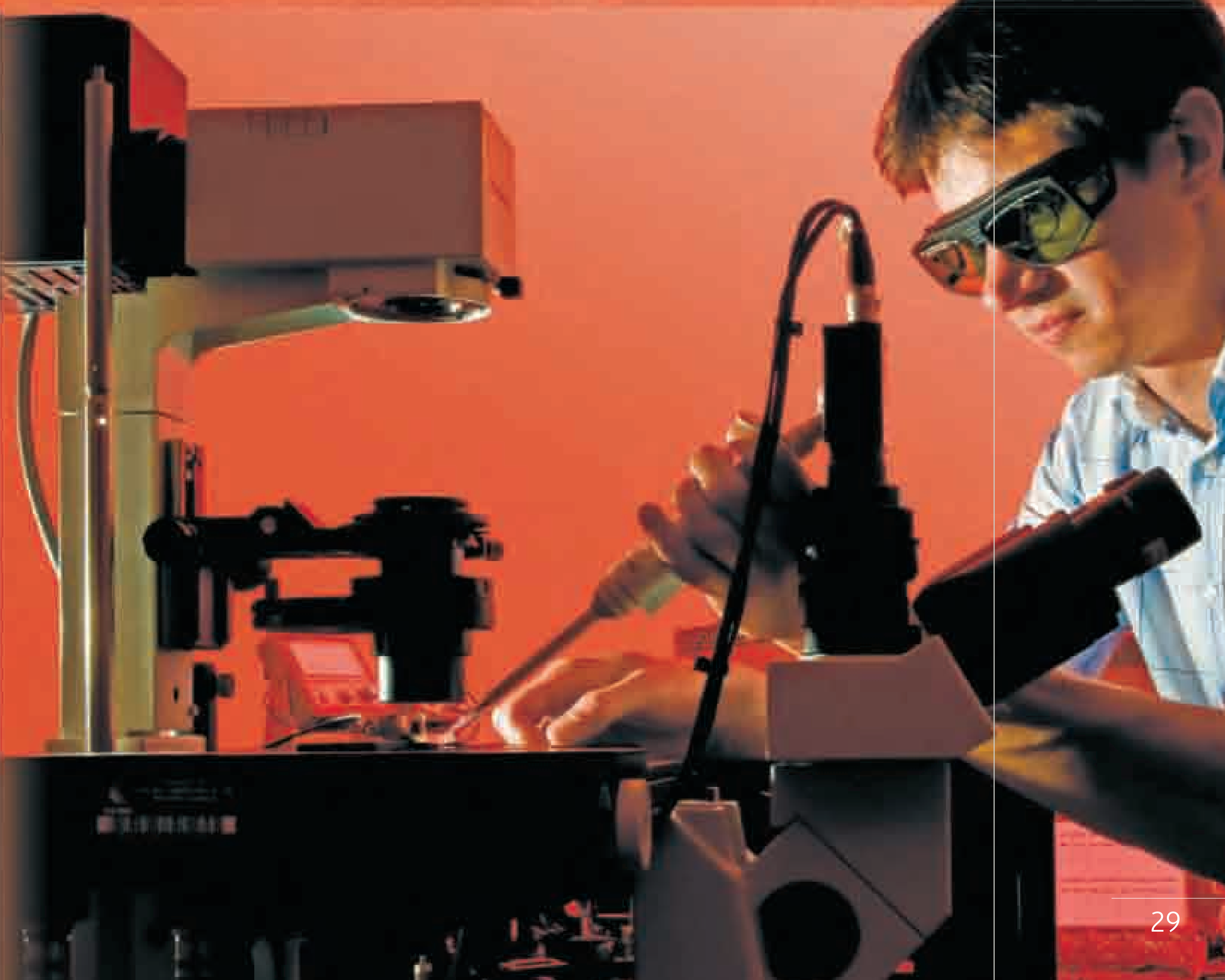
A solution to these problems is to use a microscopic probe, a so-called 'nanoprobe', one end of which can be held in the tweezers while the other end – the tip – interacts with the sample. This solution is being developed by a multidisciplinary team, exploiting the expertise of several STFC groups working in partnership with users from MRC Harwell and the University of Oxford. The probes are just a few micrometres in size, with tips which taper down to nanometres. They can be mass-produced using microfabrication systems in the STFC's Micro and Nano Technology Centre. The CLF's specialist tweezers group has developed a multi beam microscope which can independently manipulate the tool at three points, allowing it to be positioned and rotated with remarkable dexterity.

A key feature of the control system is a camera which can track the probe's position 15,000 times a second. Not only will this allow the measurement of rapidly changing forces, but with a sufficiently fast phase locked control loop it will be possible to eliminate tiny wobbles due to Brownian motion – the effect of continual bumping by individual liquid molecules. The camera and control system are being developed using the latest electronic device structures by the STFC Technology Department.

The integrated nanoprobe system can be used to address a range of problems. As well as measuring changing forces it can, by moving the tweezers to hold the force constant, track the probe tip across a surface thereby mapping out the microscale structure. In the most sophisticated experiments a pair of independent probes can be used to measure the force between individual microscopic entities.

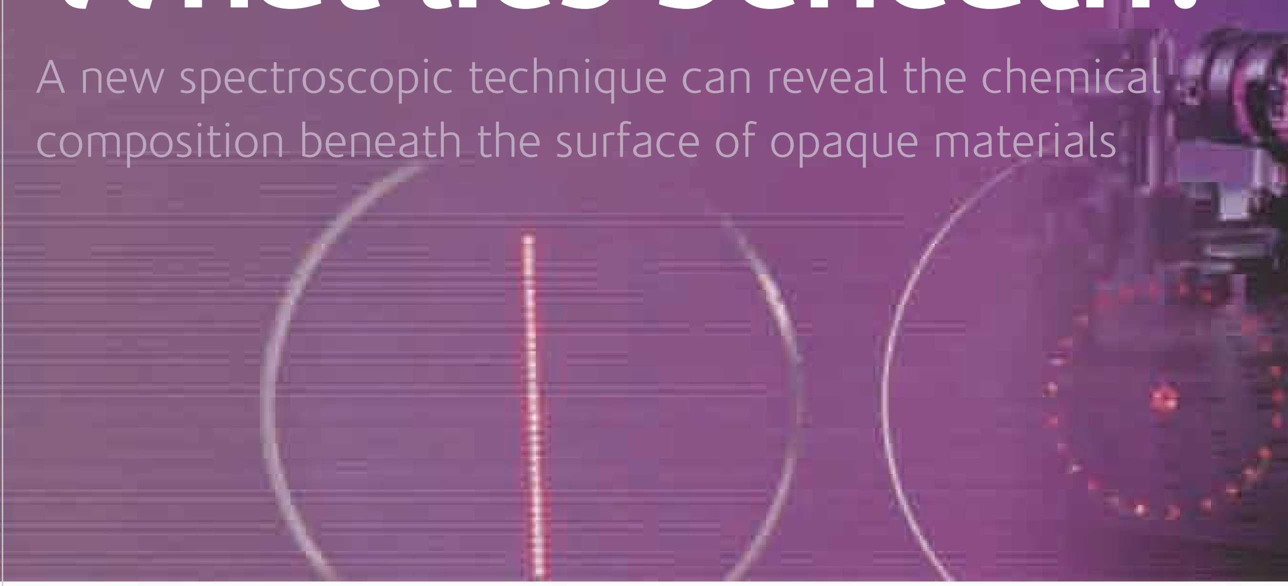






What lies beneath?

A new spectroscopic technique can reveal the chemical composition beneath the surface of opaque materials

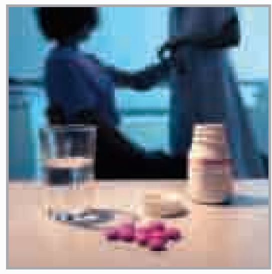


Shining light at, or through, materials provides a powerful way of finding out what they contain. Atoms and molecules respond in characteristic ways to light of specific wavelengths, leaving their telltale imprint on the transmitted or reflected light beam, to create a spectrum typifying the material's composition. Spectroscopy, particularly at infrared or near infrared wavelengths, is one of the main tools used in chemical analysis.

These techniques are usually carried out on transparent samples – often in solution, or on surfaces. Probing deep within opaque substances such as milky liquids or powders without damaging their integrity is less easy. However, researchers at the CLF have now developed a new variant of an old technique that can do just that. It promises to have a wide range of applications, from non-invasively detecting concealed liquid explosives, through checking the production quality of pharmaceutical products, to the non-invasive detection of disease.

The basic method, Raman spectroscopy, employs a laser beam which impinges on the sample and is absorbed and scattered by the constituent molecules. The scattered light comes out at a slightly different wavelength, which relates to the molecular structure and gives a unique spectral signature. Normally, if the beam is shone onto an opaque sample, the backscattered signal comes overwhelmingly from its surface. Nevertheless, a small amount of the laser light does penetrate into the bulk. However, after making its way back out of the sample, this weaker scattered light is ‘outshone’ by the surface backscattering, so is typically impossible to detect. Researchers have developed an ingenious method to separate out the signals coming from the bulk, while avoiding the interfering surface signals. As the laser light returns from ever deeper layers, it gradually diffuses sideways from the vertical line marking the original incident laser spot, and so can be collected from regions that are laterally offset. Spatially offset Raman spectroscopy (SORS) can be used to identify signals from layers several millimetres deep.

The SORS technique is now being applied in several fields. One obvious application is in security screening. The ban on carrying liquids in hand luggage

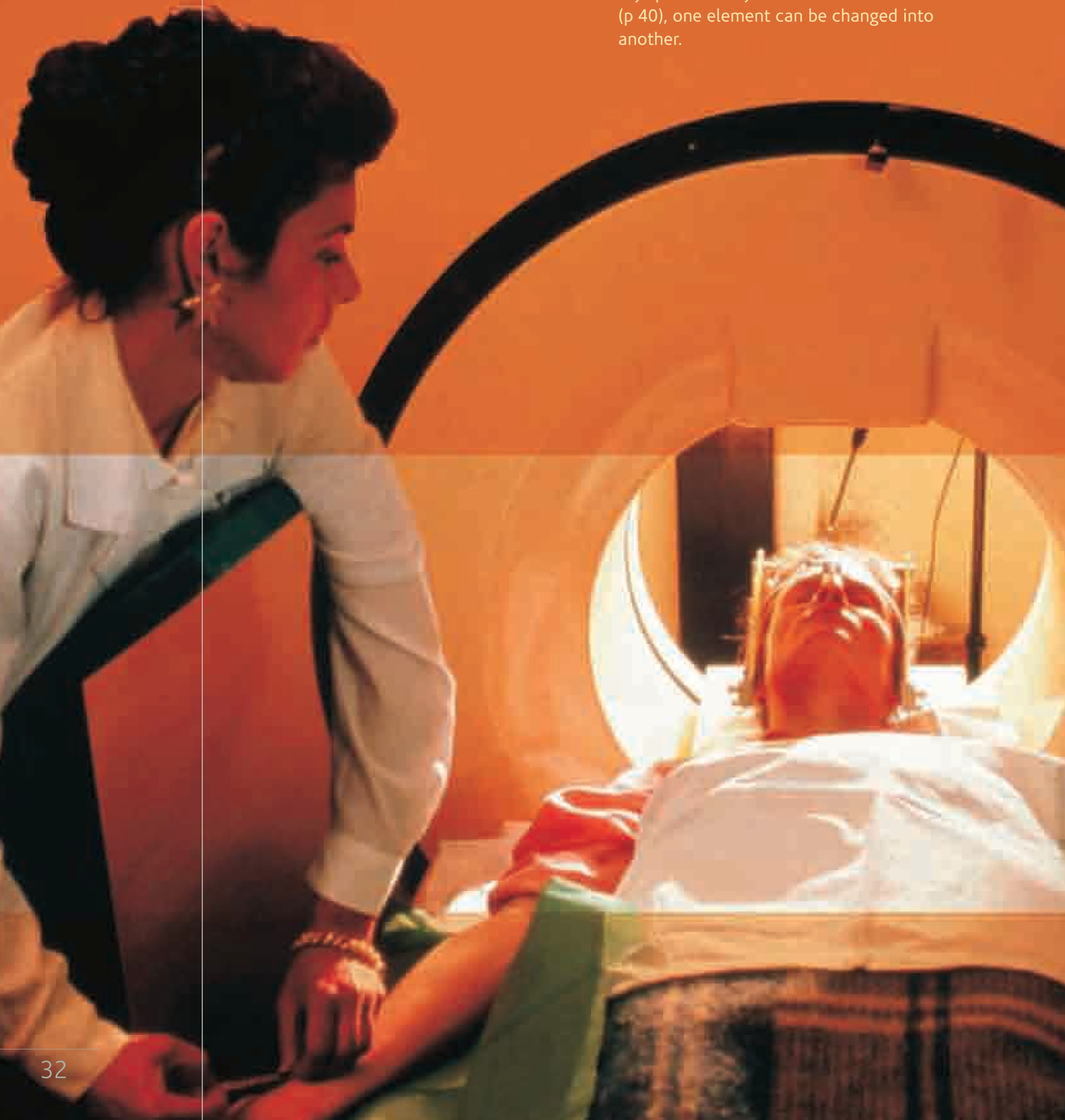


onto aeroplanes might not be necessary if suspect containers could be analysed chemically on the spot with a hand-held laser probe. Tests have shown that SORS can detect hydrogen peroxide – a constituent of home-made explosives used by terrorists – even when concealed in a typical plastic cosmetics jar. SORS also has the advantage that it works in the presence of water – unlike the similar technique of infrared spectroscopy in which the signal from water absorption completely dominates the spectrum.
A more commercial use is as a quality-control tool in pharmaceutical production. SORS, when used in transmission mode (the light is collected from the other side of a sample) is effective in monitoring the chemical purity of tablets and capsules quickly and accurately. The technology should be inexpensive and more sensitive than other competing techniques. It could also be adapted to testing foodstuffs, paints and other everyday materials.

SORS is also capable of characterising living tissue safely. The research team has two major programmes to develop the technique as a clinical diagnostic tool. One is in collaboration with University College London to detect bone disease through soft tissue, and the other, with Gloucestershire Royal Hospital, to diagnose breast cancer by looking for signs of calcification of breast tissue.

The SORS technique has been developed in close collaboration with STFC's technology transfer arm, STFC Innovations Ltd, and is being commercialised through the spin-out company Cobalt Light Systems.

Transmutation, the changing of one element into another, was the dream of the ancient alchemists. In today's laboratories, it is now possible to use ultra intense lasers to achieve transmutation in reality. By bombarding the nucleus of an atom with highly energetic laser-accelerated ions (p 34), or with gamma rays produced by laser accelerated electrons (p 40), one element can be changed into another.



Transmutation

the alchemists' dream

Laser-accelerated ions make precious medical isotopes

The underlying process was discovered over a hundred years ago, but it is only in the last few years that high power lasers capable of generating the necessary conditions have become available. The definitive transmutation – that of lead into gold – is technically viable but, unfortunately, the costs far outweigh the gains. However, the production of precious radioisotopes, vital for medical use, is possible and this is being investigated.

When the energy contained in a high power laser pulse is concentrated into a sub-millimetre sized spot it can heat the material to many millions of degrees, forming the fourth state of matter, a plasma. Within the plasma, the hottest electrons, travelling at close to the speed of light, try to escape and as they do so they generate huge electric fields, larger than anywhere else on earth. The much heavier ions in the plasma are accelerated by these electric fields and bursts of them escape the plasma and can then be used in a wide range of applications.

One scheme under study is to use high energy ions to generate the radioisotopes which are needed for Positron Emission Tomography (PET), a medical imaging technique which identifies regions within the body where cancerous cells are rapidly developing.

These isotopes have very short lifetimes (2 minutes for Oxygen 15, 20 minutes for Carbon 11 and 110 minutes for Fluorine 18). This is good for the patients, since the rapid disappearance minimises the amount of radiation that they are exposed to. But it causes significant problems for the suppliers. Transporting isotopes over long distances inevitably takes a long time and means that most of the sample decays before it is eventually injected. Laser driven particle sources can be very effective in producing high concentrations of isotopes. As the technology matures, compact laser-based systems may become the technology of choice for generating the medical isotopes close to where they are needed in hospitals.

A consortium of scientists from Queen's University Belfast, the University of Strathclyde and Imperial College London are carrying out an experimental campaign to study ion acceleration using the CLF's Astra Gemini laser. This newly commissioned system, which can deliver laser pulses of ultra high power much more rapidly than its predecessors, enables new regimes of laser-matter interactions to be studied. The experimenters are examining ways to optimise this new source of energetic particles and are considering how to develop it for real-world applications.

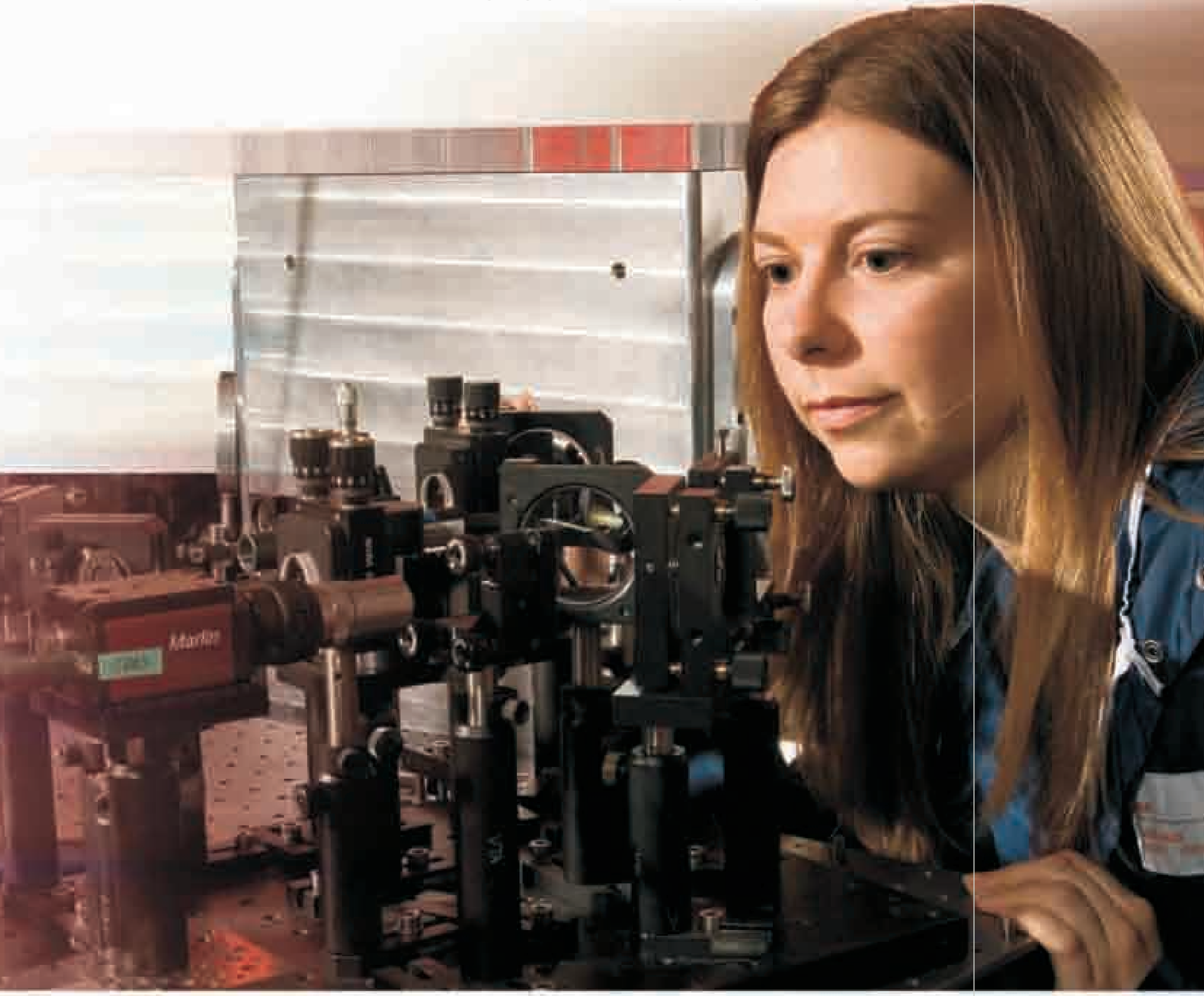
EPSRC
Engineering and Physical Sciences Research Council

Laser-accelerated particle beams potentially provide a cheaper means of treating inaccessible tumours

New technologies for cancer therapy

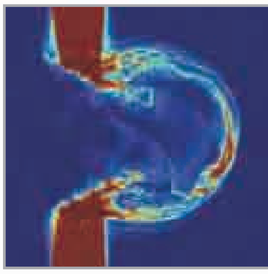
Machines that accelerate subatomic particles to high energies have a wide variety of applications including the treatment of cancer. Accelerated beams of ions – atoms with their electrons removed – can penetrate the body to reach and kill a target tumour without damaging the surrounding tissue. Today, precisely-tailored beams of protons (hydrogen ions) and carbon ions are increasingly being employed to irradiate deep-seated, inoperable cancers or those in critical organs such as the eye or brain.

Conventional accelerators are large and expensive, however, so this type of very effective therapy is far from universally available. There is great interest, therefore, in developing cheaper, more compact devices. High-power lasers, which now exist in table-top form, offer great potential for producing and accelerating ions to high energies in a limited amount of space. The process being studied at the CLF involves firing the laser obliquely at a thin metal or plastic foil target, a few micrometres thick, to create a plasma of negative electrons and positive ions. The laser pulse actually blows the highly energetic electrons through the foil, and the resulting charge separation creates a powerful electrostatic field at the rear surface of the foil. This ionises any water or organic material present on the surface, to generate both high energy protons and heavier ions, which are then emitted from the rear. Both proton and ion beams have been generated, though to obtain pure ion beams, any hydrogen-containing contaminants must first be ‘boiled’ off by heating.



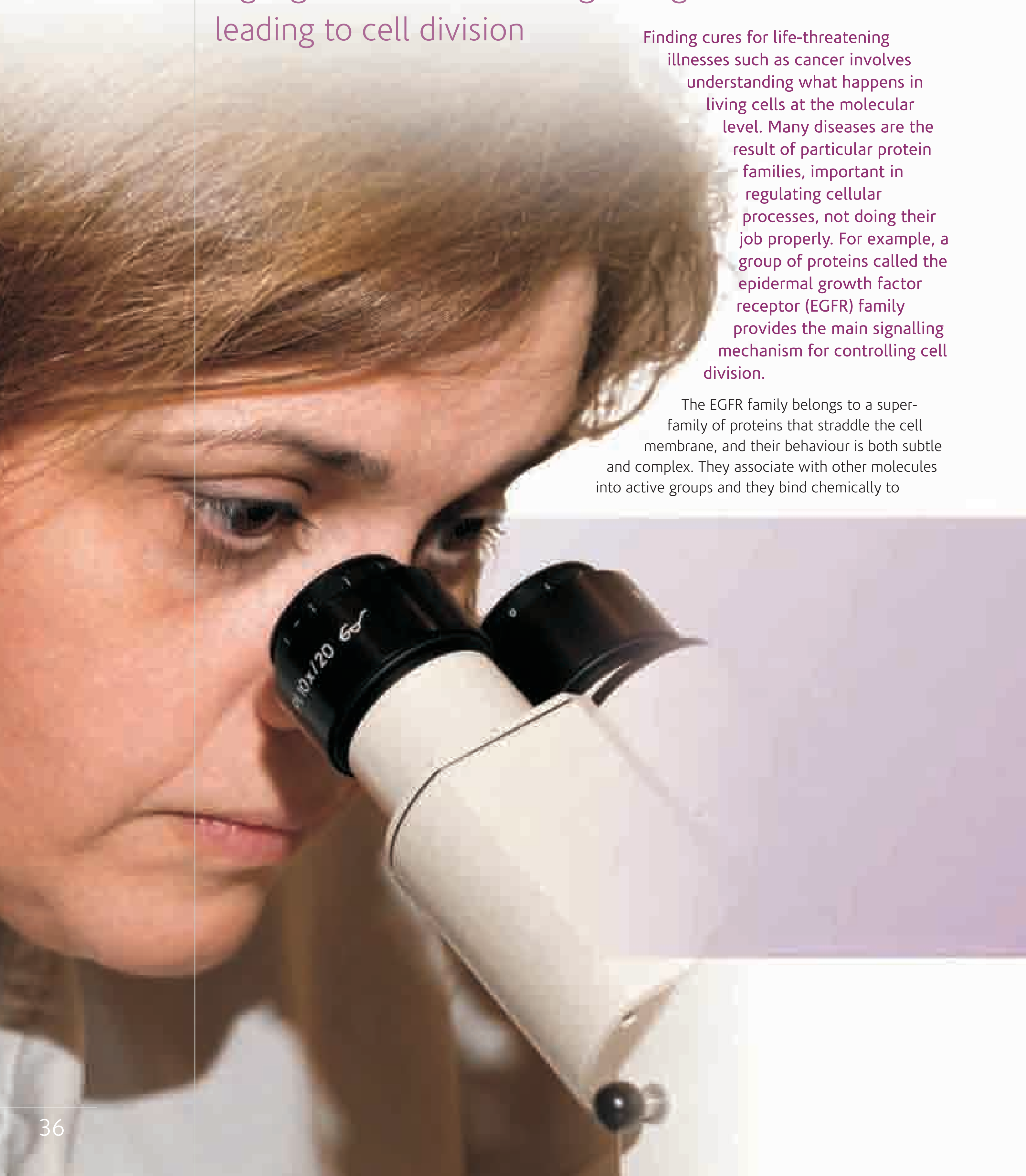
Ion therapy is not the only application of such laser acceleration schemes; in nuclear physics experiments, high energy ion beams provide the projectiles used to induce nuclear reactions when they are fired at a target. In one version of laser-induced nuclear fusion for energy generation, also being studied at the CLF (p 10), protons released by the laser pulse offer a way to 'ignite' the plasma of hydrogen isotopes already compressed to high densities. Proton and ion beams could also be employed to make radioactive isotopes for medical and biological applications (p 32) and perhaps even to transmute radioactive waste into harmless materials.

Although the approach is showing a great deal of promise there are problems to solve before laser-accelerated ion beams become a practical technology. Researchers at the University of Strathclyde, Queen's University Belfast and the CLF have been exploring how to make tight beams with a narrow range of energies – by controlling the target shape, for instance, or using multiple laser pulses.



An alternative acceleration mechanism is also being explored by the Belfast team, which is more technically challenging but could produce beams with a narrower energy spread. This is based on the same concept as the 'solar sails' which may one day propel interstellar spaceships using the pressure exerted by sunlight. The radiation pressure from an extremely intense laser pulse would be very high – tens or hundreds of billions of atmospheres. The principle is that the whole target foil, ions included, would be pushed forward at speeds close to that of light. Computer simulations show that this approach works and an experimental programme to develop it is now under way using the CLF Astra Gemini laser system.

A development in single-molecule laser microscopy highlights the molecular signalling mechanism leading to cell division



Finding cures for life-threatening illnesses such as cancer involves understanding what happens in living cells at the molecular level. Many diseases are the result of particular protein families, important in regulating cellular processes, not doing their job properly. For example, a group of proteins called the epidermal growth factor receptor (EGFR) family provides the main signalling mechanism for controlling cell division.

The EGFR family belongs to a super-family of proteins that straddle the cell membrane, and their behaviour is both subtle and complex. They associate with other molecules into active groups and they bind chemically to messenger molecules in processes involving the concerted and intricate manoeuvring of different parts of these groups. A small mutation in EGFR can result in the protein working too hard, with the result that the cell carries on dividing, leading to cancer. Drugs like Herceptin are designed to block the action of a particular EGFR family member, so understanding how structural differences between cancer and normal cells change the dynamics of signalling is of vital importance.

To unravel the details, biologists rely on a range of analytical tools. One of these is fluorescence microscopy, in which a selected molecule or part of a molecule is 'labelled' with a dye that fluoresces when exposed to laser light (a fluorophore), thus revealing its location and behaviour in a sample. Individual membrane proteins can be highlighted by trapping the laser light, using total internal reflection, in a thin layer in the sample a few hundred nanometres thick – for example, the cell surface. Highly sophisticated variations of this principle have been developed which allow researchers to probe single-molecule interactions and molecular shape changes in a living cell.

Total internal reflection microscopy can be combined with other fluorescence detection techniques. One, called spFRET, involves labelling two different parts of a target molecule or group of molecules with different fluorophores then exciting one with a laser and watching the other fluoresce. The strength of the fluorescence depends on the distance between them, and can be used to measure this distance with just a few nanometres' resolution. Another technique – smFP – uses the polarisation of the fluorescence (the orientation of the light waves) to yield information about the orientation of the labelled molecules. The separation and orientation information are independently valuable, but in combination they reveal much more than they do individually.

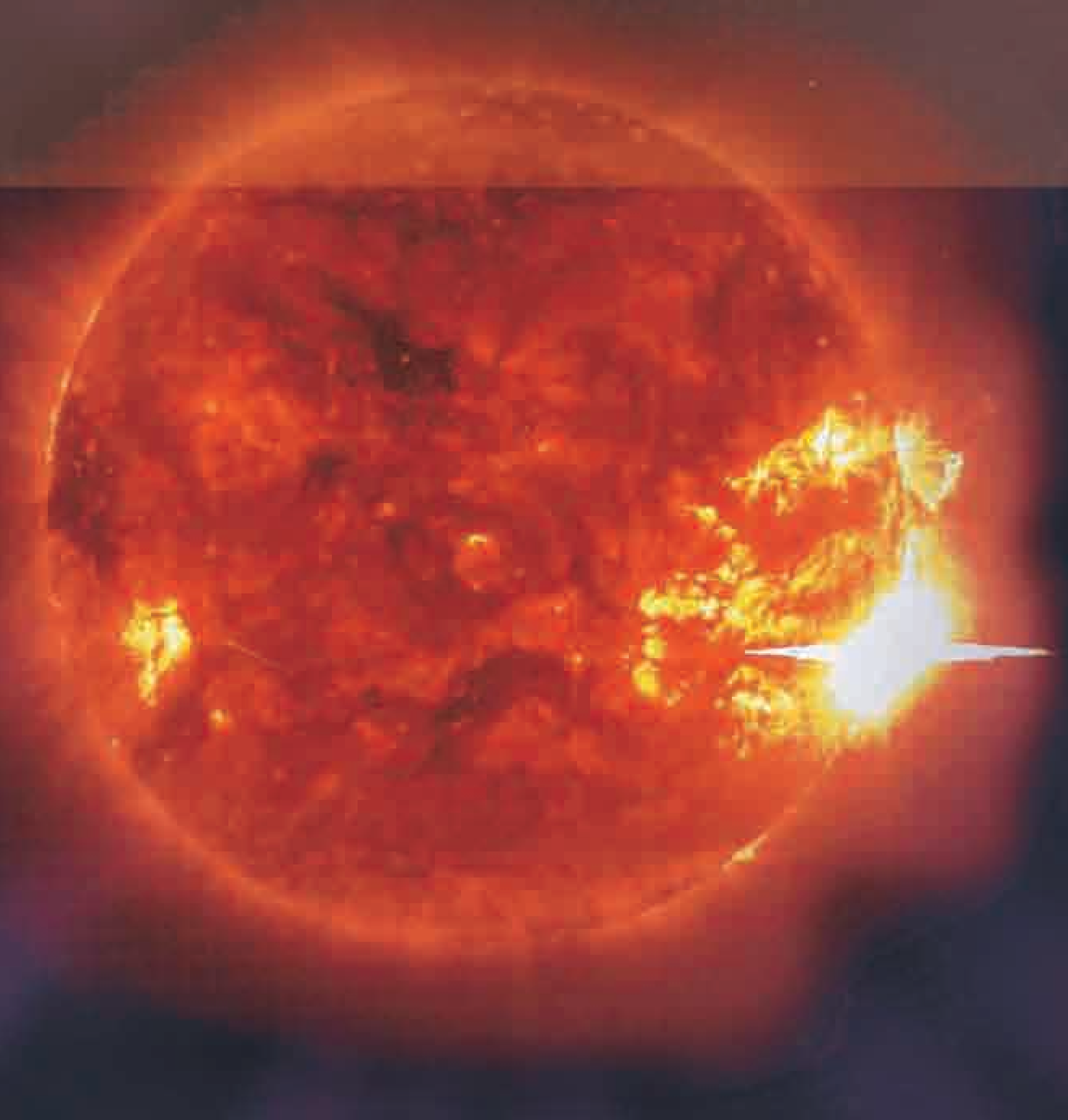
Researchers from the CLF's Lasers for Science Facility have applied these combined techniques to study the action of EGFR in live cells. By developing a new microscope system in which the sample is illuminated with polarised light (light waves all oriented in the same direction), they have been able to study the positions of the various EGFR components and their orientations. The team collected a series of images over time which, when combined with computer simulations carried out at the STFC Daresbury Laboratory, allowed them to suggest how the proteins move and reorientate themselves in three dimensions during the signalling process. These new results throw light on whether the signalling is indeed different in normal and cancer cells.

A new tool
in the fight against cancer

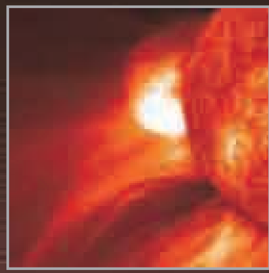


Secrets of sunshine

Laser measurements of plasmas simulating the Sun's interior are providing insights into solar radiation output and its subsequent impact on Earth



NASA/JPL-Caltech/Hubble Heritage Team



Life on Earth is dependent on the outpouring of radiation from our nearest star, the Sun. Variations in solar activity, as marked by sunspot numbers for example, affect climate and global temperatures.

Probing the complex internal processes that make the Sun shine presents a major challenge. The energy is produced by nuclear reactions in the Sun's core and is transported outwards as photons of light. However, the photons are absorbed and re-emitted many times by the plasma of ionised atoms in the so-called radiative zone around the core, so that the radiation struggles only very slowly towards the solar surface. Solar physicists have computer models of this radiative diffusion behaviour which characterises the plasma's 'opacity', although the calculations are extremely complicated because of the intricate patterns of atomic absorption and emission involved.

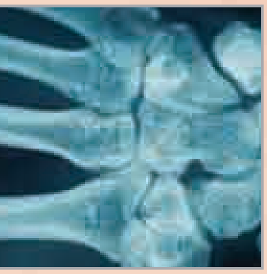
Laser-produced plasmas offer a method of testing the models by measuring this opacity directly, and this is what the University of York team has done at the CLF. In the experiment, the Vulcan laser was used to generate a soft-X-ray laser source at 13.9 nanometres wavelength. At the same time, Vulcan also created a dense iron plasma by heating a very thin target of iron, buried in plastic layers to prevent ablation, to about a million degrees. Iron is of particular importance because it is the heaviest of the more common elements found in the Sun and other stars, and has the highest opacity. The soft X-rays, which represented the solar radiation, then passed through the iron plasma. Because the X-ray beam is very much brighter than the light emitted by the plasma itself, its transmission – and thus the plasma opacity – can be measured. This was the first time that the opacity of iron had been measured in this way, and it will help to 'benchmark' the computer calculations in stellar models. Further experiments are planned using the CLF's short-pulse lasers, with the aim of probing the opacity of plasmas at higher temperatures, which is relevant to conditions in the important boundary region between the radiative and outer convection zones of the Sun.

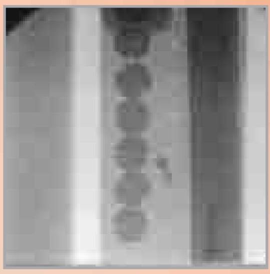
Opacity measurements on hot plasmas have cosmological relevance. Stars called Cepheid variables are used as 'standard candles' to measure the distance to astronomical objects. Their luminosity varies in an exact way, and this depends on the opacity of the star's plasma material. Measurements based on Cepheid luminosities have been important in establishing the Hubble constant, which determines the rate at which the Universe is expanding and therefore its age. Limited opacity measurements on cool plasmas have already led to a revision of the Hubble constant by showing that previous stellar opacity models were too simple.

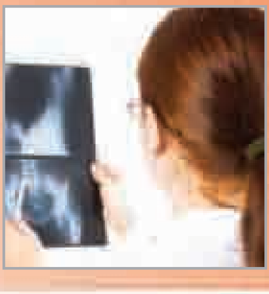
Plasma opacity measurements under well-defined conditions are needed for many important applications including a variation of inertial confinement fusion (p 10) called indirect drive ignition. The fuel pellet is placed inside a small, thin cylinder made of gold or lead. These heavy metals convert the driver beams into X-rays, which then compress the fuel in a very symmetrical way to cause fusion. The plasma opacity properties of the cylinder and the pellet are important because they control the radiation absorption and thus the rate of compression.

Laser-accelerated electron beams could provide a compact source of X-rays for materials and biomedical research

X-rays on a table top







Many of the major advances in the life sciences, as well as in chemistry and electronics, have come from the X-ray analysis of materials. The brightest X-ray sources, like the Diamond Light Source, are kilometre sized, ring-shaped particle accelerators which rely on radio-frequency electric fields and strong magnets to transport beams of electrons around them.

The electrons radiate energy, mostly as X-rays, as their paths bend. The X-rays are then diverted to experimental areas. Such large machines are very effective but they are also expensive and access can be inconvenient.

In the past decade, however, researchers working with high-power lasers such as those at the CLF have been looking at alternative methods of generating brilliant X-rays on a smaller, cheaper scale. Intense, ultra-short laser pulses impinging on a material such as helium gas will turn it into a plasma – a mix of electrically charged ions and electrons. The pressure of the laser pulse generates compressive waves in its wake, which separate the ions and electrons, creating oscillating electric fields many thousands of times greater than would be possible with a conventional radio-frequency system. The electrons surf the plasma waves, reaching very high energies in the space of just a few centimetres. In doing so, they can also generate coherent X-rays as they move up and down – an effect that can be enhanced further with external magnetic fields. Since the laser light comes in pulses, the electrons are accelerated in tight bunches and the resulting X-rays are emitted in bursts only a few femtoseconds (millionths of billionths of a second) long. Extremely short intense X-ray pulses produced in this way would be invaluable for many applications including studying fast chemical reactions and biological processes.

For the concept to be turned into a practical device a

number of difficulties need to be overcome. In particular, the energies of the electrons, which tend to spread out, must be controlled, as must the physical divergence of the electron beam. And to create dense bunches of monoenergetic electrons accelerated to high energies requires a reasonably long interaction length in the plasma. UK researchers working at the CLF have been addressing these problems in two ways. In one research programme the laser is focused into a jet of gas and ionises it to a plasma, the density of which is varied by altering the gas pressure. At a critical density the electrons break free from the plasma wave which has confined their motion, allowing them all to move with the same energy and in the same direction.

Another approach being investigated is to contain the ionised gas in a narrow-bore capillary. Heat conduction causes the plasma to be cooler and more dense at the walls of the capillary than in the centre. The plasma therefore acts as a lens, continually focusing the laser pulse as it travels down the capillary and so lengthening its interaction with the plasma. CLF experiments have already reached electron energies of half a giga-electron volt (a thousand, million electron volts), which are comparable with those generated in large-scale conventional electron accelerators.

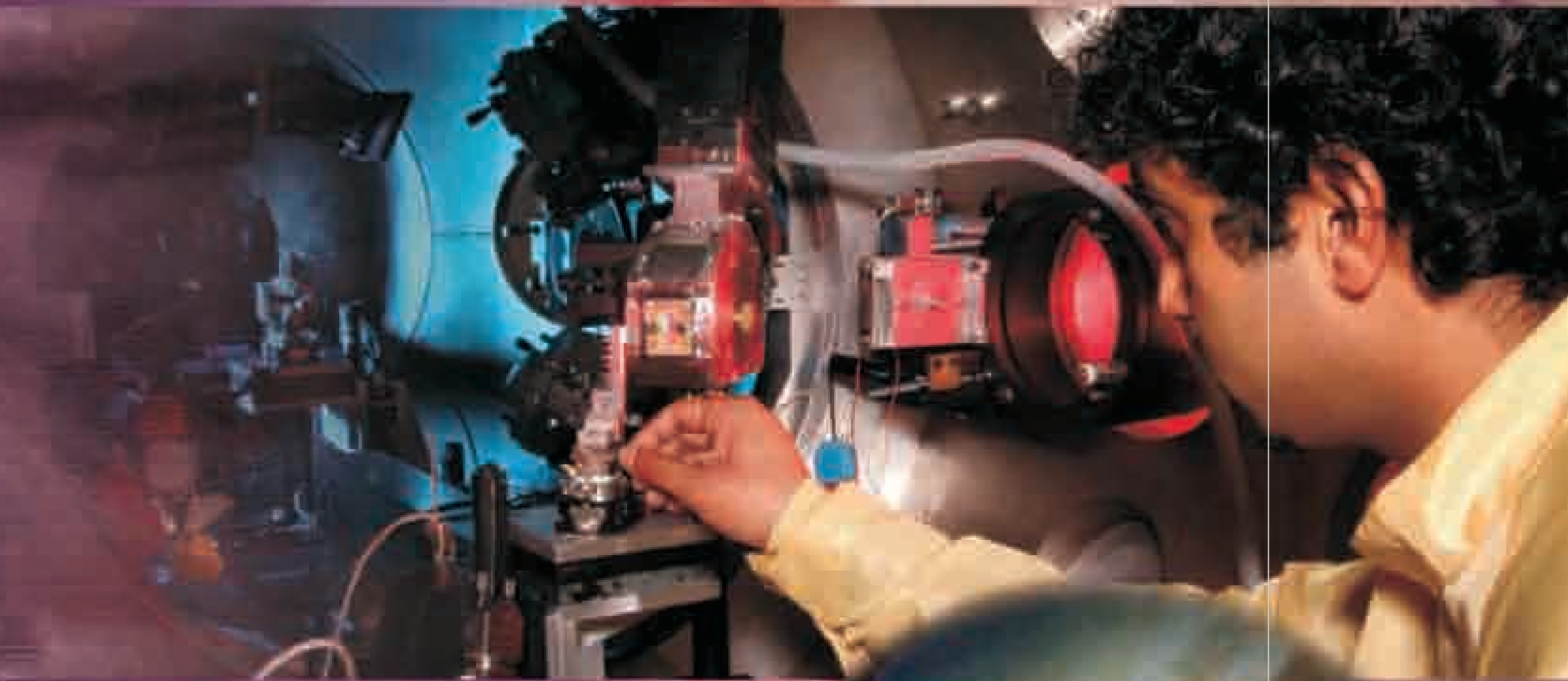
X-rays reveal the nature of a type of exotic matter found in stars and giant planets

Journey to the centre of Jupiter

Matter can exist in a wide range of physical states, from the incredibly hot dense plasma that comprised the Universe just after the Big Bang to the cold, tenuous gas now found in remote interstellar space. Between these two extremes lie many states, at different pressures and temperatures, in objects such as nebulae, stars and planets. We understand well how solids, gases and liquids – the everyday 'phases' of matter – behave under the conditions found on the earth's surface. But studying more extreme states can be both theoretically and experimentally demanding.

One type of extreme matter presents a particular challenge, and that is the phase found at the centre of gas giants like Jupiter and Saturn, on the crusts of dead stars (white dwarfs and neutron stars), and in stillborn stars whose nuclear fires were never ignited (brown dwarfs). Consisting usually of light-weight atoms, it is characterised as very dense but only moderately 'warm' – that is, with a temperature of a few tens of thousands of degrees. In these conditions, the material is half-way between a solid, in which all the atoms are arranged in an orderly manner, and a plasma, where the atoms have separated into fast-moving ions and electrons. The electrons interact in a complicated way because their energy of motion is very close to the energy needed to bind them to the ions. This means that neither the usual quantum theory of plasma behaviour nor that of solids can describe the situation adequately. Warm dense matter is regarded as a state in which the electrons and ions couple more strongly than in a very hot plasma, but not over long distances as in a cooler, non-ionised solid. It means that many properties, for example how radiation is transported, will be different.

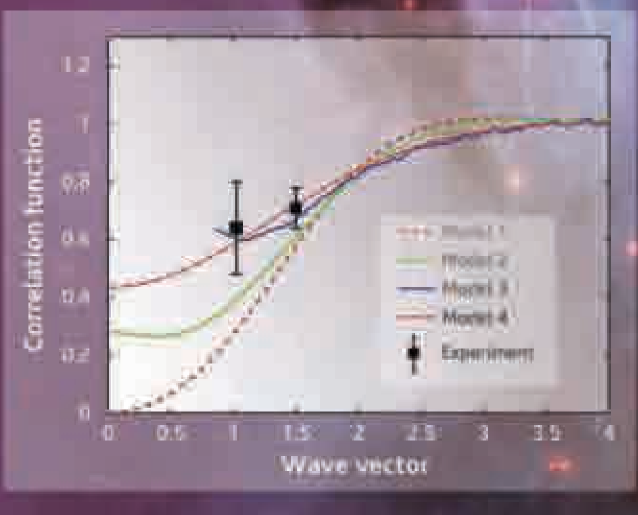
Researchers at the University of Oxford and Queen's University Belfast have been using the Vulcan multi-beam laser to create warm dense matter and probe it with X-rays. This is difficult because this phase is rather opaque to X-rays, which are scattered by the particles in a complex way depending on how they are moving and interacting with each other. A pulse of laser light, or laser-accelerated protons (p 34), is used to warm up and compress a sample of



a light metal such as lithium. A second laser pulse is fired into a plastic foil to produce a very hot plasma that emits X-rays, which then pass into the lithium. The scattered X-rays are measured at various angles and energies to obtain information about structure and energy exchange in the sample. The data from the experiments are then used to test theoretical models of warm dense matter. They show that the theories that work best are those which take into account short-range forces between the ions as well as longer-range electron-ion interactions.

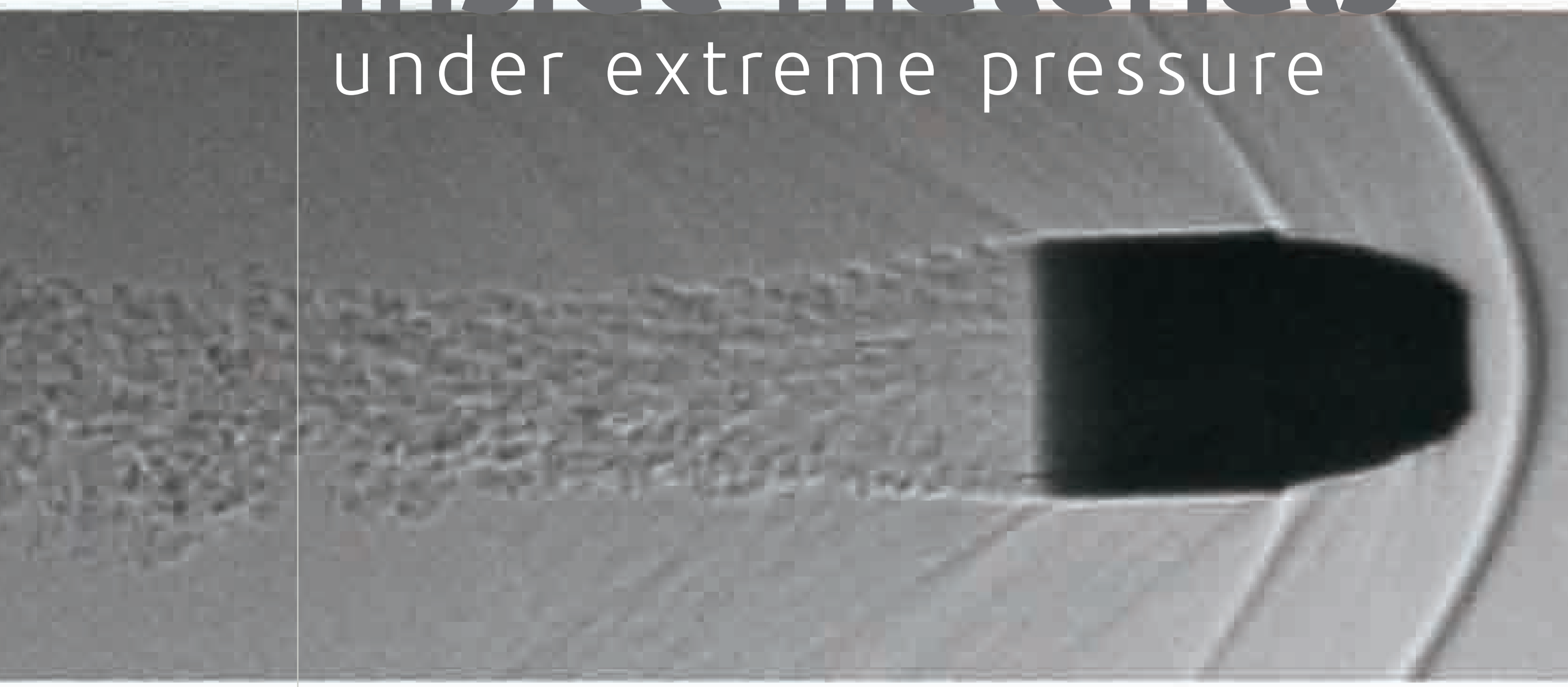
The results not only help scientists to understand processes in the outer layers of stars and in planetary cores, but also the early stages of X-ray driven implosion in inertially confined fusion (p 38).

NASA/JPL-Caltech/Hubble Heritage Team



Laser studies reveal the fast-moving structural changes in a solid when a shock wave hits it

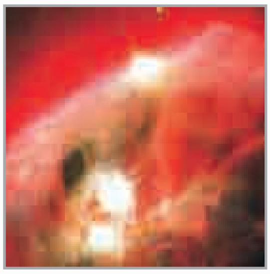
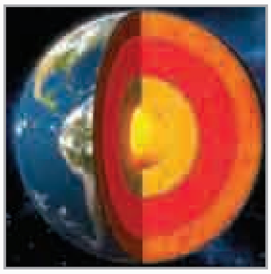
Inside materials under extreme pressure

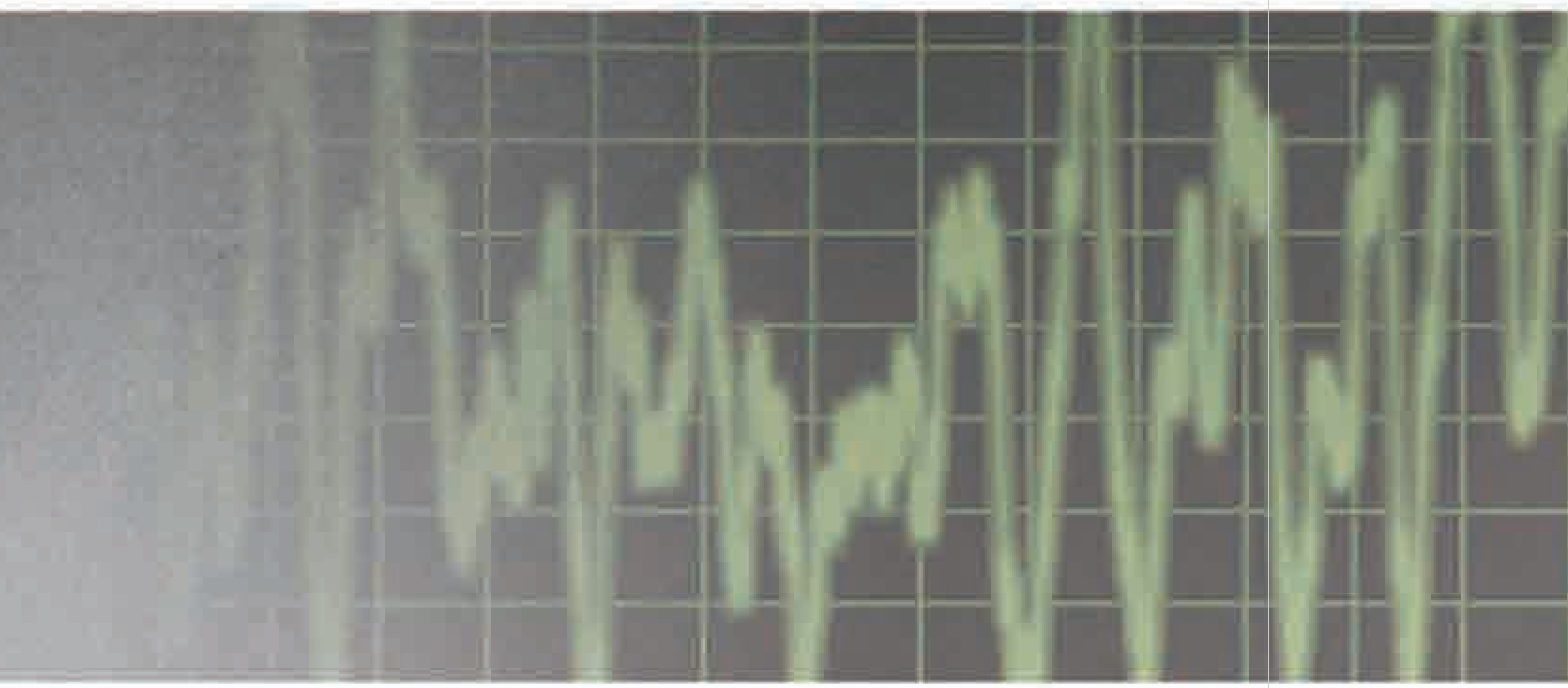


When the pulse from a high-power laser strikes a material it creates a huge, abrupt pressure gradient – a shock wave – which travels through it. The shock can generate a compression of several billion atmospheres, providing an experimental way of studying structural changes under the extreme conditions experienced in explosions, or when high-velocity objects collide, or bullets hit armour, or meteorites impact on the ground.

Laser compression, combined with simultaneous X-ray analysis, lets researchers study materials under conditions and on timescales not reachable in any other way. In a typical experiment, a multi-beam laser such as Vulcan delivers a nanosecond pulse which sends a compressive shock wave through, say, a crystalline metal like copper. At the same time, a shorter pulse is used to create a plasma which emits intense, picosecond X-ray pulses. When the X-rays pass through the sample, they are diffracted by the copper atoms and come out in a characteristic pattern that reveals the structure at the atomic level. By changing the X-ray timing and collecting the patterns, researchers can follow changes in the crystal structure as the shock wave moves through the solid.

What do they see? In a crystal, the atoms are arranged in a lattice, whose geometry partly depends on temperature and pressure. The shock wave pushes the atoms out of position causing dislocations in the lattice, and the material can 'flow' like a warm

plastic. In some cases, it may undergo a phase transition from one crystalline arrangement to another. After the shock has passed, the crystal often relaxes back to its normal state. So experiments have to take rapid snapshots to catch the changes before they reverse. A few years ago, researchers at the University of Oxford studied some puzzling behaviour in iron. In the 1950s, American physicists had noted that a compressive shock in iron travelled as two waves, rather than just one. This suggested that a new unknown crystal phase was forming under the sudden increased pressure, although it disappeared when the material recovered. Theorists thought that such a phase-change in a solid could not possibly happen so quickly, and it remained a subject of debate for many years. The advent of high-power lasers, coupled with fast X-ray diffraction, meant that crystal structure could be observed in real time. And experiments at the CLF and elsewhere confirmed that iron did undergo a phase transition when shocked.

Such observations are combined with computer simulations that calculate the simultaneous motions of millions of shocked molecules. The data then help materials scientists to understand better the behaviour of solids under extreme pressure including, for example, those used in inertial confinement fusion (p 10). The experimental results from the study of iron agree remarkably well with the computed behaviour.

The Oxford group plan to extend their studies to materials that are compressed a little more slowly, over a few nanoseconds, so that they do not get hot enough to melt, but remain solid at pressures of tens of millions of atmospheres. This would allow them to access totally novel states of matter that do not exist on Earth but might exist in the rocky cores of giant planets.

Laser experiments are providing clues to the beautiful but mysterious jets that are the signatures of the Universe's most violent events

Stellar fireworks

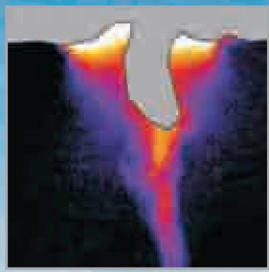
in the laboratory

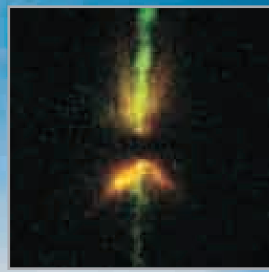
Stars are born and die violently. When dust and gases in nebulae clump together to form new stars, they spew out vast jets of plasma into space. These fast-moving outflows, which are very narrow and extend a great distance, are also seen in ageing, shrinking stars that have puffed up their outer layers of gases. They appear when the heaviest stars explode and collapse into black holes. In short, plasma jets seem to be a universal phenomenon, happening over a range of scales. The most spectacular ones emanate from the centres of distant, active galaxies which contain a supermassive black hole.

Astrophysicists do not fully understand why and how these jets form. One way of finding out more is to simulate the plasma flows in a laboratory experiment. The idea is the same as testing a model plane in a wind tunnel, on the basis that it will behave just like the real one that you board at the airport. The high-power lasers at the CLF can generate plasmas in conditions similar to those found in space. A key question, however, is whether a laser-produced plasma jet, which shoots out just a few millimetres and lasts only a few nanoseconds, is really relevant to colossal stellar objects light-years across and lasting for thousands of years.

To test whether this extreme comparison is valid, researchers have been creating plasma jets under different conditions, with the aim of comparing the results with astronomical observations. An international team working at the CLF has been generating the jets by colliding two laser-produced plasmas (see box). The experiments, so far, have shown that the processes are indeed similar – what's happening in one is also what's happening in the other. Or, to put it another way, our 'wind tunnel models' really do work the same way as the 'jumbo jets'. Having confirmed this it will now be possible to adjust conditions in the laboratory to learn what shapes, for example, the outflows from newly-forming stars.

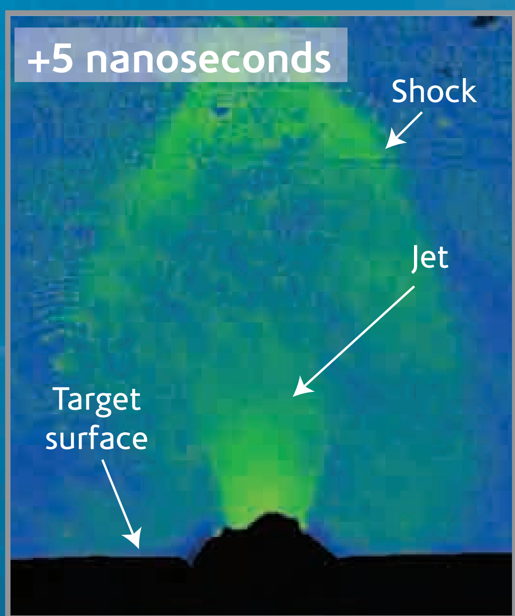
These experiments are part of an ongoing programme to study plasmas under astrophysically relevant conditions. in this way, astronomers will gain a better understanding of many of the violent, high-energy processes that govern the Universe – including those producing cosmic rays, whose origin is yet another a mystery.





The experiments

Two thin foils were placed in a V-shape and laser pulses from Vulcan irradiated them on the V's outside surfaces. Plasmas appearing on the inside surfaces then collided to create a plasma jet which was analysed with probe laser pulses. The thickness and material of the foil, together with the angle between the foils and the pulse characteristics, were varied to find the optimum conditions for jet production. The jets moved at an incredible 300 kilometres a second. To simulate the tenuous gas between the stars, small amounts of nitrogen were introduced into the experimental chamber. This narrowed the jets, and caused shock structures to form at their leading edge, where it collided with the gas. These results shed light on the role of the interstellar medium in controlling the detailed shape of the jets.



Making matter
out of light

Experiments with the Astra Gemini laser are being designed to probe the very fabric of reality – by creating particles from the quantum vacuum

Most people are familiar with Einstein's famous equation $E = Mc^2$, which so neatly encapsulates the equivalence of matter (M) and energy (E), with c being the speed of light. Indeed, matter can be converted into energy, as happens when particles such as electrons meet their antimatter partners, positrons.

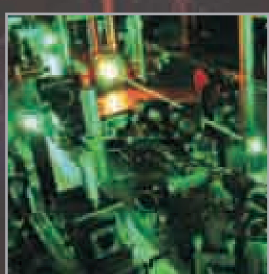
The particle pairs annihilate with the emission of very high-energy light – gamma rays. This is the basis of positron emission tomography, PET, which is regularly used for medical imaging. But can the reverse process happen? Can particle pairs be made from light?

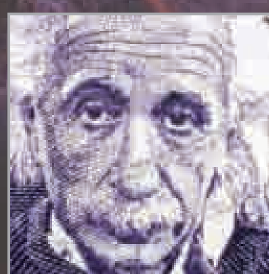
Astrophysicists believe that pair production was the main process for creating matter in the primordial universe, and that it also still happens, for example when supermassive stars collapse to form black holes. However, spontaneous pair production from intense low-energy light has never been seen. But researchers are now planning to use CLF lasers to see if they can observe the phenomenon in the laboratory for the first time. To work out how to do it involves a deep understanding of quantum physics – in particular, quantum electrodynamics (QED) which describes the interaction between light and charged particles like electrons. This immensely successful theory regards empty space – the vacuum – as actually seething with 'virtual' particles that pop in and out of existence. It predicts that if sufficiently intense light can be generated then its powerful electric field will destabilise the vacuum and cause the virtual particles to become real – emerging like bubbles in a boiling liquid.

So just how much light might be needed? Theorists predict that we will have to reach unbelievable levels of brilliance – 10^{33} watts per square metre – equivalent to focusing all of the sunlight which hits the earth onto the tip of a very sharp needle. There is a strong chance that some pair production could be seen at intensities perhaps hundreds or thousands of times lower than this. These could be reached by colliding the beams from the twin Astra Gemini lasers close to a curved solid surface. The focused beams would interfere to create a standing wave with intensity peaks bright enough to produce electron-positron pairs. Another approach to achieving extreme intensities is through high harmonic generation (p 50). Once created, the electron-positron pairs can be detected through the gamma rays they emit when they annihilate.

Such experiments using intense, low-energy light to 'boil up' the vacuum create a new physical state that is unknown on Earth, and possibly in the entire Universe. The results will help theorists test the validity of QED in this exotic regime. One prediction is that the intense light field will electrically polarise the vacuum so causing the speed of light to become dependent on its polarisation – so-called vacuum birefringence. This effect would appear at slightly lower intensities so would be easier to observe. It could be crucial to our deeper understanding of the building blocks of the universe – the fundamental forces and particles. Some versions of string theory (which attempts to provide a unified description of the forces) do not allow vacuum birefringence, so these theories will be ruled out if it is seen.

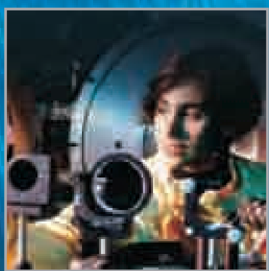
Whatever the experimental results, they will give us new insights into the nature of the vacuum – the medium that underpins our notions of reality in terms of matter, energy and space. They may even lead to efforts to manipulate the vacuum, as speculated on by some quantum physicists and so often depicted in science fiction!





NASA/JPL-Caltech/Hubble Heritage Team

Recent experiments have uncovered a new route to attosecond science via high harmonics from an oscillating plasma

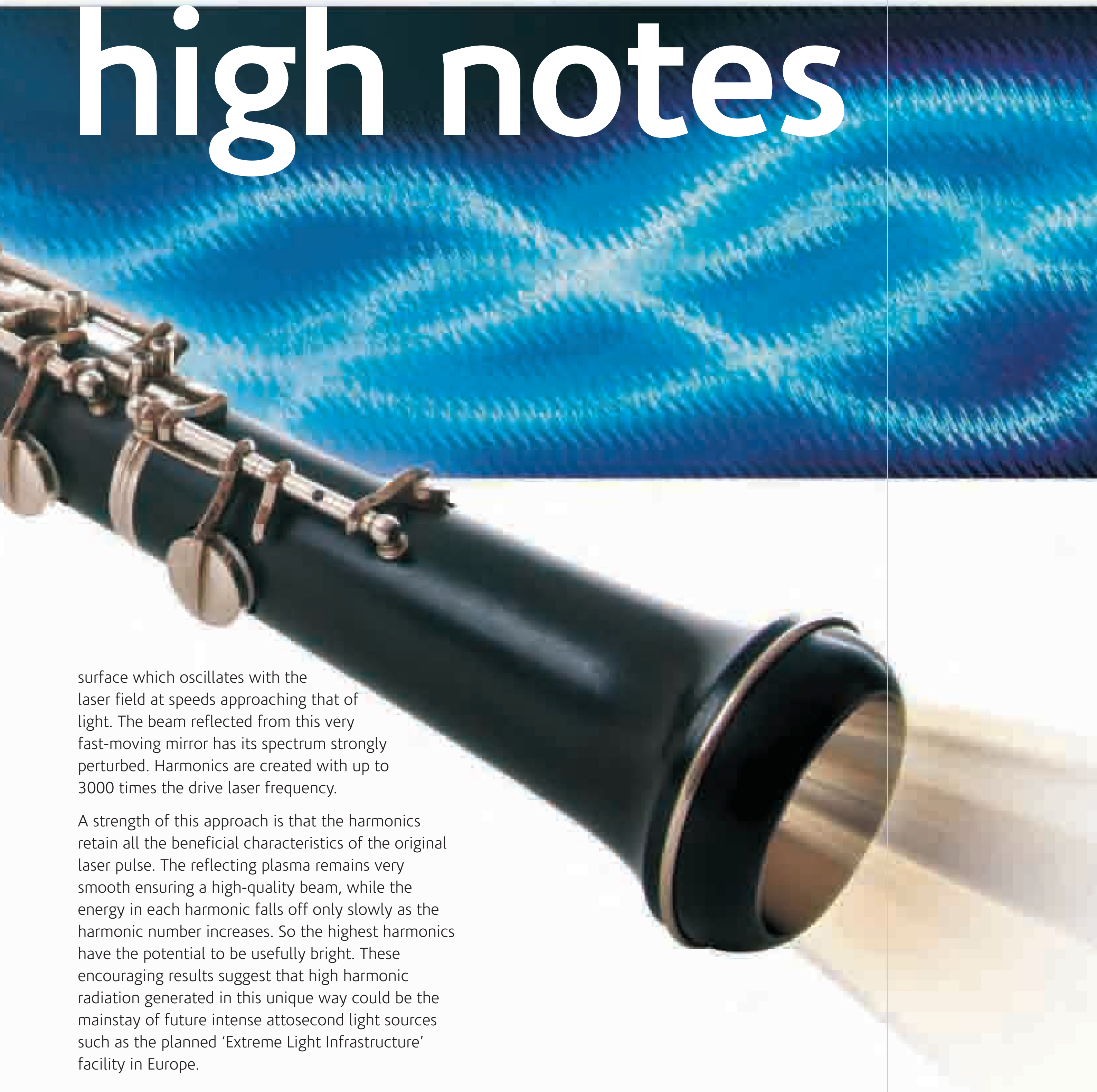


Blowing softly through a wind instrument like a recorder produces a sound with a particular frequency, the base note. Blow very hard, and the note will be one octave higher – a multiple of the base frequency, or harmonic. Physicists are keen to exploit the same principle to create high-frequency light – in the extreme ultraviolet and X-ray region – from more accessible, lower-frequency light sources. Depending on how they are generated, harmonics can extend to very high multiples of the fundamental frequency. Recently, high harmonic generation in the X-ray regime was successfully demonstrated in experiments at the CLF. Using either the Vulcan Petawatt or Astra facilities, ultra-short, infrared laser pulses were fired at a solid target to produce an oscillating plasma that generated much higher harmonics than had been achieved before.

High harmonic generation offers the exciting prospect of providing coherent radiation (all the waves moving in step) in breathtakingly short bursts in the attosecond range (one million million millionth of a second). A coherent attosecond pulsed X-ray source would open up new fields of research. For example, it could be used to freeze and capture images of subatomic processes never seen before, such as the motion of single electrons deep inside atoms. It could also be employed to follow chemical and biological reactions with unprecedented time resolution (see p 52). In industry, highly coherent X-ray beams would provide a means to carve the very accurate features needed for future computer chips and other nano-scale devices.

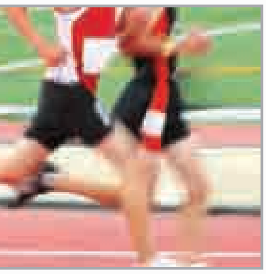
Although high harmonic generation had been studied for some years, until recently it was not clear that laser interactions with a solid target offered a viable means of realising the concept at high energy. However, with the development of very intense lasers such as Vulcan Petawatt and Astra Gemini, the situation has changed. A research team from Queen's University Belfast has carried out experiments which show that very high harmonics can be produced from flat, smooth surfaces made, for example, from hydrocarbon plastic. The focused drive laser beam produces a dense, mirror-like plasma layer on the

Lasers hit the high notes



surface which oscillates with the laser field at speeds approaching that of light. The beam reflected from this very fast-moving mirror has its spectrum strongly perturbed. Harmonics are created with up to 3000 times the drive laser frequency.

A strength of this approach is that the harmonics retain all the beneficial characteristics of the original laser pulse. The reflecting plasma remains very smooth ensuring a high-quality beam, while the energy in each harmonic falls off only slowly as the harmonic number increases. So the highest harmonics have the potential to be usefully bright. These encouraging results suggest that high harmonic radiation generated in this unique way could be the mainstay of future intense attosecond light sources such as the planned ‘Extreme Light Infrastructure’ facility in Europe.



Pictures taken with the fastest laser-based 'flash photography' may one day allow us to track changes inside the atomic nucleus

The ability of flash imaging to reveal how things really move was established in the 19th century when Eadweard Muybridge's snapshots proved that, for a short time at least, a galloping horse has all four of its hooves off the ground. Since then faster and faster exposures have allowed us to watch things changing on shorter and shorter timescales. Cameras available on the high street can freeze motion down to a millisecond. But short laser pulses have revolutionised the field with 'shutter speeds' that are a million, million times faster. Now the question is, can we go faster still?

With visible and infrared light from commercially available lasers the shortest pulses are limited to a few femtoseconds. At this point they are just a few light waves long and further reductions are impossible without shortening the wavelength. Scientists have achieved this by using the deep ultraviolet light produced in a process called 'high harmonic generation' which occurs when atoms and molecules are exposed to intense laser pulses. In another approach laser pulses can be reflected from a plasma surface which is oscillating at close to the speed of light (p 50). Again the wavelength is shortened, this time shifting the light through the ultraviolet and into the soft X-ray region of the spectrum. Over the past decade, short-wavelength techniques have pushed the temporal resolution with which we can probe motions in nature below the hundred attosecond limit.

Attosecond technology is enabling scientists to understand chemistry better by tracking the electrons in atoms and molecules on their natural timescales. However the dream of probing the motions of protons and neutrons inside the nucleus is still elusive, as these happen even more quickly – in zeptoseconds! The possibility of a zeptosecond flash might seem completely unrealistic but there are, in theory at least, ways of achieving it.

One way of generating a short pulse from a relatively slow moving system is to make use of the 'searchlight' effect, where a distant observer sees the beam flash quickly past even though the lamp itself is only rotating slowly. The light pulse is short because the searchlight beam is tight. Tight radiation beams are also produced when bunches of electrons travel along curved paths. This is the basis on which large, circular synchrotron light sources such as the Diamond facility operate. The electron bunches are small (millimetre-sized) and fast moving, so the searchlight effect results in picosecond pulses being generated. It is already well known that lasers can accelerate electron bunches in straight lines (p 40). But theory suggests that they can also spin them incredibly quickly in tiny circles if the laser beam is super-intense and circularly-polarised. Such bunches would make light beams in the X-ray part of the spectrum and the searchlight effect would then allow pulse lengths of a few zeptoseconds to be delivered.

This scheme is not the only one for producing zeptosecond pulses. There are others, but they all depend on illuminating rapidly moving electrons with the beams from very intense lasers. When such lasers were capable of just a few shots per hour (or even just a few shots per day!) zeptosecond pulses from them would still have been academically ground breaking. But now that systems like the CLF's Astra Gemini can deliver several shots per minute and ultimately many shots per second, the ultrashort pulsed beams they can yield should also open up a whole new range of practical science.

How low can

you go?

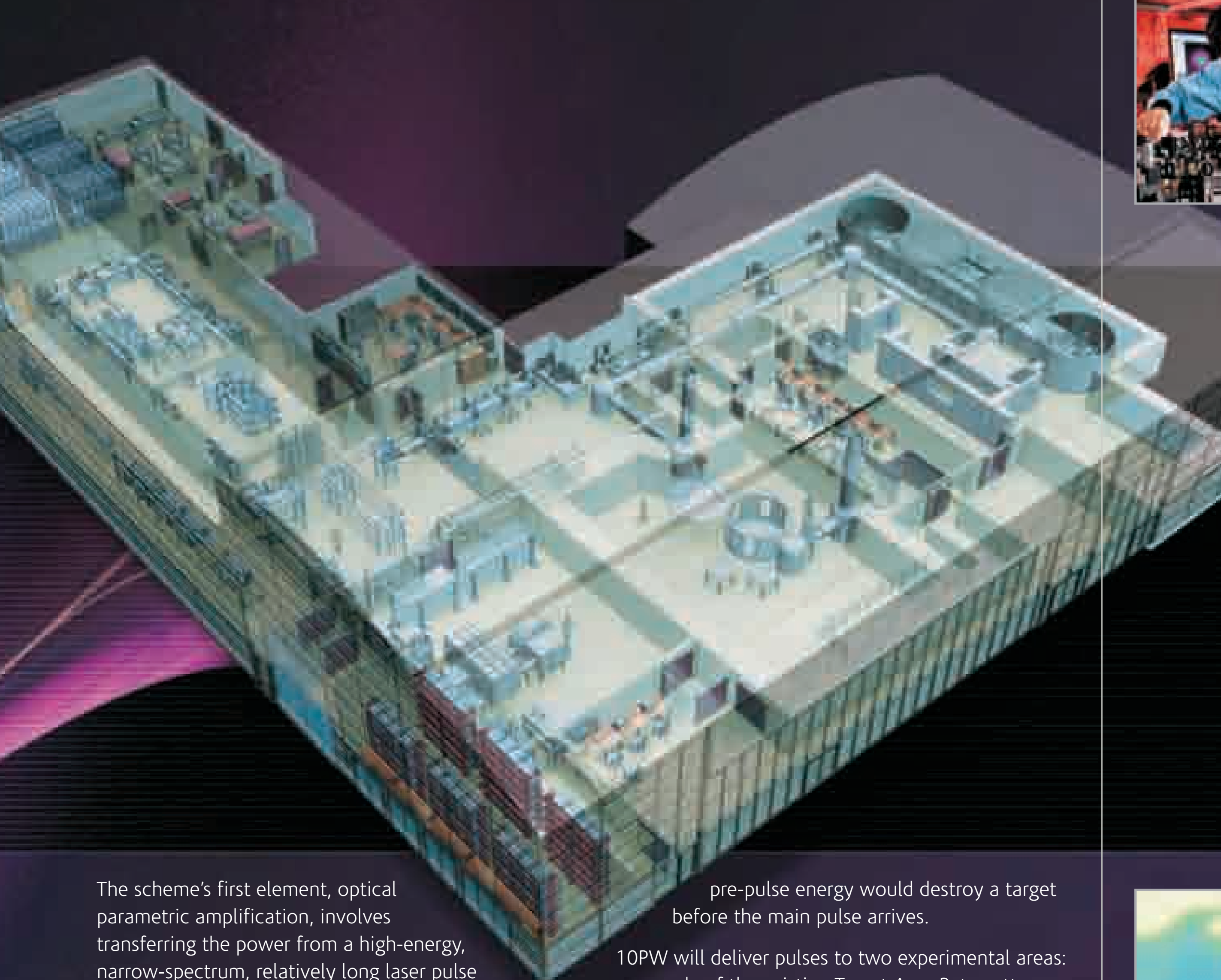
The most intense light on Earth

The CLF gears up to construct a 10 petawatt laser facility

Over the past decade, the CLF's largest laser, Vulcan (p 64), has maintained its position as one of the world's leading high-power laser facilities. Through highly innovative technology, Vulcan can now generate laser power amplified to more than 1 petawatt (1000 million million watts, or 10^{15} W). This is the equivalent of 10,000 times the UK's electricity supply, delivered in the form of fleeting pulses of light, with an unimaginable intensity of more than 1000 million, million, million (10^{21}) watts per square centimetre. These exceptional beams are used to explore a wide range of novel phenomena, as the articles elsewhere in this brochure show.

The next phase of Vulcan's development will see the limits of laser technology pushed even further. The new facility, named 10PW, will deliver 10 times as much power and 100 times more intensity, reaching 10^{23} W cm^{-2}. This ground-breaking development will take scientists into uncharted territory, enabling them to explore an environment which has never existed on Earth before in a controlled way. They will be able to test fundamental theories describing the very nature of matter, energy and space. They will gain access to physical conditions that exist only in the most violent parts of the Universe, such as supernovae and active galaxies with supermassive black holes, as well as the crushingly dense matter found in the cores of gas giant planets and even in neutron stars. The 10PW facility will also open up exciting possibilities across a range of practical fields, including laser-driven fusion for power generation (p 10) and electron and ion acceleration for biomedical and industrial applications (pp 34 and 40).

10PW has been designed to produce laser pulses just 30 femtoseconds (30 x 10^{-15} s) long with an energy of 300 joules. To generate such powerful pulses is extremely challenging and requires a completely novel approach. It will be achieved using two amplification techniques in a combination known as optical parametric chirped pulse amplification – OPCPA – which was pioneered at the CLF.

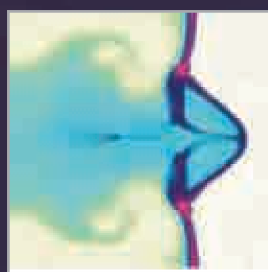


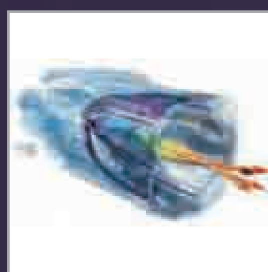
The scheme's first element, optical parametric amplification, involves transferring the power from a high-energy, narrow-spectrum, relatively long laser pulse (which can conveniently be delivered by Vulcan) into a low-energy, broad-spectrum, equally long seed pulse using an optical crystal. Because the pulses are long the power in them is kept below the level at which it would damage the system's optical components. However the seed pulse has been made long by 'chirping' (see p 7) which means that after it has been amplified to the required energy it can be compressed in time to a very short duration. This is chirped pulse amplification, the second element of the OPCPA scheme. The final 10PW layout involves two sequential OPCPA amplifiers based on two specially designed crystals.

The 10PW upgrade has been split into two phases. Phase 1, which began in 2006, concentrated on the design and testing of the technology for producing the laser pulses. It also included the detailed planning of how the facility should actually be built. A system for generating the seed pulses was developed. These are centred at a wavelength of 900 nm and have a broad spectral width – approximately 150 nm. They contain an energy of one joule. Key properties are that they must retain their ability to be compressed to very short duration and they must also, when compressed, switch on very sharply, since any pre-pulse energy would destroy a target before the main pulse arrives.

10PW will deliver pulses to two experimental areas: an upgrade of the existing Target Area Petawatt (TAP10) and a new High Intensity Area (HIA). TAP10 will be built first and will be configured to couple the new 10 PW and the existing 1 PW beams, enabling a wide range of innovative experiments. The HIA, where the highest intensities will be available, will follow. It will have appropriately heavy radiation shielding on the roof and walls. At the same time the repetition rate of Vulcan will be increased to four shots per hour, extending the potential for a broad range of experimental setups. To accommodate all the new equipment, and the improved infrastructure which will allow its potential to be realised, the Vulcan building will be extended by 8 metres and will have a second floor added.

Phase 2 will involve the construction of this major extension, and the large-scale technology implementation. The massive crystals for the high-energy amplifiers will be custom-grown during this phase and the special compressor gratings, optimised to deliver the shortest pulses and to withstand the very high powers, will be delivered. And when they are all installed and working to specification Vulcan will once again be the most intense light source in the world!





The dawn of fusion as a proven scientific concept is immensely important for future energy production since fusion releases no carbon dioxide, uses a fuel which is hugely abundant on earth, provides energy security to all nations, and does so in a manner which is both safe and compatible with our existing electricity supply grid.

The scientific 'Proof of Principle' of fusion is the near term goal of the multi-billion dollar National Ignition Facility at the Lawrence Livermore National Laboratory in California. This project, built around a very large multi-beam laser system, completed its construction and commissioning phase in April 2009. It is designed to cross the threshold at which laser energy will trigger fusion to achieve net energy gain. This proof of principle is a critical step on the path to generating base load electricity.

The final step will be to build a facility that can harness this energy production in a manner compatible with the future requirements of the power generation industry. This is the goal of HiPER. Power from fusion requires a high repetition cycle of fusion bursts, conceptually similar to the operation of a car engine – with fuel injection, compression, ignition and exhaust – repeated 5 times per second (see p 10).

HiPER is the product of a strategic alliance across Europe involving scientists from 10 nations and 26 institutions. Scheduled to complete its preparatory phase in 2011 – at around the time of the NIF demonstration, it will then enter a phase of high repetition rate technology development, leading to facility construction towards the end of next decade.

Fusion power can thus be seen in terms of a 20 year series of goals. In the immediate term, the scientific demonstration of net energy gain is anticipated. The 10 year goal of the HiPER project is to deliver the technology required to harness this demonstration, such that the construction of an integrated facility is low risk. The 20 year goal is to further demonstrate all the components required by an electricity producing power plant, such that construction of a working power plant can be undertaken with confidence.

From a scientific perspective, entry to the incredibly high temperatures, pressures and particle fluxes associated with fusion presents an exciting new range of research possibilities. Wholly new areas of study will be enabled in fields as diverse as laboratory astrophysics, turbulence, transient atomic and nuclear physics, extreme material science, relativistic plasma physics, and the applications of intense X-ray, neutron and gamma ray beams.

HiPER

High Power laser Energy Research Facility

Few scientists get the chance to work on a project whose success is likely to play a major part in changing the way we live on this planet, but that's what a team of scientists at the Central Laser Facility have been doing… putting together a plan to move rapidly from a new and important science breakthrough to deliver a demonstration of technology to produce fusion energy using some of the world's most powerful lasers.

NASA/JPL-Caltech/Hubble Heritage Team

New Light Source

reaches the parts other lasers can't reach

Free Electron Lasers (FELs) can extend the power of ultrafast science to the extremes of the spectrum. The UK's proposed New Light Source will combine FELs and conventional lasers into a unique, world-leading facility.

Experiments involving ultrafast lasers are transforming our understanding of the physical world and are allowing us to manipulate the processes which occur in everything from cells to stars. But our capabilities would be enhanced even further if we could reach outside the limits of the spectrum set by conventional laser technology. One way to do this is to use FELs. The CLF, with its extensive experience of ultrafast science, is centrally involved in the UK's FEL programmes, working with scientists from Daresbury Laboratory, Diamond Light Source and a large number of universities.

Conventional lasers can conveniently produce light with wavelengths tuneable from 200 nm (deep ultraviolet) to 20,000 nm (mid infrared). But there are science opportunities which need wavelengths as short as 0.1 nm (X-rays)! When ultrashort pulses are also required then the FEL is the perfect solution.

FELs are large facilities based around particle accelerators and are usually organised at the national and international scale. To cover the whole of the spectrum requires several machines and to this end the UK collaborates with international partners to ensure that UK scientists can get access to the FEL sources they need.

As part of this globally co-ordinated programme the UK is proposing a New Light Source based on FELs, conventional lasers and long wavelength undulators. With an extremely broad spectral range (from above 100,000 nm to below 0.25 nm), very fast pulses (as short as 20 fs) and with the ability to combine multiple light beams in sophisticated experimental setups the NLS will allow unique studies of the microscopic motions which occur in matter of all kinds.

The FELs will be 'seeded' using light pulses generated by the lasers. This will give tight control over spectra and pulse timing, which are critical for the most precise experiments. In particular, multi-photon studies, where light pulses need to be combined in a sample, or time-resolved ones, where one pulse initiates a process and a later one probes its development, will become possible across an unprecedented spectral range.

Details of the NLS proposal are online at http://www.newlightsource.org

WHAT IS A FEL?

When the paths of moving electrons are bent, the electrons emit light called 'synchrotron radiation'. By adjusting the speed of the electrons and the tightness of the bend the colour of the light (i.e. its wavelength) can be altered. If the electrons can be made to bend many times, for example by passing them through alternating magnetic fields in devices called undulators, then the light from one bend can add to (or cancel) that from its neighbours, again depending on the wavelength. The use of many bends makes the light from undulators very bright and very pure in colour. Finally, if the light gets bright enough it can act back on the electrons, forming them into microscopic bunches which then radiate even more strongly. This is what happens in a FEL. The light leaving the FEL can have laser-like properties i.e. it can travel in a very tight beam with a narrow spectrum and be very, very bright indeed. Strictly speaking the light generation process in a FEL does not involve 'stimulated emission', which is what happens in all conventional lasers. But the behaviour of FEL beams is so similar to that of other laser beams that the word laser is a very appropriate one to describe them.

ALICE

Accelerator and Lasers In Combined Experiments

A testbed for technology and techniques

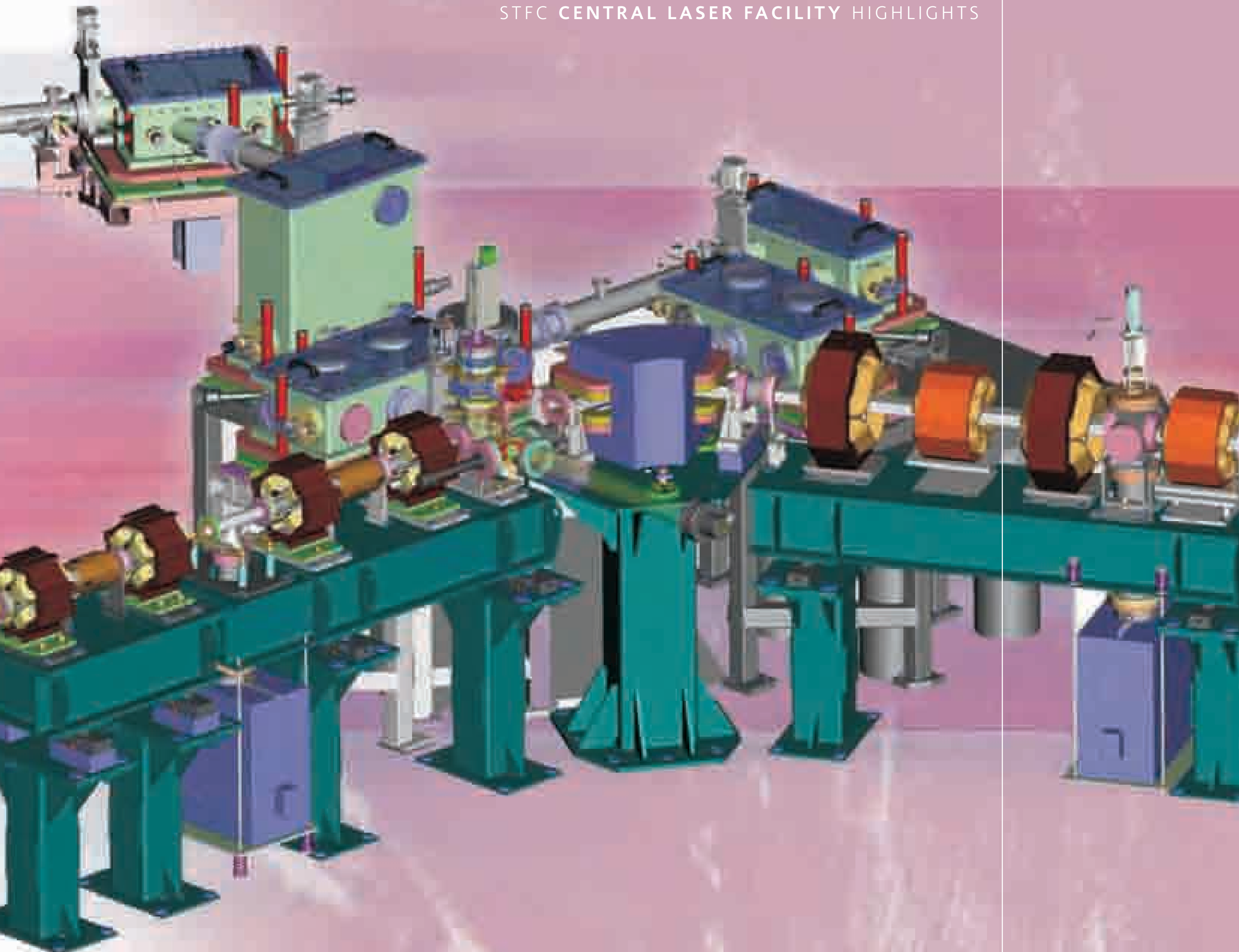
The next generation of light sources will be fully-integrated combinations of particle accelerators and lasers. The STFC is trialling this technology on its unique ALICE facility.

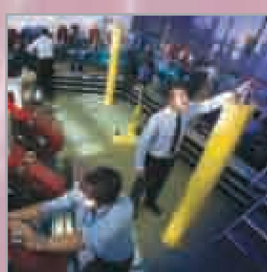
The STFC's science facilities need constant development to ensure that we continue to lead the field in the capabilities we provide. In the area of light sources, machines like the Diamond synchrotron and the CLF's lasers currently attract researchers from across the world. The proposed New Light Source will have even more to offer, including multiple beams from both laser and accelerator-based sources. But the simple fact that its performance will be world-class means that the challenge of achieving it will be world-class too.

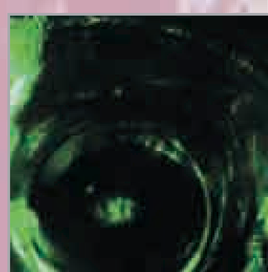
As part of the NLS development process, several of its novel features are being prototyped using an existing machine run by the STFC's Accelerator Science and Technology Centre at Daresbury Laboratory. ALICE – which stands for Accelerator and Lasers In Combined Experiments – can produce light from many sources. The accelerator drives an infrared Free Electron Laser and also produces huge amounts of far-infrared terahertz radiation. Alongside it is a 25 terawatt conventional laser, which itself was one of the UK's brightest when it was commissioned just a few years ago. The femtosecond pulses from the laser and the sub-picosecond electron bunches from the accelerator can also be combined to produce ultrashort X-ray bursts in a process known as Compton scattering. And these beams can all be combined together in dedicated experimental areas.

Not only is there a laser supplying light beams from the ALICE suite, but there are other ones which are actually component parts of the accelerator. The electron bunches themselves are produced by firing pulses of green laser light at a 'photocathode' – a material which emits electrons when illuminated. Lasers are also used in research equipment which monitors the passage of the electrons as they travel through the accelerator. And it is planned to test a scheme for managing the machine's timing using lasers, by transmitting the 'clock' signal around the accelerator in the form of femtosecond laser pulses travelling on optical fibres.

CLF staff have provided laser expertise to the ALICE accelerator from its very start. And the lessons that they will learn there will guide their work on the NLS and in other fields for years to come.







Facilities

Laser systems at the Central Laser Facility

Vulcan

A uniquely versatile system delivering world-class power and intensity

The Vulcan laser at the CLF is one of the most powerful and versatile laser systems in the world. It has an international record of achievement across a very wide range of high power laser science. Throughout its 30-plus year history it has been upgraded and improved to maintain this world-leading status. The upgrades have been based on in-house technology development, including chirped pulse amplification, temporal pulse shaping, adaptive optics for control of the beam's focusability and optical parametric chirped pulse amplification to enable the production of ultrashort pulses. These technologies now form the basis of an ambitious and technically demanding project with the aim of delivering a peak laser power of 10 PW (p 54). This will be an order of magnitude greater than is currently available from any existing laser facility.

Vulcan's versatility derives from the fact that it has specialised target areas with complementary capabilities and up to 8 simultaneous configurable beam lines, allowing complex experiments to be realised. Vulcan uses flashlamp-pumped Neodymium glass as its laser gain material – a well developed and reliable technology which produces light at the near infrared wavelength of 1054 nm. Vulcan is currently capable of delivering up to 2.6 kJ of laser energy in nanosecond pulses and one petawatt peak power in subpicosecond pulses. Frequency conversion can be used to change the light's wavelength, and converting to the second harmonic gives 1 kJ pulses in the green at 527 nm. Pulse lengths between 700 fs and 5 ns are routinely available. To achieve the highest peak powers the technique of chirped pulse amplification (CPA) is used. Here low intensity ultrashort pulses are stretched out in time, amplified in the main laser, recompressed back to their initial duration and finally focused onto the target. Using CPA it is possible to overcome destructive nonlinear effects in the laser amplifier chain. The ultrashort CPA pulse can be synchronised to Vulcan's nanosecond pulses, enabling sophisticated laser-matter interaction and probing experiments. The time profile of the nanosecond pulses can also be adjusted to compensate for distortion caused, for example, by gain saturation in the laser amplifiers. This allows the pulse shape to be tailored to match the users' requirements.

The Vulcan laser beam needs to be of very high quality, both to prevent damage to the laser itself and also to allow focusing to the smallest possible spot. The optical uniformity of the Neodymium glass is distorted by the heat which is deposited in it each time the laser is fired. So the Vulcan shot rate is limited to a few per hour, allowing adequate time for the glass to cool and the beam quality to recover.

The ultrahigh intensities produced when the Vulcan beam is focused onto a target enable plasma physics research which is critical to a number of scientific areas. These include energy generation, particle acceleration, extreme materials science and laboratory astrophysics. Vulcan makes major contributions in the area of Inertial Confinement Fusion (ICF) by enabling researchers to investigate the underpinning physics – the generation and transport of fast electrons and the processes by which they transfer energy to their surroundings. Laser-driven ICF holds great promise as a future source for the world's energy supply. The huge electric fields present at the focus of the laser can also be used to generate high-energy subatomic particles. The prospect of particle accelerators which would be much more compact than existing ones opens up potential applications in industry, science and medicine. Vulcan can create temperatures of millions of degrees and pressures of billions of atmospheres. These are unattainable in the laboratory using any other technique. They allow us to improve our understanding of the way materials behave under the most extreme conditions, for example in the centre of a giant planet. The plasmas that are formed also provide scaled analogues of much larger astrophysical objects. More details of these applications and of others are contained in the 'Science' section of this brochure.

Target Area Petawatt.

The Petawatt interaction area gives users access to one of the world's leading ultra-high intensity facilities. The laser delivers an energy of 500 J onto the target in a pulse which is only 500 fs long. The beam is focused using a parabolic mirror to a spot just a few micrometres across. The resulting intensity is greater than 10^{21} Wcm^{-2} which is 10,000 times brighter than the light in the core of the Sun!

Target Area West

Target Area West can operate in a dual-beam CPA mode with one beam delivering 100 J in a 1 ps pulse and a separate one providing 500 J in 10 ps. Long pulses (nanoseconds) are also available and these can be combined on target with the picosecond beams. The very wide range of options for pre-heating, ultra-high power irradiation and independent probing of the resulting plasmas using dedicated laser-driven sources make Target Area West an extremely versatile experimental area.

Astra Gemini

A high power, ultra-short pulse, high repetition-rate laser

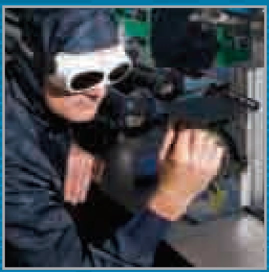
The Astra laser system works in the infrared part of the spectrum just outside the region visible to the human eye. Its pulses are so short that they are like sheets of light energy thinner than a human hair, which can also be focused to a spot a few thousandths of a millimetre across. Their energy is thus delivered to a very small target extremely quickly, allowing experimenters to study how matter behaves under extreme conditions of temperature and pressure. This concentration of energy makes Astra, with its Gemini extension, one of the most intense lasers in the world.

The system's front end consists of an ultra-short pulse titanium-sapphire (TiS) laser oscillator that provides low-energy, high-quality seed pulses of approximately 12 fs duration at a wavelength of 800 nm. These are amplified to millijoule energy, and then stretched in time using a wavelength-dependent optical delay line (a pulse stretcher). Any attempt to amplify the pulses without first stretching them would result in severe damage to the components of the laser.

Each of the subsequent amplifiers consists of a TiS crystal that is pumped by pulses of green light from another laser. The beam size and the crystals are made progressively larger to keep the intensity of the light below the level where damage will occur. After the first three amplifiers a pulse energy of more than 1 joule has been reached. At this stage the pulses can either be sent forward to Astra Gemini or delivered at 40 fs and 10 Hz to the Astra Target Area. The Astra Area also has a second, lower energy beam available which can be used as a probe to generate high resolution images of the plasma created with the main beam.

The Gemini laser system consists of two more TiS amplifiers. In the Gemini laser hall the incoming beam is split in two, and half is sent to each amplifier. The Gemini TiS crystals are pumped by up to 60 joules of green light from custom-made Neodymium glass laser systems, which can fire as often as every 20 seconds. The output energy of each amplifier is around 20 joules. The beams are then expanded to 150 mm diameter and sent to the pulse compressors.

The compressors consist of a pair of gold-coated diffraction gratings and a mirror, inside a vacuum tank. They reverse the wavelength-dependent delay that was introduced by the pulse stretcher, so that when the separation of the two gratings is exactly correct the pulse is restored to a duration close to the



original value. The compression is done in vacuum because the beam is so intense that it cannot pass through any solid optical material, or even air, without being stretched and distorted to the point where it is no longer useful for experiments. So the beam is transported in vacuum all the way to the target chamber.

In the Gemini target area the beams are focused with parabolic mirrors, and with a focal spot as small as two micrometres, intensities up to 10^{22} Wcm^{-2} can be achieved on target. This makes Gemini the most intense user facility in the world. The temperatures, pressures and magnetic fields at the focus reach levels that otherwise exist only inside stars, making Gemini a unique facility for scientists to conduct experiments that cannot be attempted anywhere else. Laser-plasma interactions under these conditions can produce energetic beams of electrons and protons as well as bright, coherent sources of X-rays and can also address fundamental questions in astrophysics and plasma physics. The first experiment performed in the Gemini target area early in 2008 demonstrated the acceleration of electrons in a gas jet to energies comparable with those from large conventional accelerators. There are also possibilities for doing quantum electrodynamics experiments (p 48).

The Astra and Gemini target areas have been designed for versatility and the experimental conditions can be optimised to allow an enormous breadth of research to be carried out. As well as playing a crucial role in advancing UK and worldwide science, there are also prospects for practical spin-offs with significant commercial potential.

Artemis

Generating synchrotron-like light from a table-top laser system

Light is an extraordinarily useful tool for examining and manipulating the properties of materials. It achieves this in very different ways, depending on its wavelength. At the longest wavelengths (radio waves) most materials are transparent. But as the waves become shorter and we pass through the microwave, infrared and visible parts of the spectrum, the light and the matter interact progressively more strongly.

Effects in the ultraviolet are so strong that all of the light can be absorbed by a very thin layer of material (think of the way that UV light from the Sun burns the skin). Finally at the shortest wavelengths – X-rays – transparency can return. The process is selective though, allowing one material to be distinguished from another as in medical and security X-ray systems.

The selectivity results from the properties of matter on the atomic scale, where atoms and molecules have discrete energy levels. When a photon of light has an energy, and therefore a wavelength, matching the difference between two levels, it can cause the molecule to move from one level to the other (p 6). In the infrared this corresponds to changes in molecular vibration or rotation. In the visible and ultraviolet it results in a reorganisation of the electrons in the atom. With high energy X-ray photons an electron can be removed completely in a process called ionization.

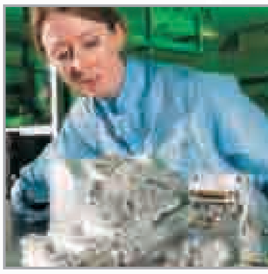
Measuring these light-matter interactions gives us a means to look inside materials and understand how they function. This understanding is not only fundamentally important but it is also vital for effective technological exploitation. Since experiments depend on studying the response of materials to light of different wavelengths,

researchers need bright, stable sources of wavelength-tuneable photons. One option is to use a synchrotron, which is a particular type of particle accelerator. Machines like this produce intense light beams by accelerating electrons around a circular path under the control of powerful magnets. Synchrotrons are large facilities, costing several hundred million pounds to build. They are cost-effective when a large user community can be gathered together, but there are also circumstances when it would be very convenient to have a laboratory scale source with similar capabilities.

The designers of the Artemis facility at the CLF have found ways to do this by exploiting the power and versatility of ultra-fast lasers. The lasers themselves are not easy to tune, so in Artemis techniques known collectively as 'nonlinear optics' have been used. These allow laser photons to be added in small numbers (frequency multiplication), added in large numbers (high harmonic generation), subtracted from one another (difference frequency generation) and even split into two (optical parametric generation). Light tuneable from the infrared (20,000 nm wavelength) to the soft X-ray (15 nm) can be made this way.

Synchrotron light comes in pulses whose duration is typically tens of picoseconds. Pulses from Artemis can be much shorter - down to a few femtoseconds – allowing fast-moving processes such as chemical reactions to be studied in much more detail (p 52). One way of doing this is to use a technique called pump-probe spectroscopy, where two pulses are used in sequence with a precisely controlled delay between them. The first one excites the sample being studied, and the second probes how it has reacted. Varying the delay allows the sample's response to be mapped out in time. The fact that in the Artemis system both pulses are derived from the same laser means that the delay can be very well controlled, allowing the response to be measured with very high precision.

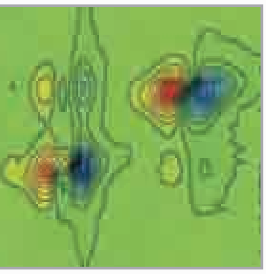
In addition to its broad tuneability, another feature that makes Artemis unique among similar facilities is the provision of high quality end-stations where user experiments are carried out. These enable the study of gas-phase and solid-state samples and provide the capacity to make measurements down to extremely low temperatures (-260°C). They extend the facility out from the photon source to include a suite of beam diagnostics, sample handling and detector systems. The aim is to allow the research teams to get maximum benefit from their time in the laboratory by minimising the need for experimental setup and characterisation.



Artemis' state-of-the-art laser capabilities combined with its integrated end-stations offer exciting new possibilities over a wide-ranging experimental programme. These include opportunities for the laser and synchrotron communities to share and benefit from each other's approach and expertise. In addition the facility can be a very effective test-bed for the techniques underpinning the next generation of accelerator-based light sources (p 58).

Lasers for Science Facility

Using some of the world's most advanced and versatile laser systems to address some of nature's most challenging problems



Lasers now play a major role in research across the physical, biological and medical sciences. The LSF delivers programmes in all of these areas and also in interdisciplinary combinations of them. In many cases these exploit specialised excitation, detection and data analysis techniques in which the LSF's staff are international leaders.

The facility's activities are divided into three main areas:

Molecular structural dynamics

Centred around the newly developed ULTRA (Ultrasensitive Life-science Time-Resolved Analysis) laser, techniques such as time-resolved Raman and infrared spectroscopy are used to monitor the structure and function of chemical/biochemical compounds as they undergo complex reaction processes. Experiments are often carried out in the solution phase, typical of the real conditions inside living organisms. ULTRA itself is a particularly versatile tool, delivering both picosecond and femtosecond pulses at rates up to 10 kHz and with continuous tuneability from the ultraviolet to the infrared. Its multi-beam capability is increasingly in demand for the most sophisticated analyses, including 2-dimensional infrared and femtosecond stimulated Raman studies. Across timescales from the femtosecond to the millisecond, ULTRA can reveal, for example, the ways in which the environment influences and frequently dictates the chemistry that drives biological processes. The team of scientists working in this field have received numerous awards for driving forward innovative laser and detection technology.

Functional bio-systems imaging

The marriage of lasers and microscopy techniques within the LSF has led to many significant developments, in particular the use of tuneable femtosecond laser systems for multiphoton microscopy. The LSF's Functional Bio-systems Imaging Group operates a suite of laser and microscopy systems that form the OCTOPUS cluster. Its overall goal is to facilitate the study of multiple molecular interactions in complex biological systems in real time. It is also pioneering the translation of super-resolution single-molecule imaging from biological systems into the prediction of clinical outcomes. OCTOPUS' integrated capabilities include ultra-high resolution microscopy (down to the level of single molecules), fluorescence lifetime imaging (p 24), optical trapping (p 12) and advanced processing of image data (e.g. Bayesian segmentation) – all backed up by expertise in the labelling of proteins and the introduction of large molecules into cells. Such technology allows detailed imaging of living cells and tissue sections and the investigation, in vivo, of the molecular interactions taking place inside them.

Laser Loan Pool *(directly funded by the EPSRC)*

The Laser Loan Pool operates a number of state-of-the-art laser systems that provide national support for a wide range of research programmes. The lasers are loaned to UK academics for use in their home institutions, giving scientists and engineers a unique way of accessing complex laser equipment. The role of the Loan Pool is:

- to support newly appointed academics before they have acquired their own home based lasers,
- to allow the feasibility of experiments to be tested prior to major grant applications,
- to augment peer-reviewed and grant funded research which requires a laser (or an additional laser) for a series of experiments. Particular beneficiaries include research groups using large non-portable equipment,
- to provide laser systems to researchers whose need for a laser is intermittent.

The expertise of the LSF staff, who provide installation, training and assistance throughout each loan, is widely recognised by the community they work with. This community's support has been a vital element in ensuring the Loan Pool's continued success in its regular, competitive bids for funding.

Over the years a particular strength of the LSF has been its ability to support multidisciplinary research. Its equipment is necessarily set up in distinct laboratories, each of which concentrates on a specific technique (IR and Raman spectroscopy, optical force control, biological imaging etc). But the proximity of these laboratories, all of which are under one roof, and the very close working relationships between the staff who run them mean that users who bring challenging problems to the facility find that a whole range of solutions are available to them. It is rare that a programme of work lies within just one domain.

For example the suite of activities aimed at unravelling the complexities of DNA chemistry and biochemistry has ranged from ultrafast molecular investigations, revealing the basic processes that lead to (or, indeed, protect against) genetic mutation, to larger scale real-time observations that follow cells as they recover from potentially fatal damage to a DNA strand. Likewise the facility's rapid exploitation of new technical opportunities encourages cross-talk between the chemistry, optics and biology programmes, which both contribute to and benefit from the technical advances.

The role of the LSF is constantly developing. Its long track record of collaboration with neighbouring organisations, including the ISIS neutron source, the Diamond synchrotron and the Medical Research Council, continues with its relocation to the Research Complex. Strong links can now be forged across the whole Harwell campus, allowing an even greater impact to be derived from the facility's multidisciplinary capabilities. The prospects are exciting – but it's well known to everyone in our community that lasers excite things!

Simulating the complexities of

Supporting laser experiments through theory and computer modelling

The CLF's Physics Modelling Group carries out advanced computational and theoretical studies needed to support and guide the work carried out on the laser systems.

The interaction between matter and the most powerful laser pulses that can be produced is complex. The target material is heated to incredible temperatures and subjected to immense pressures. At the same time, high-energy electrons moving near the speed of light (relativistic electrons) are released, accompanied by strong electric and magnetic fields.

In the face of such complexity, the experimental work needs to be guided and complemented by theoretical insights and advanced computer simulations. To support the design and interpretation of experiments, a team of theorists, armed with a 288-core computer cluster (SCARF-LEXICON), assist users and provide advice. We also carry out studies on our own ideas of how to do interesting new science with the laser systems.

Below are some of the important aspects that we work on.

Fast electron transport for power generation

The way in which beams of relativistic electrons travel inside a dense plasma is a subject that affects many high-power laser experiments. It is crucially important to the concept of fast ignition ICF for power generation (p 10), in which the relativistic electrons heat compressed fuel to achieve ignition. These beams carry enormous currents, which generate huge magnetic fields. In turn, these magnetic fields affect the guiding of the electron beam. Some of the group's conceptual studies have investigated how this guiding can be improved by structuring the target.

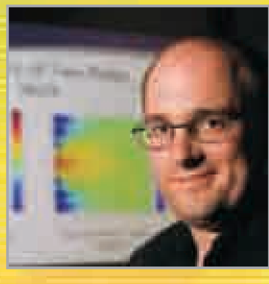
Probing novel proton acceleration

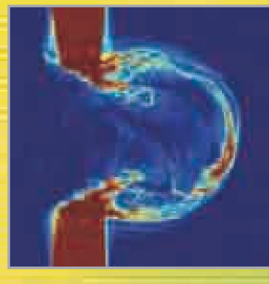
Targets irradiated by high-power lasers can produce beams of protons accelerated to high energies, useful for medical and other applications (p 34). Not all aspects of proton acceleration can be measured experimentally, so computer simulations are extremely valuable for understanding the process and interpreting the experiments. They also allow us to explore what happens over a wide range of conditions without the expense of long experimental investigations – and this can lead to the discovery of new acceleration mechanisms. Some of our recent work has involved studying how the raw light pressure exerted by extreme laser pulses can drive ion acceleration in solid target interactions.

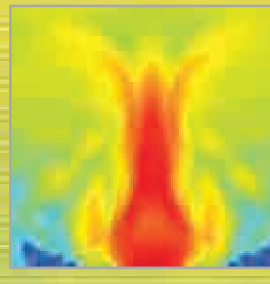
Optimising electron acceleration

A plasma can support huge electric fields creating acceleration gradients 1000 to 10,000 times larger than those obtained with radiofrequency fields used in conventional accelerators. Controlled acceleration of electrons up to 1 GeV, with a small energy spread, has been achieved using a plasma wave driven by a laser pulse over a distance of just 2 centimetres (see p 40). To prevent premature breakup of the laser pulse and to increase the distance over which it can

plasmas







drive the plasma wave, the CLF laser community has developed plasma channels to guide the laser pulse as is done with optical fibres. Experiments have shown that the quality of the accelerated electron bunches (mean energy, energy spread, total charge) depends sensitively on various laser and plasma parameters in a complex way, and computer simulations are indispensable in tailoring the laser and plasma to get the best accelerator performance.

Photon acceleration

Because the refractive index of a plasma wave varies with time, it can also change the frequency and wavelength of any photons it is interacting with. This also changes the overall 'group velocity' of the photons travelling in the plasma (which is less than the speed of light in a vacuum), so the photons are effectively accelerated. This has been used to determine various properties of laser-driven wake-fields through analysis of the transmission spectrum of the driving laser pulse. The spectral evolution is a highly nonlinear process for the laser intensities used in laser wake-field acceleration, and can therefore be modelled properly only in computer simulations.

Laser amplification

Since plasmas can tolerate much higher laser intensities than can solid-state crystals, laser amplification in a plasma has the potential to produce pulses at higher power than amplification in solids. At low laser intensities, this amplification process is well described by certain analytical theories. However, high-intensity laser amplification (terawatts to petawatts) is far beyond the range of validity of these theories, and computer simulations are required to model the amplification properly at these intensities.

Hydro code development

One of the software development projects we have carried out is to simulate hydrodynamics (fluid flows) in laser-generated plasmas. This is particularly important in laser-fusion research and in experimental simulations of astrophysical jets (p 46).

Making targets

for laser experiments

The CLF has a dedicated, highly successful laboratory for making 'microtargets', the small, solid objects designed to generate plasmas in high-power laser experiments

Projects such as laser acceleration (p 34) and inertial confinement fusion (p 10), carried out with Vulcan and Astra Gemini, require very precisely designed targets made of materials with specific properties – and shaped to produce a plasma with exactly the right characteristics for the experiments. Making these targets is extremely challenging and requires a great deal of R&D.

The Target Preparation Facility has considerable experience in the underlying technologies, and we work very closely with the CLF users in planning and carrying out an experimental run. Modifying the target is often the quickest and most efficient way to change significantly experimental parameters or conditions, and so an important aim is to minimise the time between interpreting results of one experiment and then modifying the target for the next one. In this way, targets are quickly optimised to deliver the best possible experimental results.

We also produce microtargets for other laser facilities, and we are involved in large research projects such as the RCUK-funded LIBRA project to generate radiation from a target using lasers, and HiPER (p 56).
A supporting theme is to explore mass production of targets in collaboration with other STFC groups.

Making a target

Target fabrication consists of four main activities: developing and carrying out microfabrication, making thin-film coatings, micro-assembly, and characterising the target and its components at all process stages.

Microfabrication

From the earliest planning stages of a proposed experiment, we work closely with facility users, offering advice on target feasibility and design. With more than 25 years of microtarget production, we have generated an extensive repository of techniques and are continually exploring and – where appropriate – taking up new production techniques. The STFC has significant expertise in ultra-precision micromachining and has a mature development programme in the mass production of gold microcones used in advanced fast-ignition experiments. With the move to much higher repetition rates on Astra Gemini, a range of new techniques has been developed for production and insertion. Complementing the CLF target fabrication programmes, the STFC Micro and Nanotechnology Centre at the Rutherford Appleton Laboratory has also fabricated a range of microtargets using wafer-based techniques.

Thin film coatings

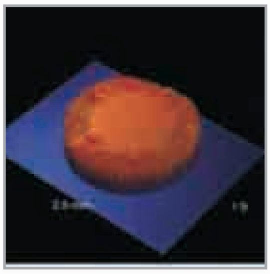
We have significant capabilities in thin-film production for microtarget components as well as other laser equipment. The facility houses a sputter-coater, two thermal evaporation plants and an e-beam coater, all equipped with real-time film thickness monitors. These can produce metallic and non-metallic coatings as pure deposits, co-deposits or multilayers with thicknesses varying from a few nanometres up to several micrometres. Coatings of the plastic parylene are produced in dedicated plants. Responding to the user community, a dedicated coater has been developed to produce low-density metal coatings which have enhanced laser absorbance (and consequently modified X-ray production characteristics).

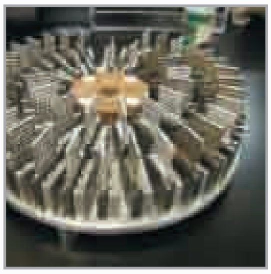
Microassembly

Many microtargets are assembled manually by highly experienced fabricators using ultra-fine hand tools and high quality microscopes. They involve components, or component features, that are extremely small, such as wire only 20 micrometres in diameter, or foils less than 100 nanometres thick. Microtargets with particularly precise specifications (tolerances of better than a few micrometres) are often assembled using custom-made assembly rigs, constructed in collaboration with the Precision Development Facility in the STFC Space Science and Technology Department in the Rutherford Appleton Laboratory.

Characterisation

Precise measurement of microcomponents and finished microtargets is an essential aspect of target fabrication, and is fully integrated into every stage of production. Optical microscopy is the main technique we use, with almost all assembly carried out under stereo microscopes; and measurements performed with dedicated microscopes equipped with a range of contrast techniques and cameras. For measurements requiring higher precision we have a scanning electron microscope, which is also fitted with advanced instrumentation for





element analysis. A white-light interferometer is used for accurately measuring surface form and roughness. There is an automated coordinate measuring machine which is proving useful in the move towards high-production numbers. Thin film thicknesses are checked using a high-precision touch probe.
The latest additions to the suite of characterisation tools are a confocal microscope (for high-speed imaging of three-dimensional microtargets) and a compact atomic force microscope. Commercial access to all these capabilities has recently been made available via a spin-out company, Scitech Precision Ltd.

Scitech PRECISION

Working in partnership

International

Modern world-class science requires very high levels of commitment and expertise and the benefits of working with others to deliver the most effective solutions are obvious. The CLF has a very long tradition of joining with its European and global partners in fully collaborative structures and projects.

These cover both the provision of access to the CLF's lasers and also high level co-operation in the delivery of new facilities. We are closely involved with many of the initiatives which are currently under development on the world scene. We often play a leading role in these. A sample is given here:

Many of the European projects are run with support from the EU's Framework Programme. The CLF has worked with EU Frameworks since their earliest days, providing transnational access to its lasers since the 1990s.

A consortium of 26 laser research organisations from 16 European countries, Laserlab Europe co-ordinates user access to facilities and manages joint laser research activities. The CLF was a founder member in 2004.

The High Power laser Energy Research project will design and deliver a laser-driven fusion reactor to demonstrate the capabilities needed for a power plant. Based in Europe, and led by the CLF, HiPER's partnerships make it a truly global project.

partnerships

The CLF's international work is vital for its own success and contributes substantially to worldwide developments in the field

The very limits of what is possible with large-scale laser technology will be explored with the Extreme Light Infrastructure, in which the CLF plays a leading technical and strategic role.

The International Committee on Ultrahigh Intensity Lasers co-ordinates international aspects of ultrahigh intensity laser science, technology and education. It operates under the aegis of the International Union of Pure and Applied Physics. CLF Directors have been Committee members since it was formed in 2002.

Collaborative work with partners in the US takes place at many different levels and with many different institutions. Particularly close relationships exist with the Lawrence Livermore National Laboratory, General Atomics, the University of Rochester Laboratory for Laser Energetics and the US Department of Energy.

The EuroFEL consortium is a distributed Free Electron Laser facility that joins complementary national FELs into a unique European research infrastructure. CLF staff have worked on a range of technical and policy issues in the context of the UK's New Light Source.

The UK China Partners in Science initiative aims to increase links and collaborations between the two countries in the fields of science and technology. The CLF has a long history of working with Chinese laser experts across a range of areas of common interest.

A Memorandum of Understanding between the STFC and the Japan Society for the Promotion of Science supports joint activities, including work on laser-driven fusion for energy where collaboration has been strong for many years.

Knowledge and awards

Recognising and benefiting from the CLF's strengths

The articles in this brochure reveal the breadth and diversity of the CLF's science programme, with subjects as different as plasma physics and cell biology studied at scales ranging from the astronomical to the microscopic. The CLF's impact in these fields is recognised in many different ways. Two examples are knowledge transfer, where external partners work with facility staff to develop our research for maximum benefit to society and the economy, and science awards, presented by external organisations in recognition of the originality and importance of the contributions that we make.

Knowledge Transfer

The knowledge transfer process takes different forms depending on the scale and nature of the work. The most far-reaching ideas with the largest potential impact need the organised involvement of the whole international community. The HiPER initiative (see p 56) led by the CLF is a prime example of such a programme. It takes a staged approach to exploiting laser-driven plasmas as an abundant, reliable, carbon-free solution to the world's energy supply problems.

Smaller-scale applications which are closer to market can be taken forward by setting up a dedicated company around intellectual property and/or technology with genuine commercial value. The CLF has a long track record of initiating and supporting these (see box) and it continues to do so. Over time the STFC and its predecessors have developed infrastructure to maximise companies' chances of success. Issues such as intellectual property protection and licensing, product development and the raising of capital are now covered by STFC Innovations Ltd, a dedicated technology transfer company. The facilities and expertise co-located on the Harwell Science and Innovation Campus provide an ideal environment for start-up companies.

As well as specific activities which exploit particular opportunities, the CLF also has more general commercial connections. There are routes for businesses to get access to the laser facilities themselves and also to the expertise of the staff. There is an internal company, Rutherford Optics, which supplies products and services based on these. The CLF is involved with several business-oriented organisations including Knowledge Transfer Networks, the regional South-East Photonics Network and the national Association of Industrial Laser Users, all of whom have held events at the Rutherford Appleton Laboratory.

The benefits of knowledge transfer are two-way. Its value to the economy and to the external community is obvious. But it also benefits the CLF's own R&D and user programmes. It can provide access to specialised equipment and staff and insight into technical areas which are relevant elsewhere in the facility. The exposure to modern business practice also brings a fresh perspective to the way that the facility's management is developed.

Awards

With so much cutting-edge science taking place at the CLF, it's not surprising that our staff are frequently recognised for their notable research contributions. Some international examples include:

2006 Prof Peter Norreys
The American Physical Society Award for Excellence in Plasma Physics Research

2007 Prof Peter Norreys
The Daiwa-Adrian Prize, with Prof Ryosuke Kodama, for High Energy Density Science

2008 Prof David Neely
A Professor Mitsuyuki Abe Chair at the JAEA Photo Medical Research Center, Japan

2009 Prof Pavel Matousek
The Charles Mann Award for Applied Raman Spectroscopy

2009 Dr Rajeev Pattathil
INSA Young Scientist Award for notable contributions in Science and Technology

Examples of CLF start-up companies

Exitech – supplier of high-specification industrial laser production tools to the international semiconductor and micromachining industries.

Oxford Framestore Applications – image grabbing and analysis, specialising in precision interferometric and pulsed-laser techniques.

Colsi Coat – custom optical coatings based on spun colloidal silica for the lowest stresses and the highest laser damage thresholds.

LaserThor – use of very high average power lasers for railhead cleaning, addressing the difficult problem of leaf residues pressure-bonded to railway lines.

L3T – developing compact systems for blood testing (e.g. for distinguishing 'good' and 'bad' cholesterol) based on fluorescent tagging The company began in STFC's Synchrotron Radiation Department and continues with support from the CLF.

Cobalt Light Systems – use of the SORS technique (see p 30) for non-destructive analysis of the composition of materials hidden behind or within other layers. Examples range from packaged tablets to bottled liquids being taken onto aircraft to living bone covered by flesh and skin.

Scitech Precision – provides a focus for the exploitation of STFC's expertise in micro-assembly and micro-engineering. A particular speciality is the fabrication of micro-structured targets for use in high energy photon science experiments.

STFC | Innovations Ltd

transfer

Outreach

Communicating the importance and excitement of

Investment in science research is justified on many grounds. The direct benefits include solutions to problems in areas as diverse as energy, health and security leading, in turn, to new products and improved processes for business and industry. In addition, those who work in research develop valuable skills alongside their specialist expertise – team-working, problem-solving, creativity and resource management are just a few examples – which form an excellent basis for any subsequent career.

In the most general case an understanding of the way the universe works is an important challenge for individuals and society as a whole. And seeing the research process in action can be truly inspirational. However realising these benefits in full depends on good communication. This is why outreach is built into the CLF's mission.

The facility pursues a wide range of outreach activities. We engage the general public directly and also through schools, colleges and the media. Other beneficiaries, including academics, industry, policy makers and funding bodies, are contacted through specialised events and briefings. All of the CLF's staff are encouraged to participate, but among them are a number of 'key communicators' who are well versed at working with such a diverse audience. It is important to note that all of these interactions are dialogues. As well as describing and explaining our work we are also keen to answer questions, listen to opinions and respond to ideas.

Tours

The lasers and the experimental areas are regularly open for tours and there are opportunities to watch the work in action from laser viewing booths and the balcony over the Vulcan petawatt experimental area. We host a large programme of facility visits from external organisations, averaging at least one per week. We are also active members of the 'Other People's Business' scheme which allows colleagues from other STFC departments to learn about the CLF's work.

Science and Engineering Ambassadors (SEA)

Many members of the CLF belong to the SEA scheme. This runs events in schools, universities, research laboratories and other establishments and it provides training for the ambassadors to ensure that standards are high. Activities are wide-ranging and include lectures, careers days, and problem-solving events.

NOISE

New Outlooks In Science and Engineering is a national programme run by the EPSRC for 16-19 year olds. Role models, who are typically PhD students or early career researchers, engage the target audience through local and national media and large science

the CLF's work is an activity which involves the whole facility

events. One of the CLF's staff is a NOISE role model and has appeared at the BA Festival and the Cheltenham Festival and on high profile public panels.

Royal Society MP Pairing Scheme

The opportunity for scientists and MPs to learn more about each other's work is a very valuable one. In November 2007 the Royal Society arranged for the CLF's Kate Lancaster to be paired with Anne Snelgrove MP. Dr Lancaster spent four days in Westminster shadowing Ms Snelgrove's activities including attendance at select committee meetings, seminars and briefings. In return Ms Snelgrove visited the CLF and was able to see how science is done in the laboratory and how the research process works from the point of view of the people and the organisations who deliver it.

Website and printed publicity material

It goes without saying that the CLF's website, http://www.clf.rl.ac.uk/, is a vital communication channel. As well as explaining our science and describing our resources it also informs our research users and publicises the work that they carry out. Printed material includes leaflets on individual CLF facilities, detailed annual reports of the experimental programme and, of course, this Highlights document!

Lectures

The tradition of public science lectures is a very long one in the UK and their popularity persists despite competition from radio, TV and the internet. Clearly there is something special about an enthusiastic expert discussing his or her subject in the flesh. CLF staff regularly travel near and far to tell the general public about the facility and the science that's done here. This has been extended more formally with participation in 'GCSE science live', a lecture tour aimed at inspiring GCSE students in the fields of science and technology.

Print and broadcast media

Recent examples of media appearances by CLF staff include Material World (BBC R4), Naked Scientists (BBC Radio Cambridge), RTE Breakfast Show, and The Today Programme (BBC R4). Articles about the facility and its work have been printed in publications including The Telegraph, The Guardian, The Times, The Economist and on the BBC News website.

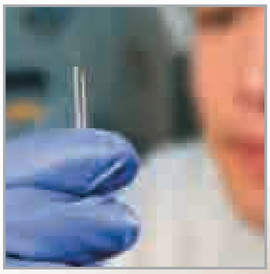
As well as its scientific and technical achievements, the CLF also maintains and develops a highly skilled staff and user community.

The CLF's position as a world-leading research facility is critically dependent on the training of its staff and users. Without training, the safe and effective operation of our very sophisticated laser systems would be impossible. And in the longer term the introduction of new scientific techniques and innovative ways of working, which has kept the CLF at the forefront of its field, also requires the constant development of people's skills.

As an 'Investor in People' the STFC's commitment to developing every member of its staff is independently assured. Within the CLF individuals have been trained in areas as diverse as project management, data protection and communications, as well as the more obvious engineering, science and safety competencies. Training is delivered through short courses, attendance at college and university and 'on the job' learning. The facility also participates actively in the STFC's graduate and apprentice schemes. The result of all this investment is an extremely capable and versatile workforce.

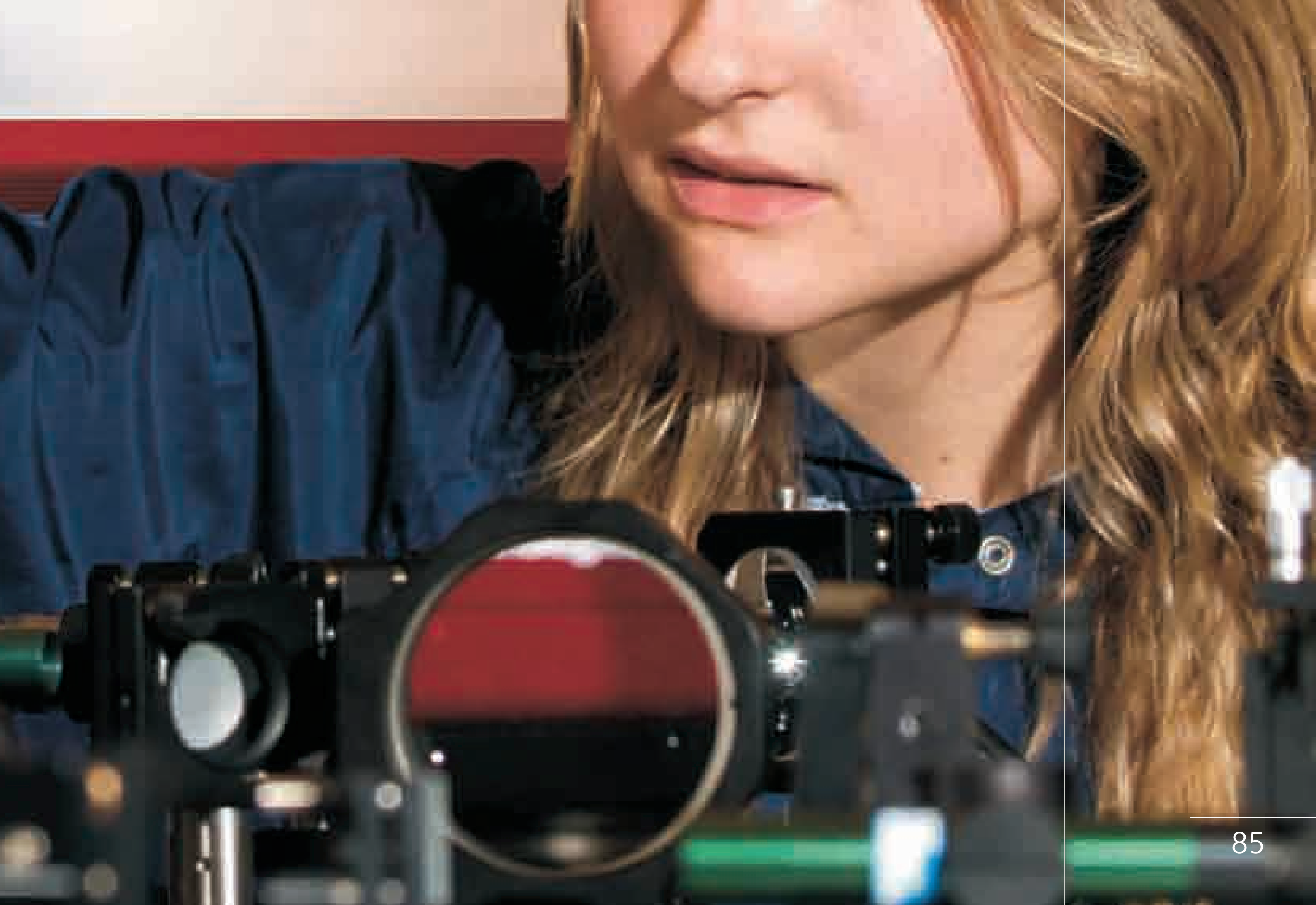
The researchers who use the CLF need to be very familiar with the facility's capabilities if they are to get the most from their allocated experimental time. To this end both one-to-one and group training is provided. A good example is the 'Training Weeks' scheme for new high power laser users. This brings them quickly up to speed with the practicalities of working on an advanced laser research project. It forms an excellent basis from which they can progress as members and eventually, perhaps, leaders of research groups. Likewise the analytical and

Training

management skills acquired while working at the CLF equip them for a wide range of other postdoctoral careers. It is not surprising that the scheme is very popular, attracting interest and attendees from across the CLF community.

Beyond the need to support the facility's work directly, the CLF also recognises the benefits of wider education. Opportunities are available for students at every level. As well as researchers studying for PhDs, a number of undergraduates on university sandwich courses also join the CLF each year. They spend 12 months as fully paid members of facility teams, working both on operations and on their own research projects. Even school pupils can find out what a science career is like 'from the inside' on a work experience placement from a local school.



Definitions, Glossary and Units

Many scientific terms have been used in this brochure. In pulsed laser science three of the most useful are:

Energy – defined as 'the capacity to do work'. Without a supply of energy, work can't be done. And when work is done the energy is usually converted into another form. Some examples of the many different forms of energy are heat, light, electrical energy, energy of motion, energy stored in chemicals (e.g. fuel), and energy stored in the nuclei of atoms. Einstein explained, in his theory of special relativity, that energy and matter could be turned into one another. The unit of energy is the joule, whose symbol is J. When an apple falls a distance of one metre it converts approximately 1 J of gravitational energy into 1 J of energy of motion. 1 J is also the energy needed to warm up one litre of air by approximately 1°C. The energy in a laser pulse is an important design parameter. High pulse energy lasers tend to be physically large and correspondingly expensive.

Power – defined as the rate at which energy is delivered. Power is measured in watts (symbol W) where 1 watt is 1 joule per second. We are all familiar with how bright an energy-saving light bulb (say 11 W) is, or how loud a powerful stereo (say 100 W) is or how quickly an electric kettle (say 2000 W) heats water. But these numbers are misleading. They all measure how much electrical power is fed into the process. In the case of the kettle most of this actually heats the water. But in the case of the light bulb a significant fraction is converted into heat, not light. And in the case of the stereo relatively little of the amplifier's electrical output is turned into sound power. Most of it becomes heat. For pulsed systems it is important to distinguish between average and peak power. Average power is just the total energy delivered in a period of time divided by the length of the period. Peak power is the energy in a single pulse divided by the length of the pulse. For scientific lasers a high average power might be a few tens of watts. But because of the very short pulse lengths the highest peak powers can be tens of millions of millions of times higher than this. This is 10,000 times the capacity of the whole UK electricity supply!

Intensity – defined as power per unit area. Much of the science carried out by the CLF's users is concerned with the effects of very high intensity light. This is produced by taking a high peak power beam (i.e. a high energy delivered in a short pulse) and focusing it down to a very small spot. Achieving a tight focus depends on careful alignment of very precisely polished mirrors and lenses. Stresses and beam distortions in the laser itself and in any air in the beam path must also be avoided. Intensity is measured in watts per square metre or, often, watts per square centimetre ($W\ m^{-2}$, $W\ cm^{-2}$). The highest power lasers in the CLF can produce intensities of $10^{21}\ W\ cm^{-2}$. Nothing that we are familiar with comes even remotely close to this. It is 10,000 times greater than the intensity inside the Sun!

Units and Glossary

To avoid having to keep saying thousands, millions, billions etc the scientific community has agreed a shorthand way, based on prefixes, to denote the multiplication and division of units. Many of its terms have entered everyday use – a kilogramme (kg) is a thousand grammes, a millimetre (mm) is a thousandth of a metre etc. The prefixes encountered in laser science are listed below:

Prefix	Symbol	Multiplier	Number
exa	E	million million million	1,000,000,000,000,000,000 = 10^{18}
peta	P	thousand million million	1,000,000,000,000,000 = 10^{15}
tera	T	million million (= trillion)	1,000,000,000, 000 = 10^{12}
giga	G	thousand million (= billion)	1,000,000,000 = 10^{9}
mega	M	million	1,000,000 = 10^{6}
kilo	k	thousand	1,000 = 10^{3}
milli	m	thousandth	0.001 = 10^{-3}
micro	μ	millionth	0.000001 = 10^{-6}
nano	n	thousandth of a millionth (= billionth)	0.000000001 = 10^{-9}
pico	p	millionth of a millionth (= trillionth)	0.000000000001 = 10^{-12}
femto	f	thousandth of a millionth of a millionth	0.000000000000001 = 10^{-15}
atto	a	millionth of a millionth of a millionth	0.000000000000000001 = 10^{-18}
zepto	z	thousandth of a millionth of a millionth of a millionth	0.000000000000000000001 = 10^{-21}

As examples of what these units mean in practice, a picosecond is the time taken for light to travel 0.3 millimetres, the diameter of human hairs ranges from below 20 micrometres to above 150 micrometres and the total capacity of all of the world's power stations is a few terawatts. The energy released when a chocolate bar is consumed is of the order of 1 megajoule.

Abbreviations and names used in the Highlights brochure include:

10PW The ten petawatt upgrade of the CLF's Vulcan laser

ALICE Accelerator and Lasers In Combined Experiments (a joint technology system at the STFC's Daresbury Laboratory – see p 60)

ARTEMIS An ultrafast CLF laser system with extreme UV capability and advanced experimental facilities (see p 68)

ASTRA The CLF's high repetition rate high-power laser system (see p 66)

BBSRC The Biotechnology and Biological Sciences Research Council

CCD Charge-coupled device (a technology used in solid-state cameras)

CLF The Central Laser Facility

CPA Chirped pulse amplification (a technique for producing high peak laser powers – see p 7)

DNA Deoxyribonucleic acid (a molecule containing the instructions for living organisms)

EGFR Epidermal Growth Factor Receptor (a family of proteins involved in cell division)

ELI The Extreme Light Infrastructure (a European facility project to advance the state of the art in high-intensity lasers)

EPSRC The Engineering and Physical Sciences Research Council

ESA The European Space Agency

FEL Free Electron Laser (an accelerator-based light source with a laser-like beam)

HiPER High Power laser Energy Research Facility (a CLF-led international programme to deliver the technology for an IFE power plant – see p 56)

ICF Inertial Confinement Fusion (a scheme for fusing atomic nuclei based on very rapid heating)

IFE Inertial Fusion Energy (the use of ICF to drive electric power production)

IR Infrared

ISIS The STFC's accelerator-based pulsed neutron facility

LIBRA Laser-Induced Beams of Radiation and their Applications (a programme to develop laser-driven sources of subatomic particles)

LSF The Lasers for Science Facility (a suite of specialised CLF laser laboratories – see p 70)

MRC The Medical Research Council

NIF The National Ignition Facility (a very large ICF laser system in the USA)

NLS The New Light Source (a proposed UK facility using both accelerator-based and conventional laser light sources – see p 58)

NOISE New Outlooks In Science and Engineering (an outreach scheme aimed at 16-19 year olds)

OCTOPUS The LSF's suite of laser and microscopy systems used for functional biosystems imaging

OPCPA Optical Parametric Chirped Pulse Amplification (the combination of CPA with nonlinear optical techniques to produce the very highest laser powers)

PET Positron Emission Tomography (a medical technique used for body scanning)

PIRATE Picosecond Infrared Absorption and Transient Excitation (a sensitive infrared spectrometry system based in the LSF)

QED Quantum Electrodynamics (the theory of electricity and magnetism with quantum-mechanical effects included)

QMUL Queen Mary University of London

RCUK Research Councils UK (the Research Councils' strategic partnership organisation)

RNA Ribonucleic acid (a molecule similar to DNA and used in protein synthesis)

SCARF-LEXICON The CLF's computer cluster used for physics modelling

SEA Science and Engineering Ambassadors (a broad outreach scheme)

SORS Spatially Offset Raman Spectroscopy (a technique for analysing materials which are buried beneath or within others – see p 30)

STFC The Science and Technology Facilities Council

TiS Titanium-doped Sapphire (a laser material which can produce very short pulses)

TRIR Time-Resolved Infrared (a class of spectroscopies used to probe electron dynamics)

ULTRA Ultrasensitive Time-Resolved Life-Science Analysis (an LSF laser system used for molecular structural dynamics studies)

UV Ultraviolet

VULCAN The CLF's large Neodymium: glass laser system (see p 64)

Acknowledgements

The articles in this brochure report just a sample of the CLF's activities, all of which are made possible by the skill and hard work of the facility's staff and users. Given their extremely busy schedules, I have been very grateful for the effort and enthusiasm shown by everyone who has provided me with material. They are too numerous to name individually, but my special thanks must go to my colleague Vicky Stowell, without whose steadfast support and commitment Highlights would probably still be in preparation! It is also a pleasure to acknowledge the professional contributions of Nina Hall, who produced and edited several of the articles, and of Barry Miles at Ampersand Design, who transformed our raw words and pictures into the finished product.

Graeme Hirst – Editor

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