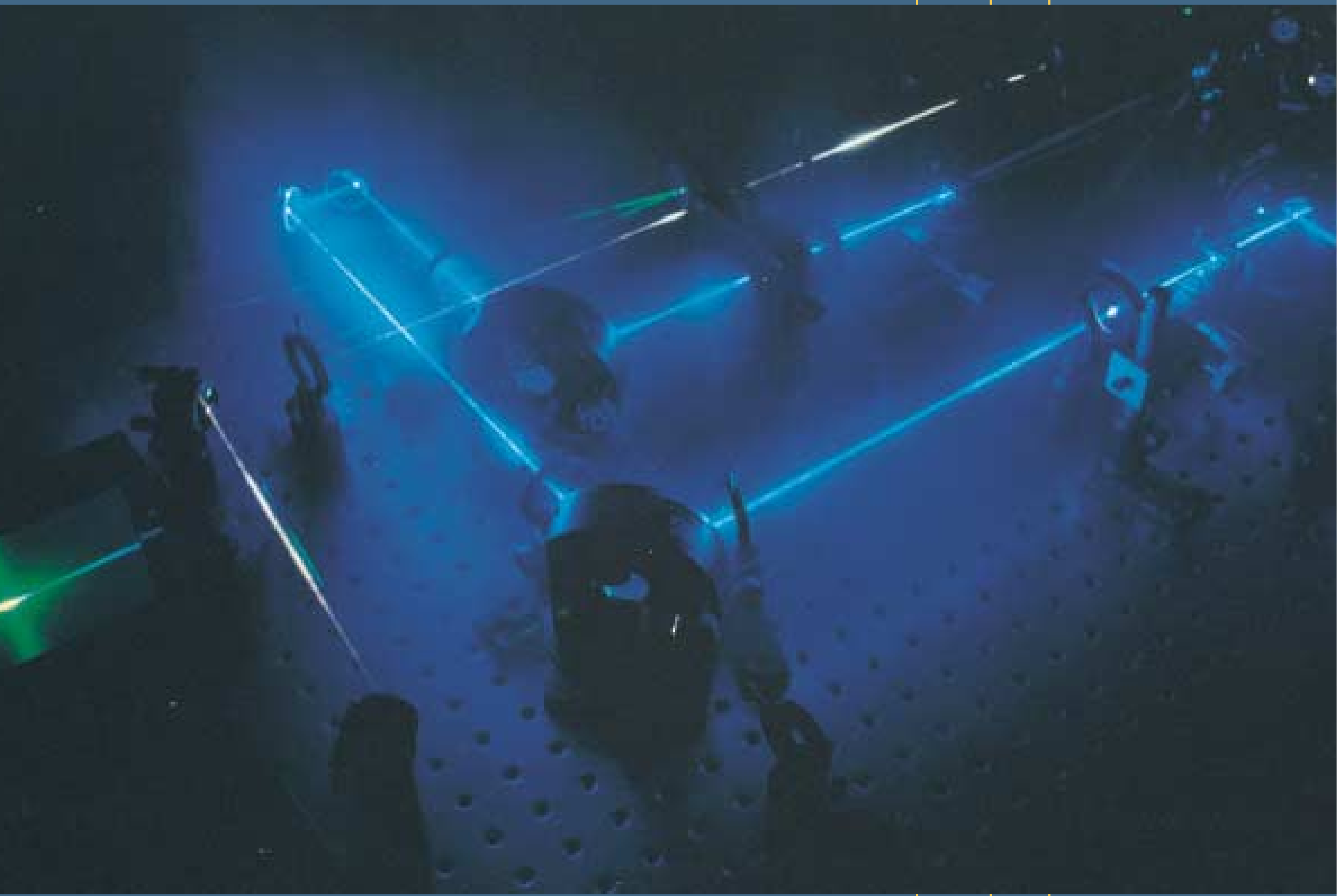
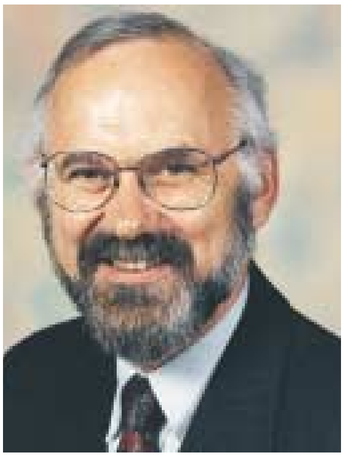
HIGHLIGHTS

Central Laser Facility



Preface



Research at the Central Laser Facility is a partnership between its staff and members of the UK and overseas scientific communities who use the specialised laser equipment provided to carry out a broad range of experiments in physics, chemistry and biology. We hope that this booklet will convey some of the excitement and achievements of this community.

MHR Hutchinson
Director, Central Laser Facility

Lasers

The world of high intensity lasers is a world of extremes: extremely tiny pulses of light and extremely high power.

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory (RAL) near Oxford is one of the world's leading laser facilities which provides scientists from universities in the UK and Europe with an unparalleled range of state-of-the-art laser technology. The research is funded predominantly by the Engineering and Physical Sciences Research Council (EPSRC).

Lasers are one of the most versatile and useful tools available to scientists. They have a wide range of applications from re-creating the extreme conditions found in the centre of planets to tracking the movement of drug molecules in living cells. Extremely high intensity laser energy, for example, can be focused to a tiny spot where the temperature reaches tens of thousands of degrees and the pressure, millions 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. By studying the physics of these plasmas, scientists can for example begin to learn more about how we can harness nuclear fusion as a potential source of energy.

Chemists can learn about the nature of the bonds between atoms by observing how high intensity light energy interacts with the bonds. Laser light can be used to monitor chemical reactions that are occurring in a few thousand millionths of a second, highlighting short-lived intermediate molecules which could not otherwise be detected.

This booklet describes the laser technology which has been developed at the CLF together with examples of the cutting edge science which has been carried out at the facility.





What is a Laser?

A laser is a device that amplifies light. By shining a light beam in at one end of a laser a more intense beam emerges at the other. There are many hundreds of different kinds of laser which amplify visible, infrared or ultraviolet light.

Laser light is very different from the light produced by, for example, a torch. It spreads out less, it contains light of only one colour, or wavelength, and it can be produced in intense pulses.

To produce laser light it is necessary to pump energy into a suitable type of atom or molecule so that the electrons of the atom become excited and jump from one energy level to a higher energy level. If the excited electron returns to its original energy level it emits energy as a photon, or packet of light. However, if another photon of similar energy to that which is about to be released strikes the excited atom, a second photon is emitted which is exactly in step, or in phase, with the first. This is called stimulated emission of radiation. These two identical photons can each produce more, and so on, leading to a cascade of identical photons.

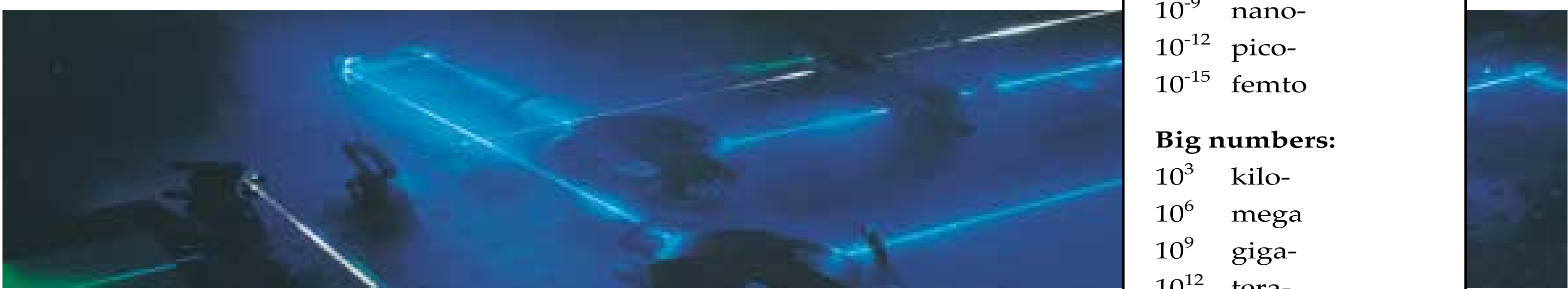
This light amplification by stimulated emission of radiation - or 'Laser' - leads to a beam of light where all the photons are in phase and are travelling in the same direction.

In order to amplify the light, energy needs to be pumped into the laser. The process is rather like pumping up a balloon. The power we use to pump up the balloon is small, but the balloon stores the total energy (power x time) as air under pressure. When the balloon is burst, this energy is released in a short time, giving a high output of power. The same principle applies to pulsed lasers: in a neodymium-glass laser, for example, the pumping time is typically one millisecond. The energy is then released in a nanosecond giving a million times increase in power. So for a pulsed laser, the shorter the duration of the pulse of light, the greater its power.

Most of the laser systems at the CLF consist of three principal components: an oscillator, where the initial seed pulse of light is produced; an amplifier, where energy is pumped into the system; and the experimental area, where the laser energy emerges and is focused on to the chosen target.

At the CLF there are three main laser facilities: Vulcan, Astra and the Lasers *for* Science Facility.

A pulse of light might last a thousand times less than a billionth of a second; the focused power it produces could be of the order of a thousand billion billion Watts per square centimetre.



When dealing with numbers of these magnitudes, standard prefixes are used.

Small numbers:

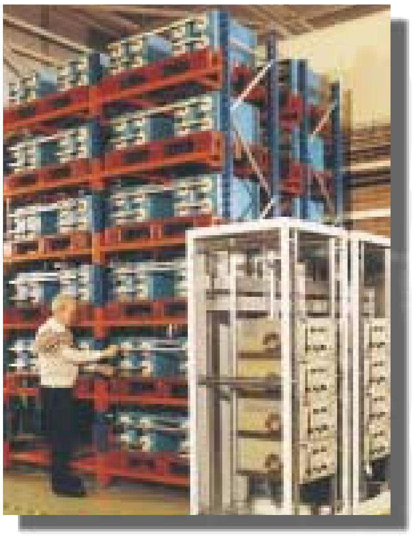
10^{-3}	milli-
10^{-6}	micro-
10^{-9}	nano-
10^{-12}	pico-
10^{-15}	femto

Big numbers:

10^{3}	kilo-
10^{6}	mega
10^{9}	giga-
10^{12}	tera-
10^{15}	peta-

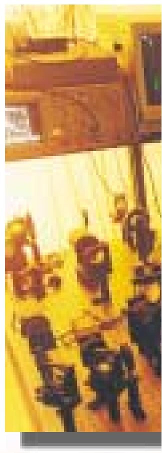
High Power Lasers

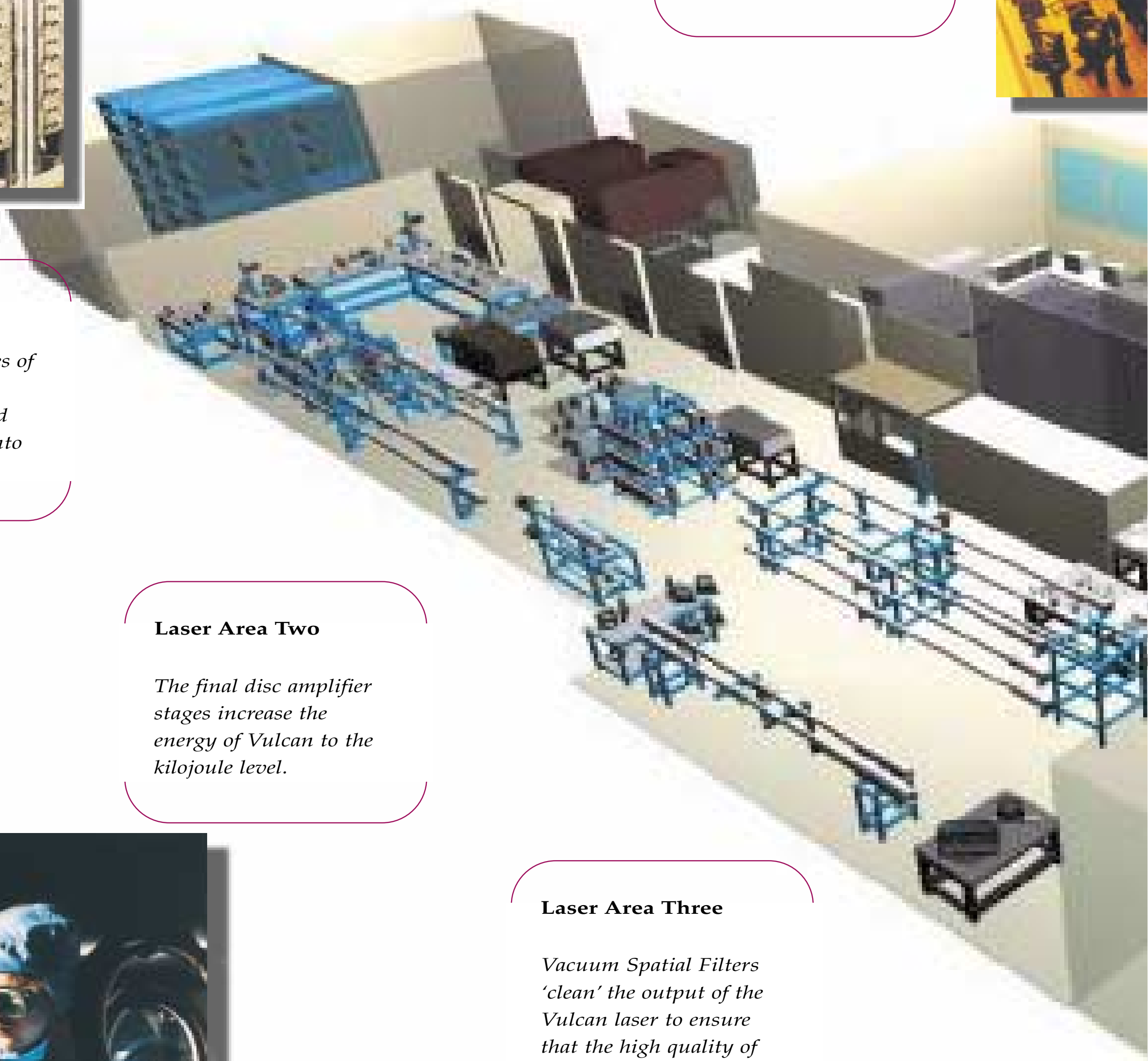
High power lasers at the Central Laser Facility offer UK and European researchers unique facilities for studies in ultra-high intensity laser interactions with solids, gases and plasmas. The CLF provides two complementary laser facilities for this work: Vulcan a high energy neodymium:glass laser and Astra a high repetition rate titanium-sapphire laser.



Oscillator Room

State of the art optical pulse generation systems are used to produce the initial seed pulse for the main system.





Capacitor Room

The two million Joules of energy required for a Vulcan shot are stored here until switched into the system.

Laser Area Two

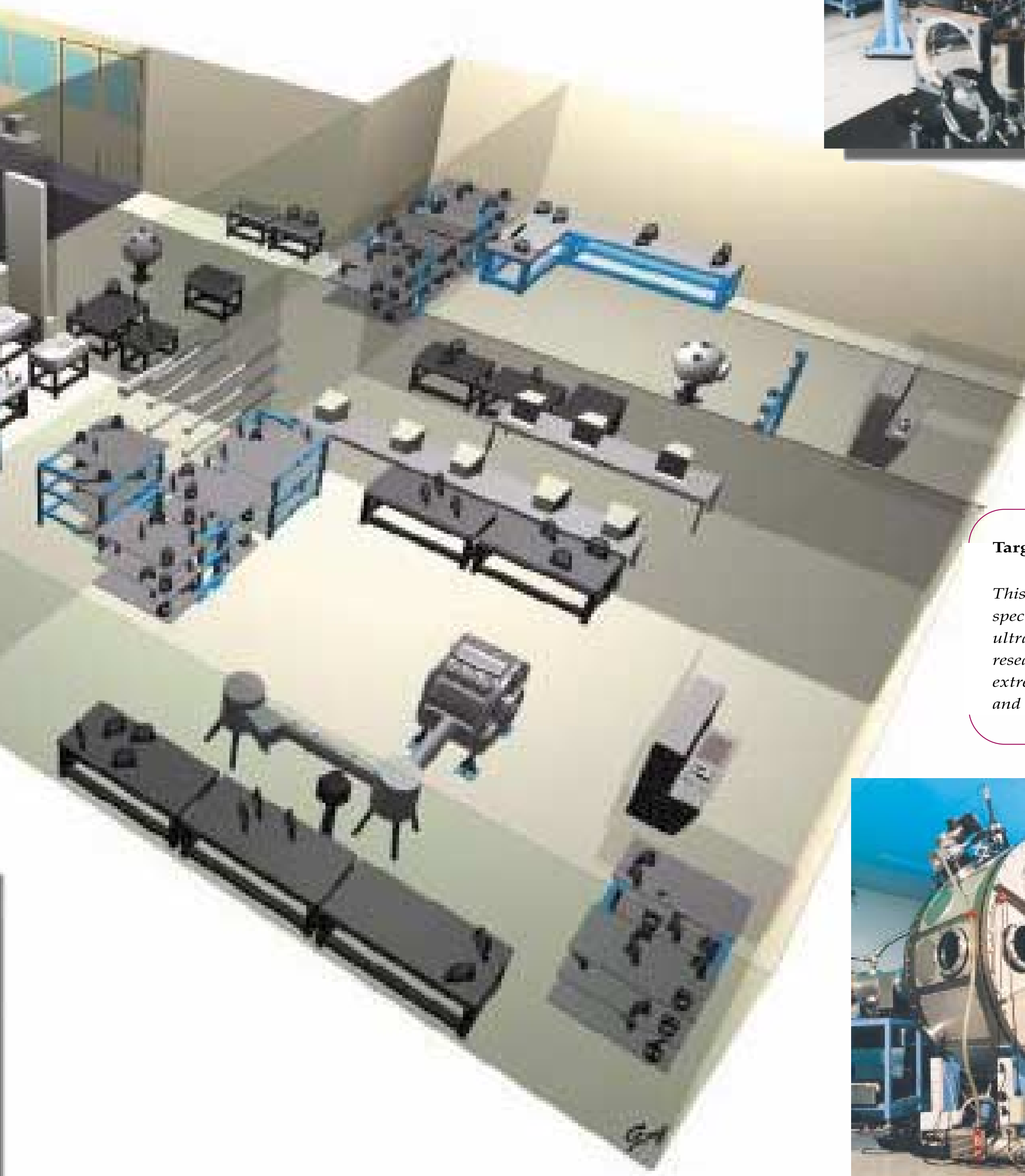
The final disc amplifier stages increase the energy of Vulcan to the kilojoule level.

Laser Area Three

Vacuum Spatial Filters 'clean' the output of the Vulcan laser to ensure that the high quality of the beams is preserved into the target areas.

Target Area East

This target area is seen configured in cylindrical geometry for an X-ray scattering experiment.



Target Area West

This target area specialises in the ultra-high intensity research that generates extremes of temperature and pressure.

Vulcan Petawatt upgrade

Vulcan's ultra-short pulse beam is currently being upgraded to 500J in a pulse of 500 fs duration, giving a power on target of 1 Petawatt - 10^{15} Watts. Using sophisticated optics this beam can be focused to a spot producing an intensity of 10^{21} Wcm^{-2}. This level of performance is opening up new regimes of plasma physics to scientists, including the ability to simulate plasmas found only in space. The Vulcan Petawatt upgrade represents an important stride forward in ultra-high intensity laser physics.

Vulcan is the main high power laser facility at the CLF

Vulcan is the world's leading ultra-high intensity laser, capable of delivering more than 100 Terawatts of power in pulses of energy with a duration of less than a picosecond. Vulcan is a neodymium:glass laser - the pulses of laser light are generated by stimulating neodymium, a transition metal, which is embedded in a glass matrix.

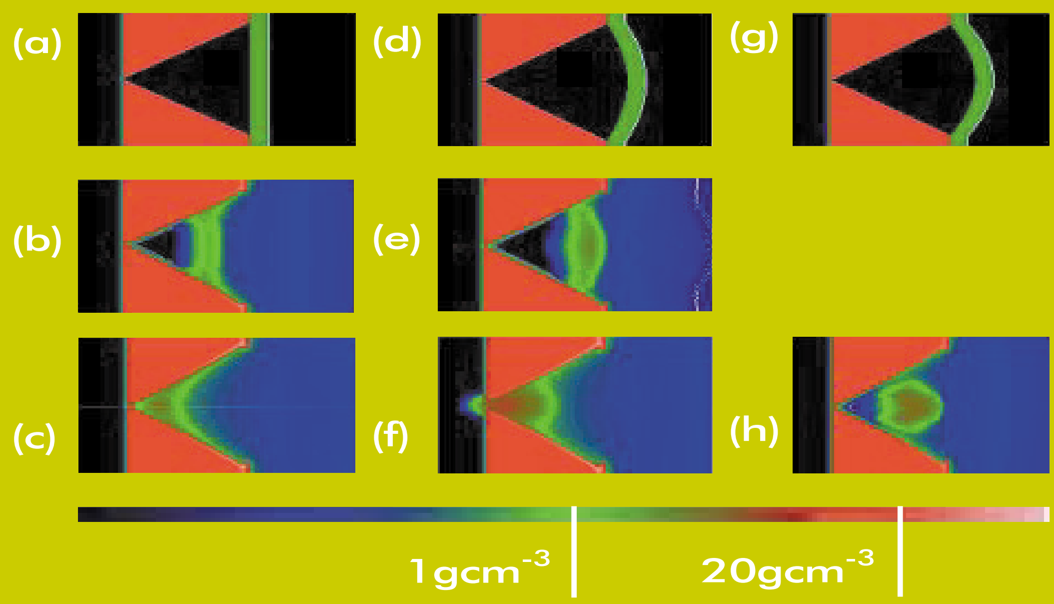
The initial seed pulse of laser light is generated in Nd:glass in the oscillator. This pulse then passes into successive amplifiers of Nd:glass where it is pumped with energy from flashlamps. After amplification it is split into either two beams, of 150 mm and 200 mm diameter, or six beams, each of 108 mm diameter. This gives the system more versatility and flexibility. For example it is possible to synchronise two or more pulses on the target to observe their effect, or to arrange the beams in a variety of geometries.

The beams of laser light are focused to a spot as small as 10 microns in diameter. This can result in intensities in excess of 10^{20} Wcm^{-2} - effectively creating a 'mini-Sun'.

After Vulcan fires, it takes 20 minutes for the system to cool sufficiently to allow the next pulse to be generated. This limits the repetition rate of Vulcan to 3 pulses per hour.

Chirped pulse amplification.

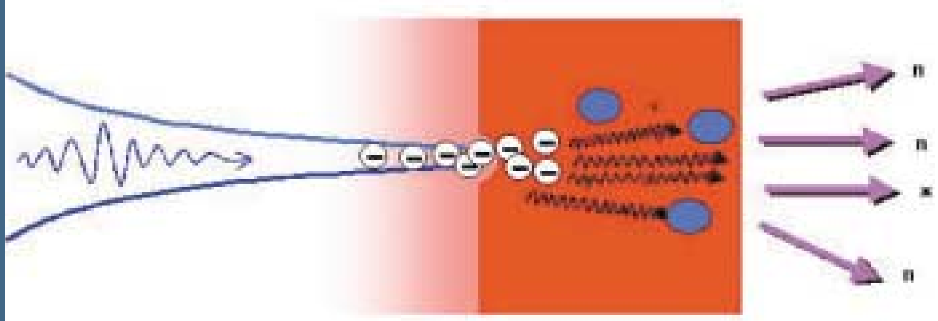
As the pulse of laser light is successively amplified, various optical phenomena begin to occur causing the beam to focus. Unchecked, this would limit the intensity which could be generated safely. To overcome this problem a technique called chirped pulse amplification, or CPA, is used. In this scheme a low intensity pulse is stretched in time from a few hundred femtoseconds to a few hundred picoseconds. In this form the pulse can be safely amplified before being recompressed and focused on to the target. CPA dramatically increases the intensity of a short pulse - by a factor of up to 1000.

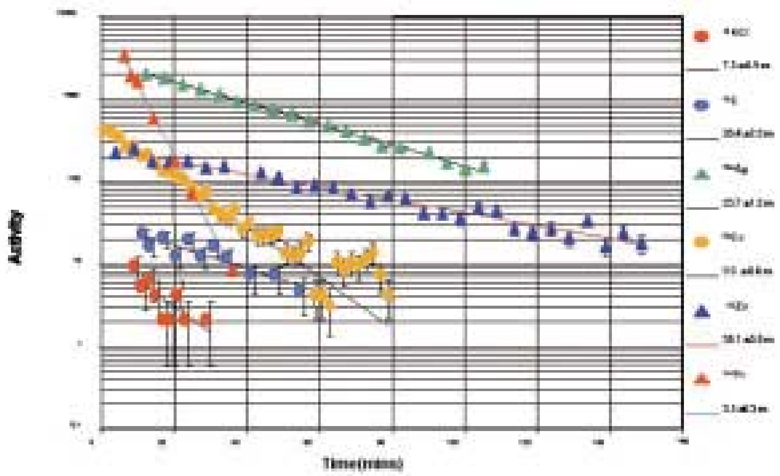


Novel geometries for nuclear fusion

For many years scientists have been investigating the possibility of using nuclear fusion as a source of essentially limitless energy. Laboratories across the world are investigating the fundamental aspects of fusion. To initiate a fusion reaction, an initial pulse of energy is required. One scheme, called Inertial Confinement Fusion, uses a nanosecond long laser pulse to drive an implosion of a small capsule containing thermonuclear fuel. The implosion results in a hot central region surrounded by a cool outer layer. The central core provides the spark which launches a 'thermonuclear burn wave' through the fuel, releasing energy. However, a more efficient way of launching the reaction is to implode all the fuel to a cool state using nanosecond long laser pulses followed by a short pulse laser. This directly heats one side of the fuel and thereby launches the thermonuclear burn wave. Researchers from the UK and Japan have used Vulcan to investigate this so-called fast ignition route to fusion. Uniquely the experiments examined an implosion driven down a cone, rather than spherically as in conventional systems. The results of the work demonstrated that this approach to fast ignition appears to have certain inherent advantages and should be investigated further.

High-energy sub-atomic snooker



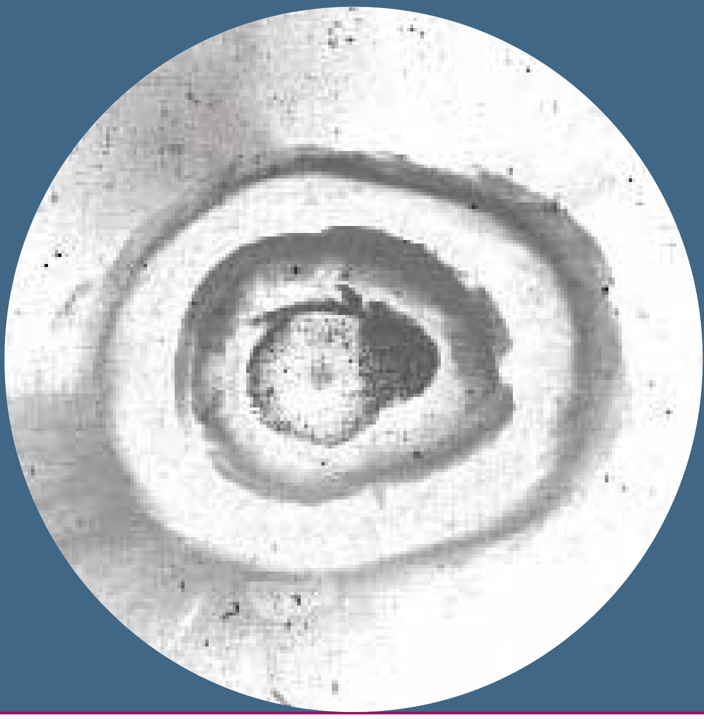


A team of UK researchers has created a series of novel interactions by shooting ultra-high intensity pulses of laser energy into various targets. By aiming the laser pulse into a thick target with a high atomic number, a narrow beam of electrons was produced with incredibly high energies. The electrons stream into the dense target and are stopped by collisions with target atoms, liberating high energy gamma and X-ray photons. These photons in turn interact with atomic nuclei. Photons with sufficient energy remove neutrons from the nucleus, making it radioactive. The researchers used this process, known as a (γ,n) reaction, to generate a number of intense radioactive sources. They also used the laser to induce fission of uranium, something which previously had been only been predicted theoretically. The techniques could provide a novel route to the production of short-lived radioisotopes for medical applications.

Record for accelerating laser plasma electrons

A team of researchers from the UK, France and the US has used Vulcan to accelerate electrons at a rate 10,000 times more than can be achieved conventionally. The result is important because it opens the way to the next generation of particle accelerators for the fundamental study of particle physics. The experiment focused a sub-picosecond pulse of laser energy into a jet of helium gas, generating a 'plasma wave' of large amplitude. This wave traps plasma electrons and accelerates them to very high energies (100 MeV). The next challenge for the team is to establish the accelerating field over a greater length. This would produce even higher particle energies and refine the plasma wave generation process to enable fine control of the characteristics of the electron beam.

Electron acceleration to ultra-high energies is limited in conventional accelerators, such as those found at CERN, by electrical breakdown within the accelerating components. Using a plasma as a medium to accelerate electrons overcomes this problem as the material, the plasma within which the acceleration takes place, is already ionized and hence not susceptible to electrical breakdown.

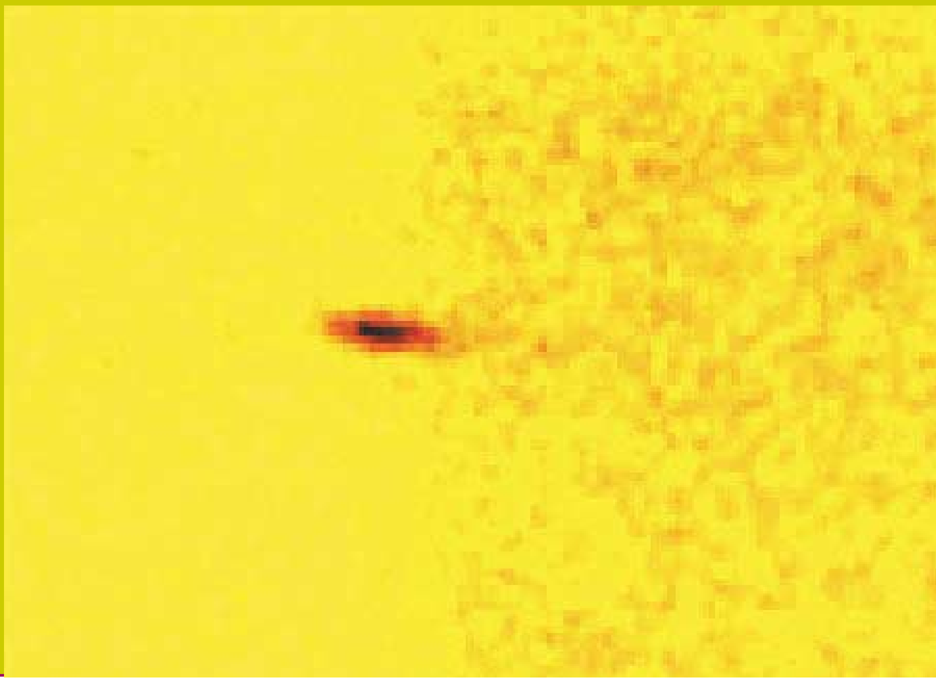


World's first high-energy laser-produced protons

By using extreme laser intensities on solid targets, UK researchers have demonstrated the first observations of the production of high energy protons and heavy ion beams. At these ultra-high intensities, up to 10^{20} Wcm^{-2}, the plasma produced by the laser can have a 'temperature' of millions of degrees and a 'pressure' of billions of atmospheres.This results in very energetic particles being produced. Because of the exotic nature of the matter, it is difficult to talk about temperatures and pressures in conventional terms. The high energy protons are emitted in a characteristic pattern which would seem to indicate the presence of the largest ever magnetic fields measured in a laboratory. These energetic protons have potential uses for medicine in imaging techniques such as positron emission tomography and in proton radiotherapy.

Protons reveal the inner workings of plasmas

Scientists are continually looking for new ways to determine what is happening within plasmas. The interaction of laser energy with plasmas can reveal fundamental information about the nature of the plasma's constituents. When ultra-intense laser pulses interact with matter, a significant fraction of the laser energy is deposited into highly energetic proton and ion beams. UK researchers have used these beams to probe high-density laser-produced plasmas. In particular, proton imaging can be used to detect magnetic and electric fields within the plasma. The researchers successfully used protons generated in this way to observe the effect of short-pulse, high intensity laser energy on plasmas.



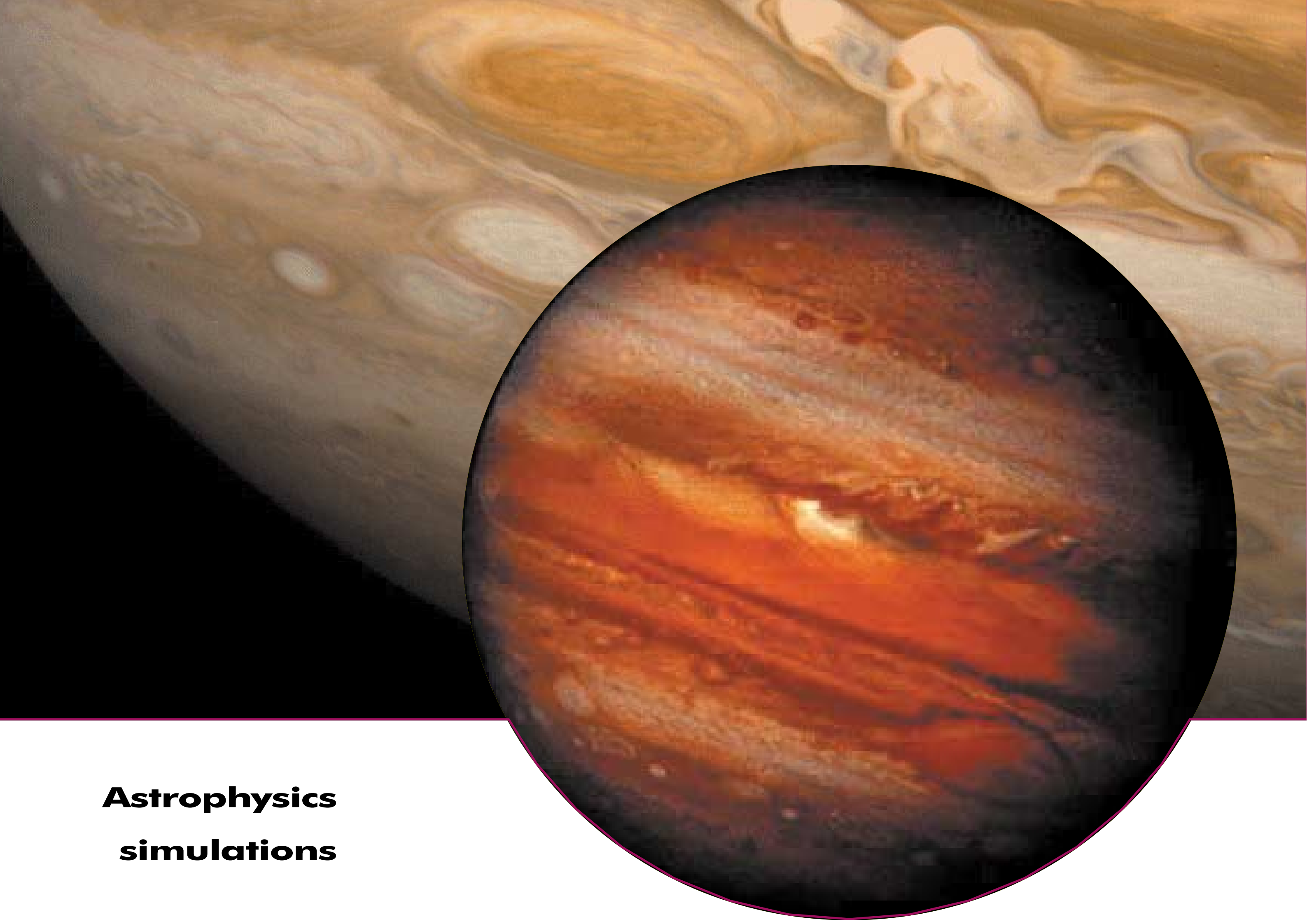
Shortest-ever soft X-ray lasers

Low-energy, or 'soft', X-ray lasers have many applications in both science and engineering, for example by using the X-rays to 'micromachine' tiny three-dimensional electronic components. However, it is difficult to produce soft X-ray lasers by conventional methods. A team of French, British and German scientists have used Vulcan to generate soft X-ray laser light in a novel way. These researchers first generated a plasma capable of emitting soft X-rays. They then configured Vulcan to deliver a series of ultra-short laser sweeps across the plasma column so that the laser pulses were exactly in step with the X-ray beam being generated. The effect was to 'pump' the X-rays, delivering the shortest-ever pulse of soft X-ray laser light. Because of its highly efficient short-pulse operation, this pumping scheme has a real chance of providing the basis for a user-friendly, table-top source of soft X-ray laser radiation for a wide range of applications.

The image above shows a 2-3 picosecond x-ray laser pulse recorded on an ultra-fast streak camera. This state of the art diagnostic works in a similar way to a single line television. The x-ray laser pulse is converted to a beam of electrons which is then scanned across a light emitting phosphor. The light can be detected using a conventional camera where the pulse can be analysed.

Vulcan helps in development of large area flat-screen displays

Researchers from Nottingham Trent University are developing tiny transparent flat-screen display devices that can be positioned in front of the wearer's eyes to deliver information. Such head-mounted displays, or HMDs, are built on silicon chips and use a technique called thin-film electroluminescence to produce images that are sufficiently bright to be seen clearly by the user. The research team has used Vulcan to generate high power ultraviolet laser light to treat the display materials. This has the effect of annealing the materials - essentially 'ironing out' molecular flaws within the structure. This improves the performance of the displays, producing the intensity necessary to project useful images against a bright, sunlit sky.

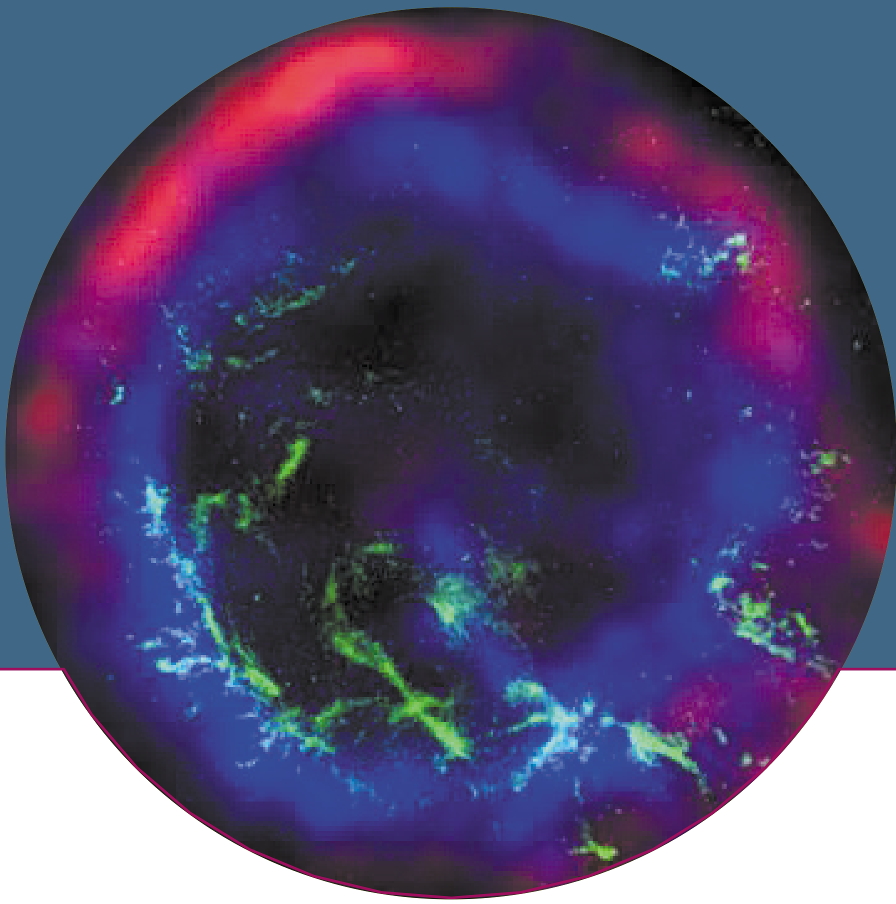


Astrophysics simulations

Researchers have used the Vulcan laser to generate conditions that are observed in space in environments as diverse as the interiors of planets and stars, and the plasmas found in regions between stars.

Forming planetary cores on Vulcan

An international team of scientists used Vulcan to study new states of materials relevant to those found in the interiors of planets such as Jupiter. At the extreme densities found in the cores of planets - the centre of Jupiter is at 80 million times the Earth's atmospheric pressure and 1300°C - matter is predicted to have quite unearthly properties, such as high temperature superconductivity and low temperature fusion. However, very little information exists for regimes similar to these. The researchers compressed water under huge pressure by using a combination of 'static' compression and 'dynamic' compression from laser-driven shocks. In this way the scientists recreated material states similar to those seen in the interior of Jupiter and at the core of the Earth, providing valuable new data about them.



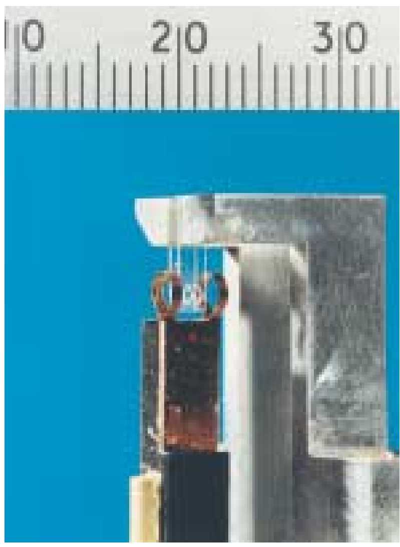
Picture to left courtesy of NASA, picture to right courtesy of NASA/CXC/SAO/HST/CSIRO/ATNF/ATCA.

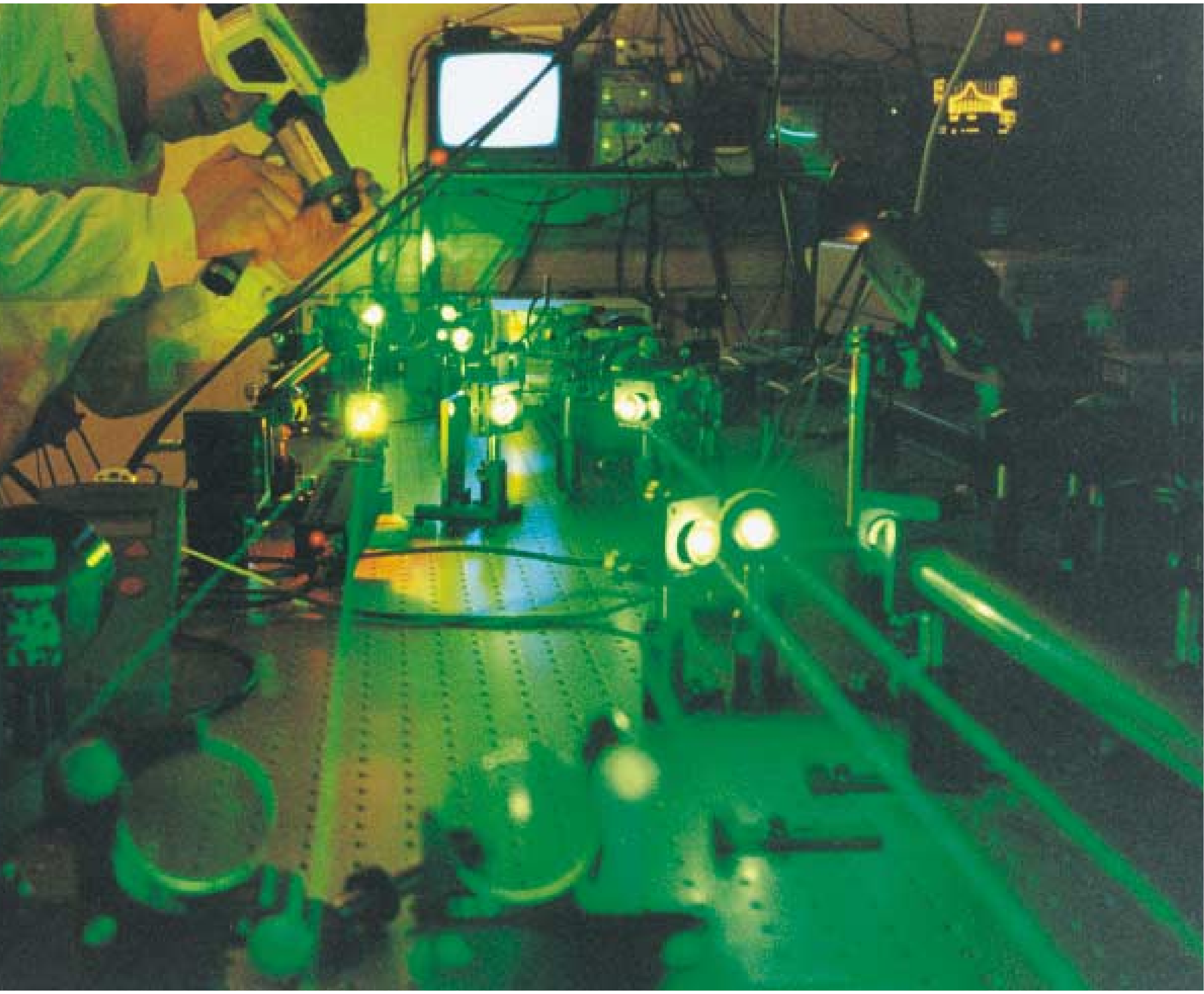
Simulating the exotic centre of giant planets

At the centre of giant planets the temperatures can reach tens of thousands of degrees and the pressure millions of times our own atmospheric pressure. Such environments are home to a range of exotic matter. One way of investigating such matter is to create small samples in the laboratory using pulsed laser beams. A team from Queen's University Belfast focused three beams of the Vulcan high power laser on to each side of a thin foil. The result was to drive shock waves and X-ray radiation into the sample, which both compressed and heated it. Other laser beams were then used to generate a separate intense burst of X-ray energy. These X-rays were used to probe the sample. While most of the X-rays passed through the sample, a small fraction were scattered into a detector. By analysing how many X-rays were scattered at different angles, the research team were able to obtain important information about the behaviour of the sample at temperatures of over 20,000°C and pressures of millions of atmospheres.

The remnants of a starburst

A supernova is a rare, spectacular explosion resulting in the destruction of a massive star. A team of scientists from the UK and Germany used Vulcan to recreate some of the important features of the physics of the remnants of a supernova. The two essential ingredients for these simulations were a powerful magnetic field and a realistic plasma. The team developed a small coil (pictured right) capable of generating the magnetic field within the laser target area. The plasma was created by directing the laser on to thin plastic foils. In this way the team created a tiny facsimile of the remnant of a supernova, providing important new insights into this stellar phenomenon.





Astra Laser

Astra is a high power laser which uses ultrafast laser technology to provide pulses whose energy is 0.5 J in a duration of 50 femtoseconds. When focused these pulses reach intensities on the target exceeding 10^{19} Wcm^{-2} - intense enough to make and study plasmas as hot as those found inside stars.

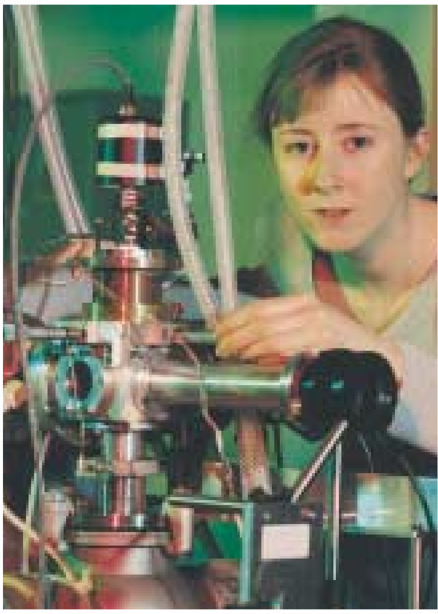
Astra is a solid-state laser and uses crystals of titanium-sapphire (TiS) as the lasing and amplifying medium. TiS produces laser pulses which have a wide range of wavelengths - which is essential for the generation of ultrashort pulses of high energy. A laser oscillator provides a source of low-energy (of the order of nJ) short pulses (around 20 femtoseconds). The energy contained within these pulses is increased by passing them through three amplifier stages in turn. The amplified pulses acquire energy stored in the amplifying TiS crystals. This stored energy is provided by exciting each crystal with energetic pulses of light produced by a secondary laser.

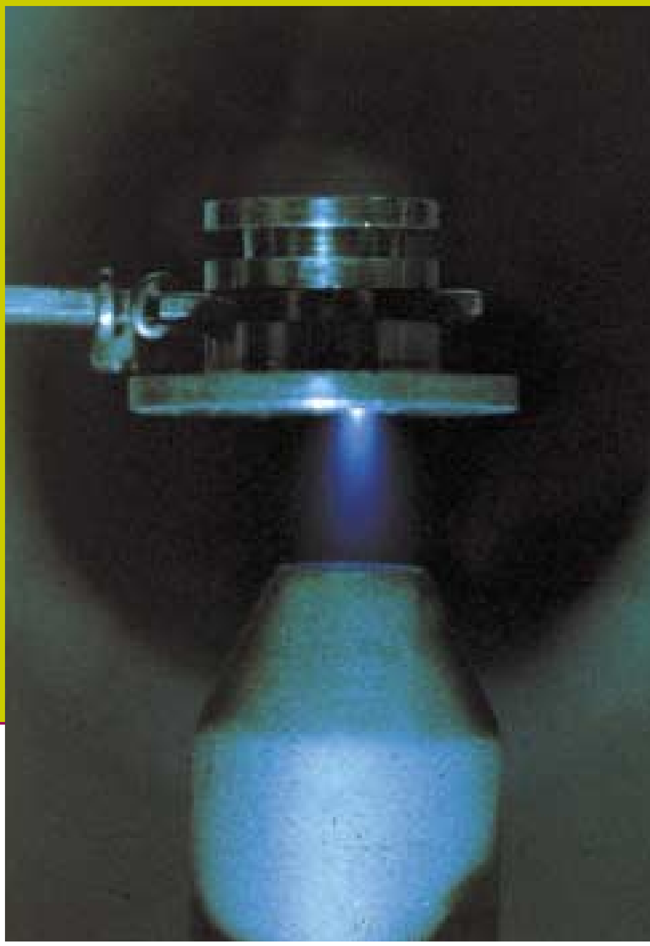
Some of the energy of the pulse produced after the second amplifier is directed towards a target area used for high-energy pulsed experiments - called Target Area 1, or TA1. These are experiments which require intensities of between 10^{14} and 10^{17} Wcm^{-2} when the beam is focused.

The remaining energy in the pulse is amplified in the third amplifier and this is directed towards an ultra-high energy target area, TA2. All the experiments in this area are carried out in an evacuated target chamber because the pulses are now so intense that they would ionise the air.

In TA1, the laser light is sufficiently intense to distort the electric fields within atoms or molecules, causing them to ionise and dissociate. By studying the energies of the emitted electrons, ions or dissociated fragments, scientists can obtain information about the basic physical processes involved in the interaction of light with matter.

At the higher intensities available in TA2 the electrons present in solid targets can be accelerated to very high energies and their energy is converted into gamma rays, which can induce reactions in atomic nuclei. The interactions of very intense laser radiation with matter are used in the study of X-ray lasers, the acceleration of electrons and protons to high energies and the production of radioactive isotopes.

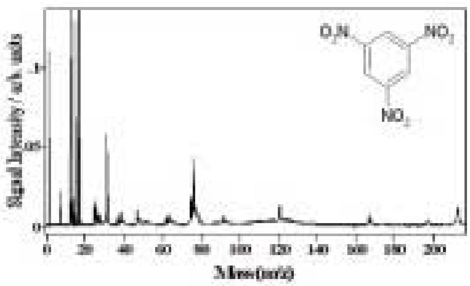


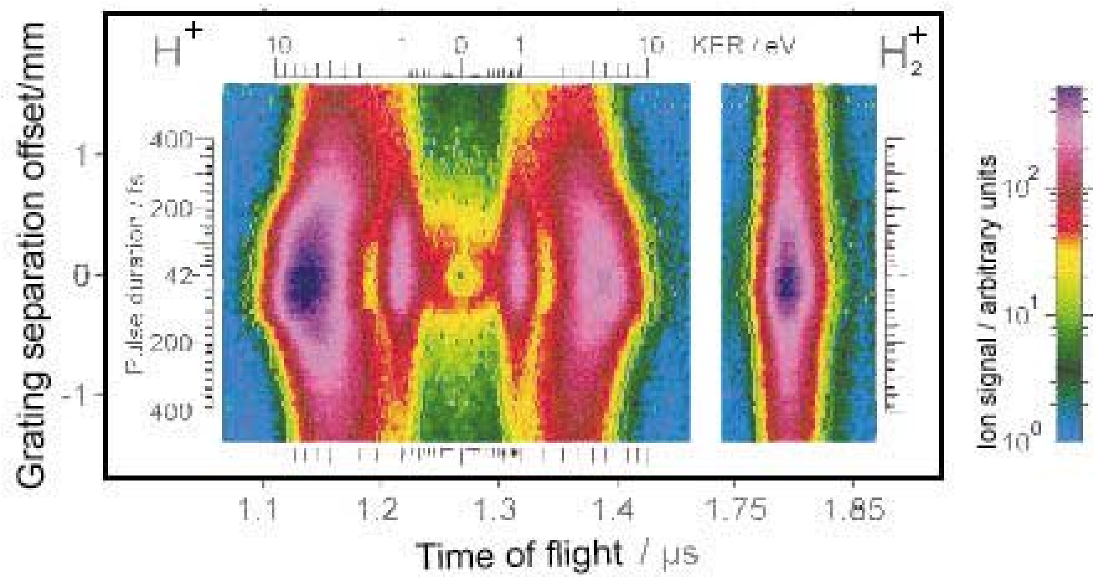


Detecting small traces of explosive

Ablation of a graphite target using laser pulses from a nanosecond Nd:YAG laser operating at 1064nm is shown to generate a plume of material, identified by time-of-flight mass spectrometry as carbon clusters (including C-60 and C-70 fullerenes). The blue colour is fluorescence from these carbon clusters produced in the excited plume.

Researchers from the University of Glasgow have exploited the very high intensity and short pulse length of Astra to develop a new way of detecting molecules. One way of analysing molecules is to blast them into small fragments with a pulse of high energy and then measure the time that it takes for the fragments to reach a detector. As the 'time of flight' of the fragments is related to their mass and charge, it is possible to piece together the constituents and obtain information about the parent molecule. However, the pulses of energy produced by Astra are so short that the molecule it is striking does not have time to dissociate, only to become ionised. Because the parent molecule remains intact, it is possible to rapidly identify it by measuring its 'time of flight'. The technique is called femtosecond laser mass spectrometry, and the Glasgow group has been using this system to detect small traces of explosives, pesticides and particle-borne atmospheric pollutants.

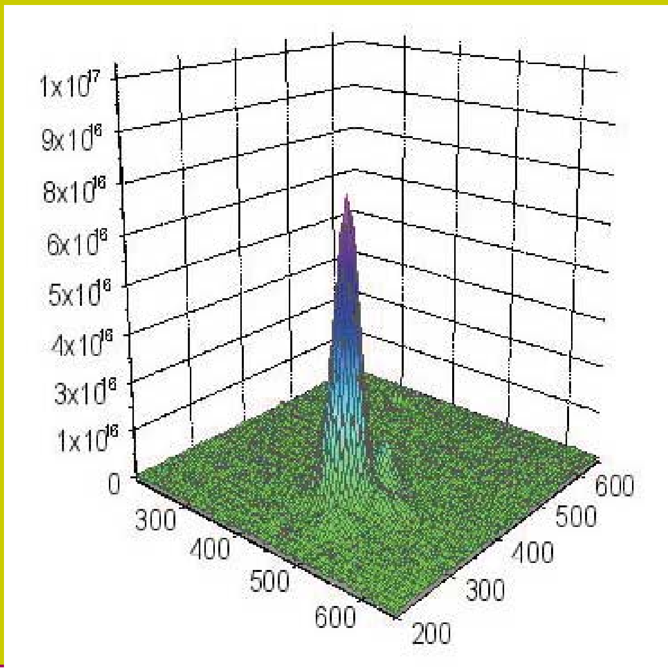




Hardening molecular bonds

When molecular bonds are exposed to strong laser fields, they normally become weaker - a process called 'bond-softening.' However, a group from the University of Reading has used Astra to make the first observations of the elusive process of 'bond-hardening' in the simplest molecular ion, H_2^+. Bond-hardening occurs due to the distortion of the internal electric fields of the molecule by the intense laser pulse and lasts only as long as the pulse is applied - that is around 100 femtoseconds. This makes direct observation of the process challenging. The occurrence of bond-hardening can be inferred from the kinetic energies of the fragments of the ion once it has dissociated into a proton and a hydrogen atom. By measuring the time of flight of the fragments - how long they take to reach a detector - it is possible to infer their kinetic energy. The kinetic energies of the fragments depend on the duration of the laser pulse used to ionise them.

The figure shows how the time-of-flight spectrum of hydrogen ions varies with the duration of the pulse. The round crater in the centre is a signature of bond-hardening.

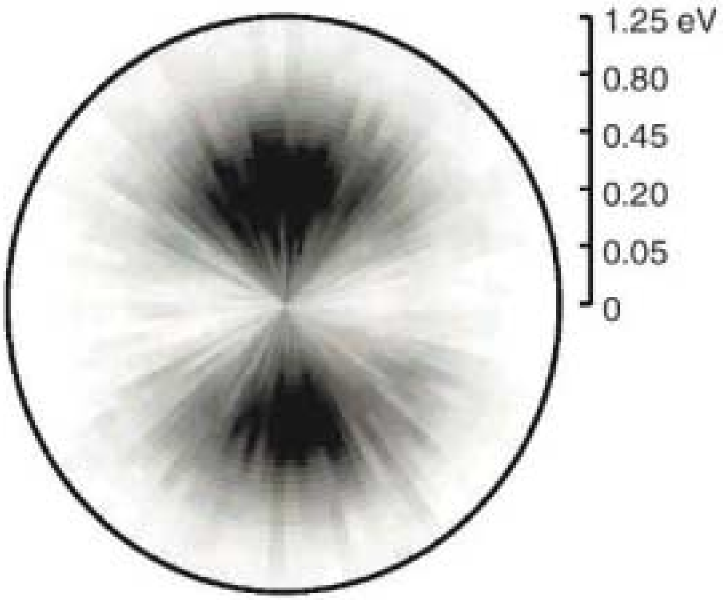


Guiding intense laser pulses through plasmas

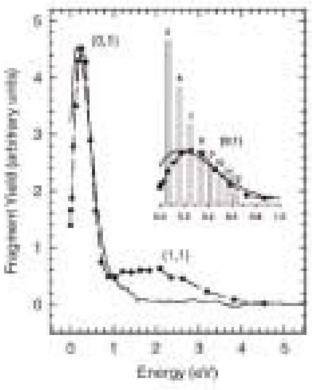
A number of important applications of high-power lasers, such as novel X-ray laser and laser particle acceleration, require an intense laser pulse to propagate over long distances through a plasma. This is difficult to achieve, however, since the propagating laser pulse is strongly defocused by diffraction and refraction in the plasma.

One possible solution is to guide the laser pulses with a device called a waveguide. However, at the high intensities of interest - 10^{16} Wcm^{-2} and higher - this is far from trivial as most waveguide structures would be destroyed.

Researchers from the University of Oxford have conducted experiments on Astra in an attempt to overcome these problems. They have used a structure called a gas-filled capillary discharge waveguide, in which a small discharge pulse breaks down the gas inside a small capillary to form a plasma, which remains confined within the capillary. Because of the pattern of the conduction of heat within the capillary, the density of the plasma is lower at the capillary axis than at the wall. The profile of the plasma's density causes the refractive index to reach a peak on the axis. This gradient of refractivity continually counteracts diffraction, causing the light to be guided along the length of the capillary. Experiments on Astra were able to demonstrate guiding in a device of this type for the first time. Pulses from Astra were focused to a spot of approximately 30 microns, corresponding to a peak intensity of 10^{17} Wcm^{-2} at the entrance of a ceramic capillary which had a diameter of 300 microns and was 20 mm long. When the discharge was fired, the pulses were guided with an energy transmission of greater than 90%. For capillaries 40 mm long the transmission was better than 85%. The results are a significant improvement on alternative techniques and suggest that gas-filled capillary discharge waveguides could be used in a wide range of applications.



Ultrafast processes in molecular ions



Chemistry essentially involves breaking and making bonds between atoms and molecules. One possible way of tailoring chemical reactions is by manipulating individual molecular bonds with pulses of laser energy. To achieve this goal, scientists must understand the fundamental nature of how laser energy interacts with chemical bonds. A team of researchers from University College London, Queen's University Belfast and the CLF have used the Astra laser to carry out a series of pioneering investigations into how laser energy interacts with the simplest molecular system, the H_2^+ molecular ion, consisting of two protons bounded by a single electron.

In a unique series of experiments the research team generated a beam of H_2^+ molecular ions and then focused intense laser pulses of 790 nm wavelength and 60 femtoseconds duration onto the ion beam. The focused laser power, where it met the ion beam, was in excess of 10^{16} Wcm^{-2}.

There are three possible outcomes when the H_2^+ molecular ion interacts with laser energy. If one photon, or 'packet', of laser light causes the ion to fragment, a single hydrogen atom is produced, together with a proton. These have characteristic energies. If this fragmentation is caused by two photons of laser light, the same species are produced but with higher kinetic energy. The third possibility is that the molecular ion undergoes a 'Coulomb explosion', resulting in two protons and an electron. By measuring the different kinetic energies released in the reactions, the researchers could differentiate between the three processes, obtaining valuable information about the fundamental chemistry and physics of the system. The research team also gained valuable data about how molecular species can become oriented by laser light.

Light generated from an Optical Parametric Generator (OPG) using a 400 nm femtosecond laser pulse in the Ultrafast Spectroscopy Laboratory.

Lasers *for* Science Facility

The Lasers *for* Science Facility (LSF) provides a broad range of lasers, laser-based techniques and expertise for scientists and industry. It is divided into four laser laboratories together with a Laser Loan Pool facility, where lasers can be installed in the scientists' own laboratories for a period of time.

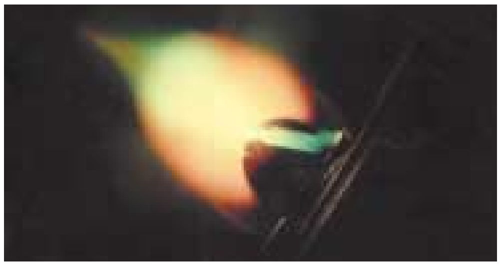
Confocal Microscopy Lab

The lasers in this laboratory emit light over a wavelength from the ultraviolet to the near infrared. The laser is used for imaging studies, such as, in stimulating certain molecules to fluoresce. Such fluorescent 'tags' can be attached to a drug molecule and the microscope used to track the movement of the drug in a living cell by measuring the distribution of the laser-induced fluorescence at very short time intervals.

The facility also houses an 'optical tweezers' system which can measure extremely small forces between particles. Light has a momentum, albeit tiny, and an intense beam of laser light can exert a mechanical force on very small particles. In this way, it is possible to pin a particle, such as a tiny polystyrene bead or a cell, in place with a laser beam. If the particle is subjected to a force, for example by being attracted to a neighbouring particle, its displacement can be measured. In this way the forces between the particles can be calculated.

Nanosecond Science Lab

This laboratory offers a diverse range of techniques for investigating the dynamics of chemical reactions. As chemical reactions occur, bonds break and re-form to create so-called intermediates, which themselves react to form new products. These reactions occur very quickly. By using the lasers in this laboratory, scientists can characterise the structure and reactivity of intermediates on a time scale of a few nanoseconds.



Laser X-ray Source

This laboratory generates a bright source of X-rays of high average power which have applications in fields as diverse as radiation medicine and X-ray lithography. The laboratory efficiently converts laser light to X-rays by using a train of picosecond pulses amplified to high power in two high repetition rate excimer (KrF) lasers. A wide range of wavelengths are available and average X-ray powers of 1Watt, in the forward direction, have been obtained at a wavelength of 1 nm.

Ultrafast Spectroscopy Lab

This laboratory specialises in producing very fast pulses of laser light to excite the molecule under study, then observing how the excited molecule interacts with a second pulse of laser light. This technique is called ‘pump and probe’, and because of the speed of the system, it is possible to observe even the movement of electrons. By characterising the different chemical intermediates produced during the ‘pump’ process, scientists can unravel the sequences of very fast reactions at the molecular scale.

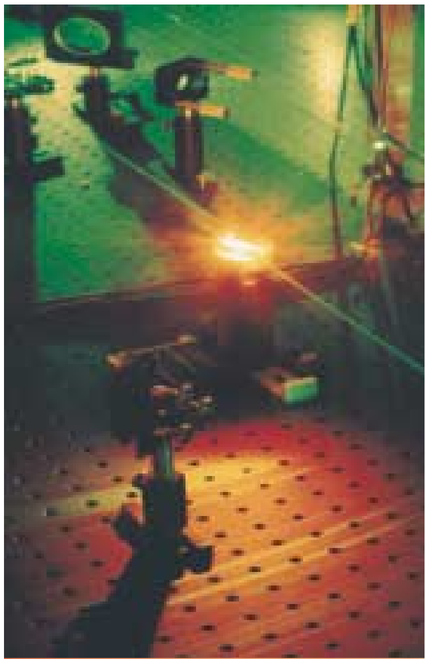
The CLF developed the world’s first ‘double tunable picosecond laser’ system that generates two synchronised and independently tunable beams, covering the spectral region between 220 nm (UV) to 10,000 nm (mid IR). This is a highly versatile system for studying the kinetics of chemical reactions.

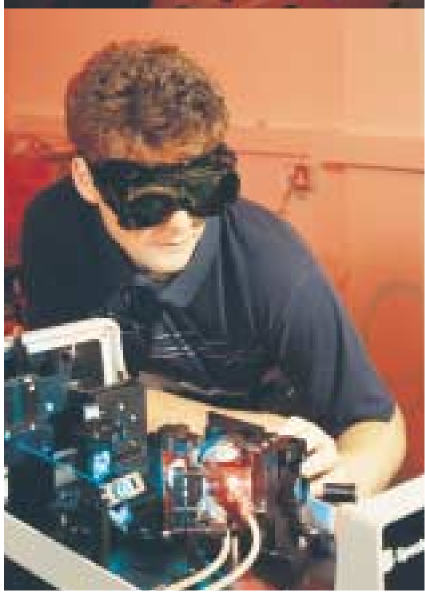
PIRATE

PIRATE, Picosecond Infrared Absorption and Transient Excitation, is a facility that brings together the experienced time-resolved infrared (TRIR) spectroscopy group at Nottingham University and the CLF laser expertise at RAL. The laser system uses developments in solid state lasers to generate pump and probe, both narrow and broadband, wavelengths into the mid infrared - the so-called ‘finger-print’ region of molecules. This provides a unique method for studying changes in structure of molecules during a chemical reaction on a picosecond time scale. These techniques will offer a method of studying fundamental chemical processes such as the mechanism of DNA and protein folding.

Laser Loan Pool

Through a loan pool, the CLF provides scientific lasers for researchers to use in their own laboratories. The lasers can be borrowed for feasibility experiments, used in extended research programmes or to enhance users’ existing research facilities. The loan periods are normally between 3 and 6 months. A range of lasers is available for a wide variety of applications in physics, chemistry, biology, engineering and materials science.



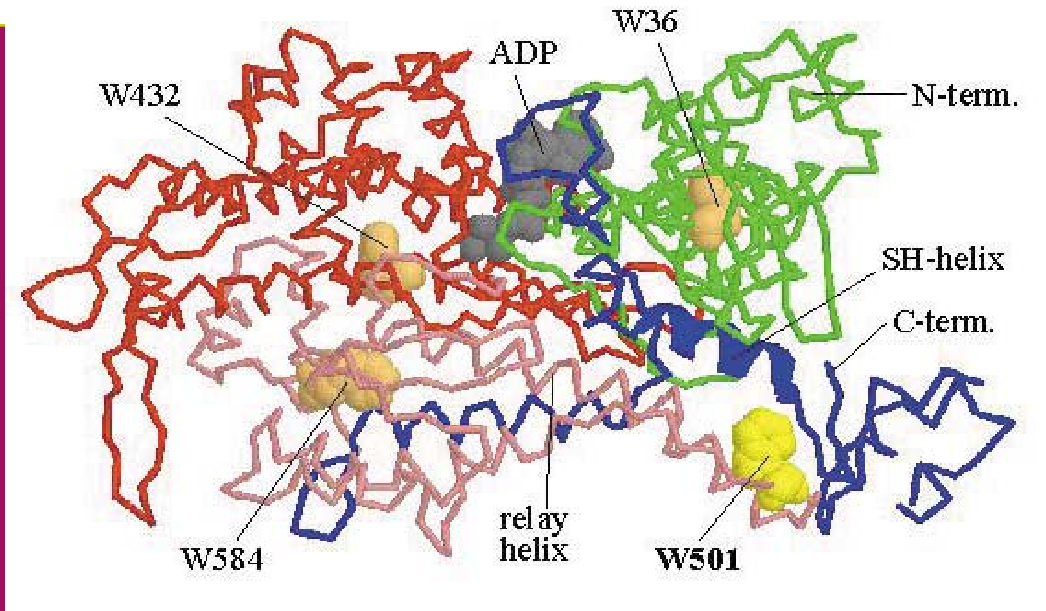


Laser Microscopy Laboratory: observing early events in muscle contraction

Biochemists have known for decades that muscle contracts by binding ATP, a molecule which provides energy for nearly all the processes in living cells. Researchers have used the pulsed lasers in the LSF to observe the changes that happen in the muscle protein, Myosin, when it binds and hydrolyses ATP. After exciting the system with picosecond pulse laser light, fluorescence is emitted over several nanoseconds. The nature of the emitted fluorescent light changes as the shape of the protein undergoes structural changes. By monitoring the emitted fluorescence scientists can learn about the early events in muscle contraction.

By combining these experiments with a laser scanning confocal microscope other systems can be imaged when excited by a single photon of light to generate 'fluorescence lifetime maps' of the protein and see it moving in it's natural state.

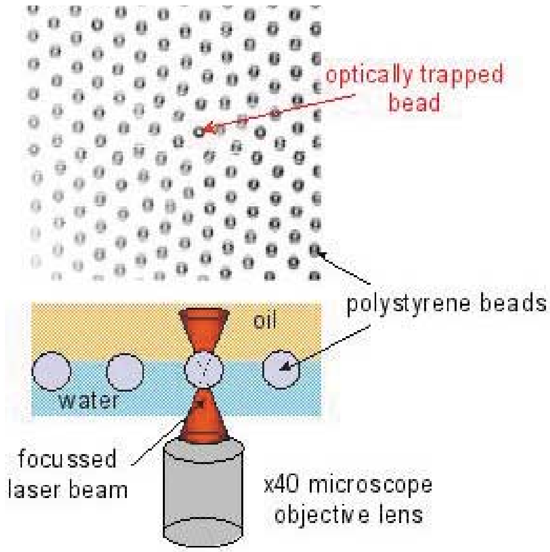
The protein Myosin showing the location of the amino acid tryptophan in yellow (bottom right).



Malnasi - Csizmadia et al (2000)

Laser Microscopy Laboratory: optical tweezers

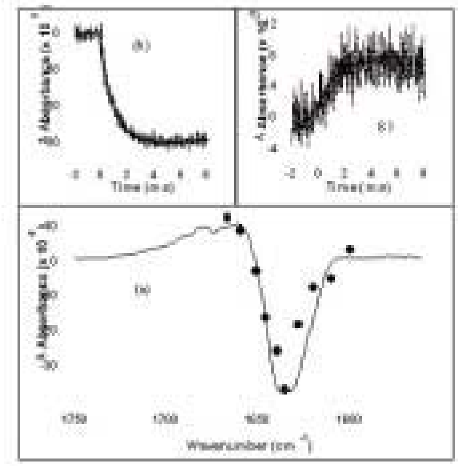
Optical tweezers offer the unique ability to manipulate particles dispersed in a liquid medium and to measure small forces on those particles in a non-intrusive and non-destructive manner. A tightly focused laser beam generates an 'optical potential' across a particle allowing the forces on that particle to be measured. The nature of the technique has led to its predominant use in the fields of medicine and microbiology. Laser tweezers also offer great possibilities for the study of colloidal particles such as those found in paints and surfactants. The application of the technique can range from the direct measurement of forces between individual particles to the determination of the elasticity of a polymer stretched between two beads held in place by a laser beam. The image shows the symmetric lattice structure created when tiny polystyrene beads are placed on the surface of water. The image of all the beads is blurred due to random 'Brownian' motion except the one held in the laser trap. The trap can be used to measure the minuscule forces that cause these lattices to form. The experiment can readily be adapted to measure the distribution of lattice forces surrounding crystal defects or to study the crystallisation and melting phenomenon of colloidal arrays that can in turn be related to atomic lattices.

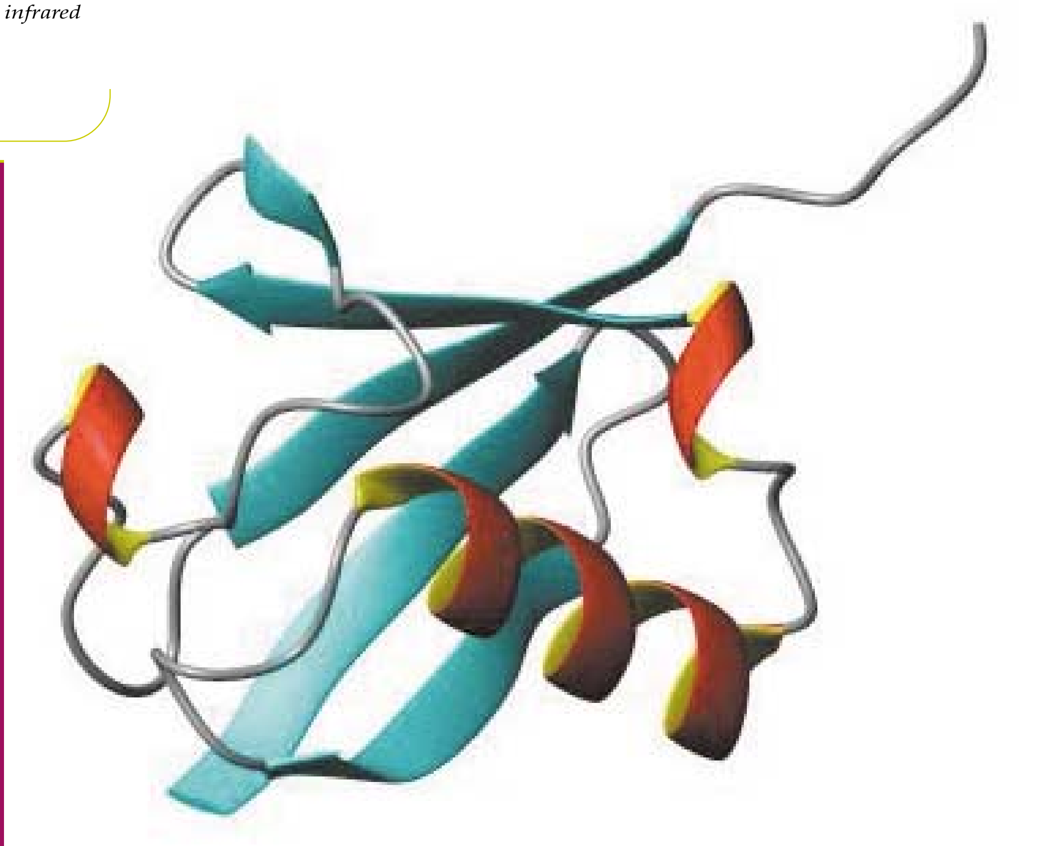


Nanosecond Laboratory: watching proteins fold

Proteins are the 'engines' that drive the processes in living cells. The three-dimensional structure of a protein is crucial to its function. The way that proteins fold is highly complex, involving numerous weak molecular interactions. But despite the complexity, many small proteins (of fewer than 100 amino acid residues) fold on a timescale of only a few milliseconds. In an attempt to unravel some of the processes involved in protein folding, researchers in the Nanosecond Laboratory have used lasers to unfold proteins and then watch them re-fold. By selecting an appropriate sample temperature and using an infrared laser pulse, it is possible to induce a rapid temperature rise or 'temperature-jump' in a protein, causing it to pass through its melting point and consequently unfold. A second laser pulse can then monitor the structural modifications taking place as the protein re-folds: the various partially folded states interact differently with the laser light. In this way scientists can begin to understand the complex 'molecular origami' of protein folding.

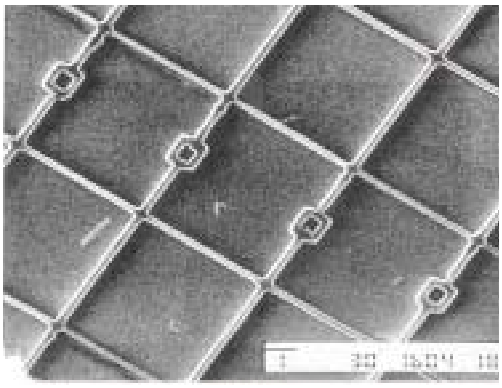
The image below shows the structure of the 'simple' protein (bovine ubiquitin) from its co-ordinates obtained from X-ray diffraction. The graphs show the infrared spectrum (dots) of the protein recorded 4 milliseconds after the temperature jump showing loss of the parent protein. The laser heating of the water in which the protein is dissolved causes the structure of the protein to unfold which is also observed in the growth of an infrared absorption band.



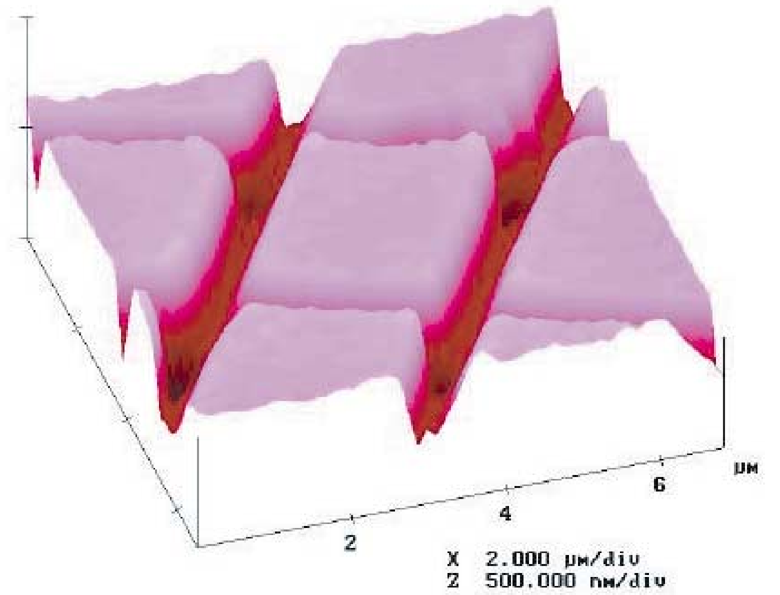


X-Ray Laboratory: making masks for chip manufacture

A vital step in the production of silicon chips involves the transfer of circuit designs to the surface of the silicon. This is achieved by using ultraviolet light to project the required circuit pattern through a so-called photomask. However, the complexity of the circuits transferred in this way is limited by the wavelength of the UV light. In order to produce more sophisticated chips, the world semiconductor industry will eventually have to replace conventional UV based lithography. One possible replacement technology is X-ray lithography. Researchers from the University of Dundee have used the X-ray laser source at the CLF to develop a novel method of X-ray mask manufacture. This involves the use of organometallic compounds, which can be decomposed under the influence of a focused electron beam to leave behind metal patterns.



An example of an X-ray mask, (left) consisting of 200 nm platinum tracks on a silicon nitride membrane. Once produced, the masks are irradiated with soft X-rays, generated by the laser plasma source at the CLF. In this way, an image of the pattern is transferred to an X-ray-sensitive material placed behind the mask. The image below shows a typical X-ray transfer.

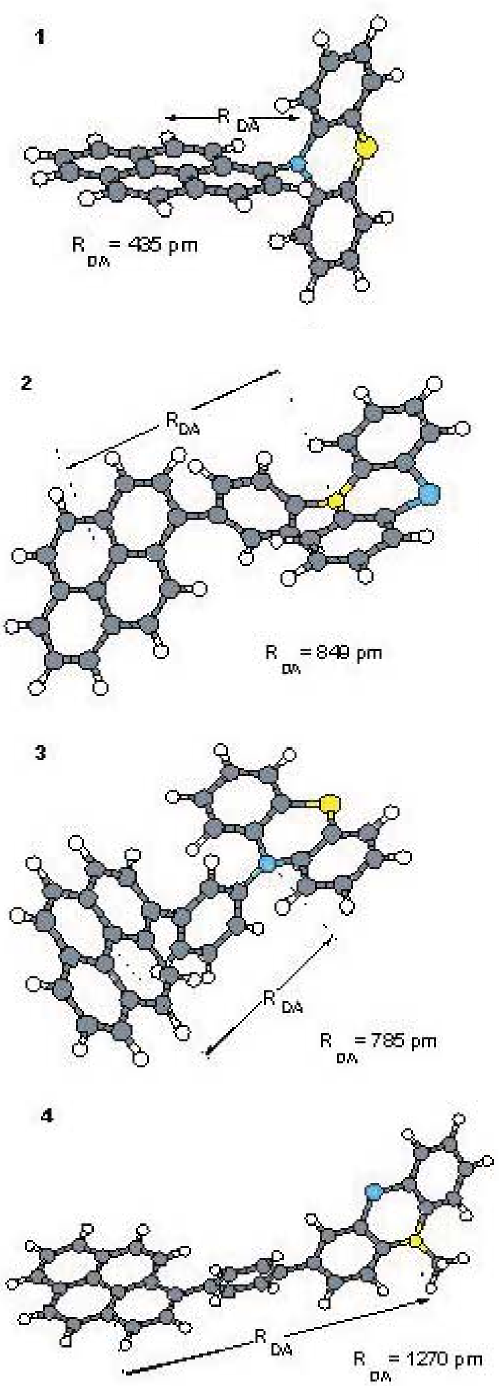


Ultrafast Laboratory: obtaining 'brighter' spectra

Resonance Raman spectroscopy, which relies on the interaction of light with chemical bonds, is a powerful and sensitive analytical tool for determining the structure of molecules. However, it has not been possible to apply the technique to samples that produce fluorescence which easily swamps the weaker Raman signals and this has limited the application of this powerful tool. Using a system developed in the Ultrafast Spectroscopy Laboratory, it is now possible to separate the Raman signal from the fluorescence signal. The Raman signal is instantaneous in contrast to the 'long-lived' (picoseconds) fluorescence and so the two signals can be separated in time. The world-leading Kerr gating system enables Raman spectra to be measured from strongly fluorescing samples. The set-up uses a series of polarisers, which can be switched on and off in 3 picoseconds, allowing the Raman signal to pass but blocking the longer-lived fluorescence. The importance of the Kerr gate has recently been demonstrated by solving a 40-year long debate between experimentalists and theoreticians regarding the structural change that occurs in a molecule called DMABN (4-dimethylaminobenzonitrile) following the absorption of a photon. Unique experimental evidence has shown that, in particular solvents, part of the molecule twists. This provides fundamental insights into how the fate of chemical reactions is decided within just a few picoseconds.

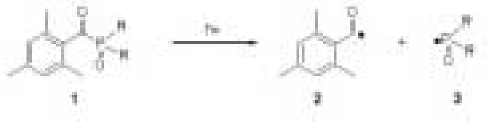
Ultrafast Laboratory: shedding light on the mysteries of electron transfer

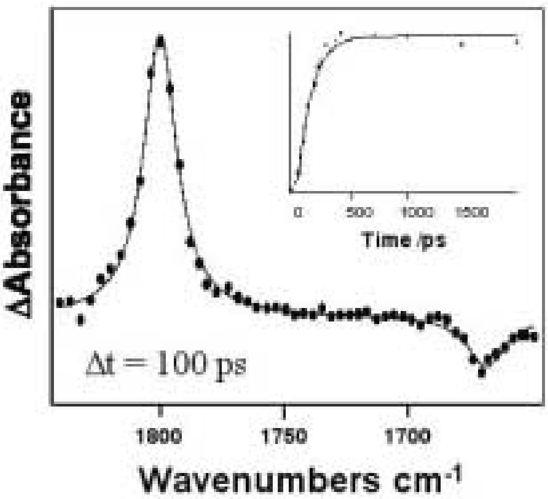
By designing molecular systems in which an electron donor and acceptor are separated by a 'spacer' group with well-defined properties, scientists can get a better understanding of electron transfer within molecules. Important parameters that govern the rates can be varied, such as the distance and orientation of donor and acceptor portions of the molecule, or the strength of the electronic coupling between them. The chemical nature of the donor or the solvent will also determine the efficiency of electron transfer processes. Using the Ultrafast Spectroscopy facility, researchers studied electron transfer between a model system (phenothiazine as donor and pyrene as acceptor with a phenyl group as spacer) which gives rise to various stereoisomers with significantly different spatial arrangements of donor and acceptor portions, (Scheme 1). A technique called time-resolved resonance Raman spectroscopy showed the electron is localized on the pyrene in the systems 1 - 3 but for the more extended system 4, photoinduced electron transfer is either not occurring or leads to a state in which the excited electron is largely delocalized. Such experiments give scientists important insights into electron-transfer phenomena.



PIRATE a new infrared facility

PIRATE, Picosecond InfraRed Absorption and Transient Excitation, brings together novel laser technology and expertise in time-resolved infrared (TRIR) spectroscopy and supercritical fluids to provide a unique method to study the energetics, structure and reactivity of short lived (picosecond) intermediates during a chemical reaction. The laser system uses developments in solid state laser technology to generate laser wavelengths into the mid-infrared region, the so-called 'finger-print' region where a molecule can be identified by its characteristic infrared spectrum. These techniques can be used to study fundamental chemical processes such as the mechanism of DNA and protein folding. The first experiments using the PIRATE system showed a measurement of the vibration of a phosphine compound (1) which is used commercially to cure polymer resins. It reacts by breaking the phosphor-oxygen bond to create the radicals (2) and (3). The aim of the experiment was to measure how fast this type of reaction proceeds and results show that the bonds break on a 100 ps timescale.



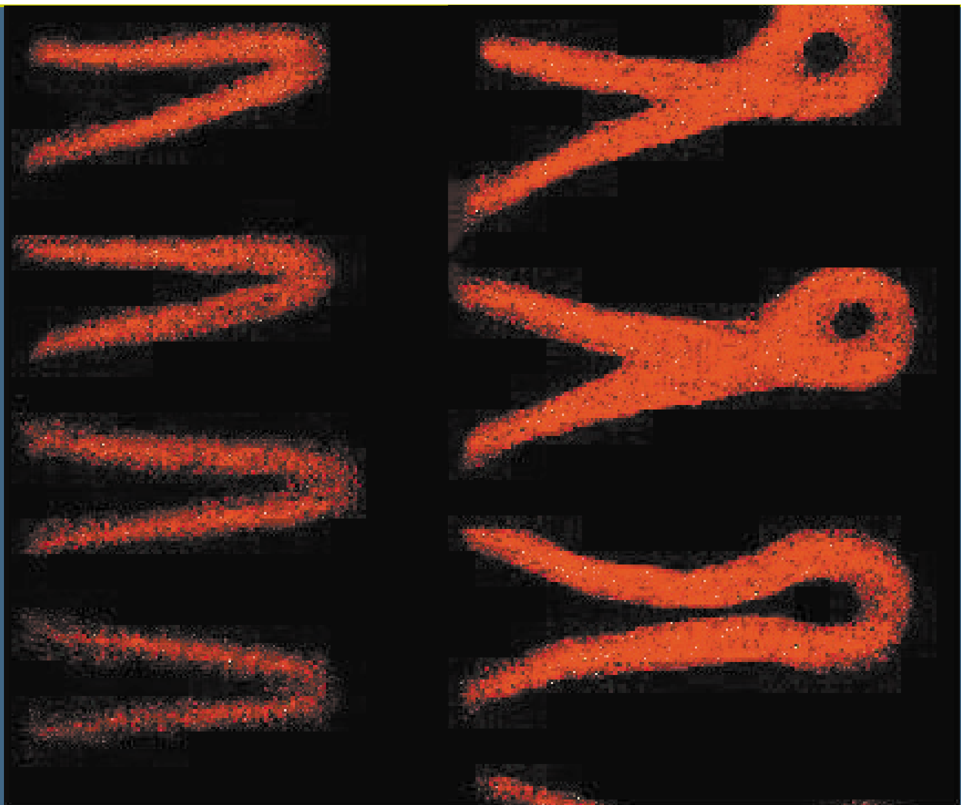


The trace shows the infrared spectrum obtained 100 ps after photolysis of 2,4,6-trimethyl phosphine oxide and identifies the timescale for the bond cleavage is 130 ps thus providing a valuable insight into the dynamics of the excited state process.

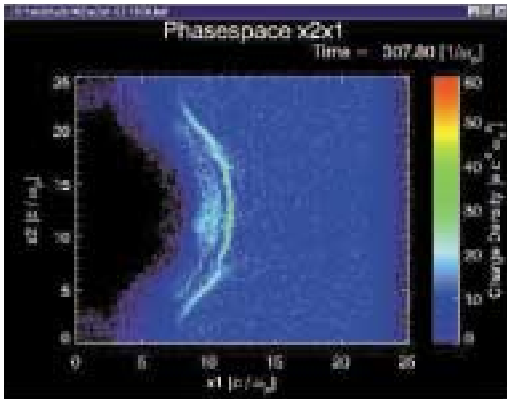
Loan Pool: lasers visualise oscillating flames

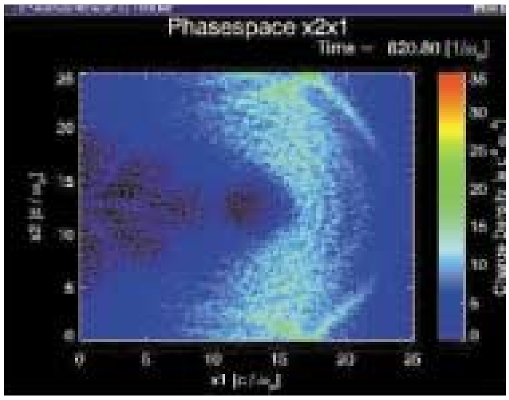
An effective way of reducing pollutant emission from the combustion of fossil fuels is to mix the fuel and air in a controlled way before combustion commences. This reduces the production of oxides of nitrogen (NOx) in the flame and, in some applications, can also lead to significant increases in thermal efficiency and thus to reduced emissions of carbon dioxide. However, burners which premix the reactants also have a tendency to generate unacceptable levels of noise and vibration when installed in practical combustion systems and this remains a serious obstacle to their use. The noise and vibration arise because any unsteadiness in premixed flames generates sound waves and, in enclosed situations, a proportion of the sound energy can be reflected back towards the flame and repeatedly amplified by it. Researchers investigating this problem at the University of Leicester have used a Loan Pool laser to study the way in which premixed flames amplify acoustic feedback of different frequencies and amplitudes. The laser is used to excite one of the chemical species formed within the flame, causing it to fluoresce. In this way it is possible to visualise the flame as it oscillates in response to an applied acoustic field. By imaging the flame at different phases of the incoming sound waves, the researchers can obtain information about the flame response mechanism and measure directly the exchange of energy between the flame and the acoustic field.

Typical images are illustrated and characterise the fundamental nature of the thermo-acoustic vibrations and will hopefully lead to improved burner design.



User Support





Engineering

Mechanical, electrical and computing engineering expertise is provided in support of the experimental programmes and to underpin the research and development activities of the CLF. Scheduled experiments are supported by experienced staff who are available at all stages of the work, from initial planning, through the design, manufacture, assembly, and commissioning of dedicated systems and instruments, to the running of the experiments. Mechanical and electrical workshops give a rapid response service to users in support of scheduled experiments.

Theory & computation

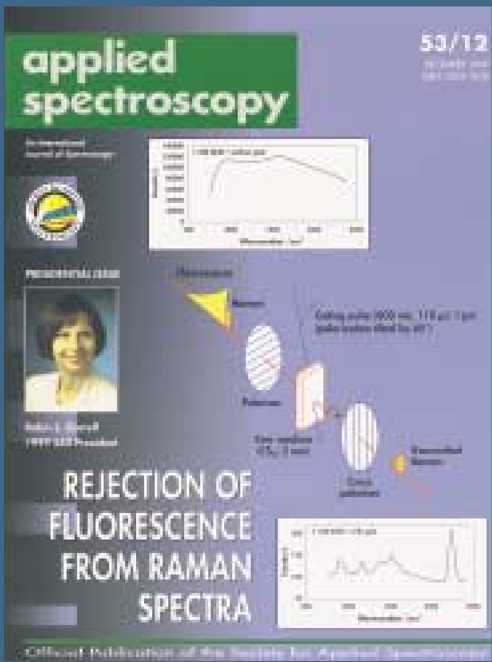
Theory and simulation support is provided for the design and interpretation of high-power laser experiments. A suite of hydrodynamic and atomic physics modelling codes are operated and developed to simulate the plasmas produced by the interaction of high-power laser light with solid gas targets.

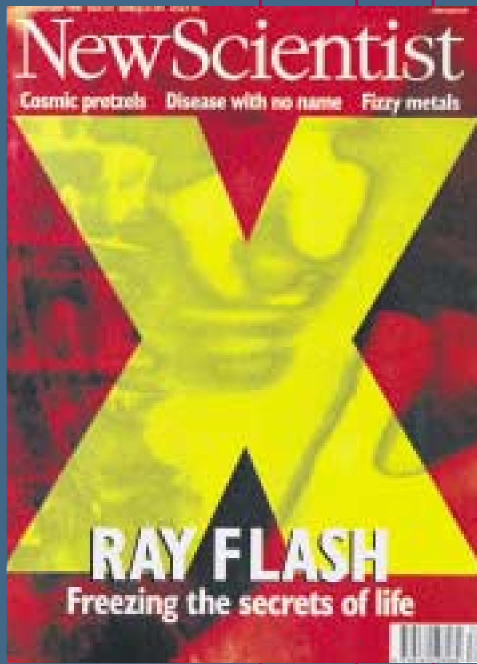
Instrumentation

A wide range of diagnostics is provided for visiting scientists to measure the extreme conditions generated in laser matter interactions. Specialised instrumentation is used to examine radiation emitted from plasmas covering a large portion of the electromagnetic spectrum from gamma rays to the infrared. Ultra-fast optical and x-ray streak cameras can measure the rapid changes as conditions evolve in the plasma, and particle detectors are used to measure the high energy interaction products left as the plasma expands.

Target fabrication

A target fabrication facility is operated within the CLF. It is equipped with a wide range of target production and characterisation equipment, including evaporation and sputter coating plants, interference microscopes and a plasma etch facility. A rapid turnaround service responds quickly to the developing demands for targets, essential for maintaining the scientific productivity of the programme.


applied spectroscopy
53/12
REJECTION OF FLUORESCENCE FROM RAMAN SPECTRA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Cosmic pretzels
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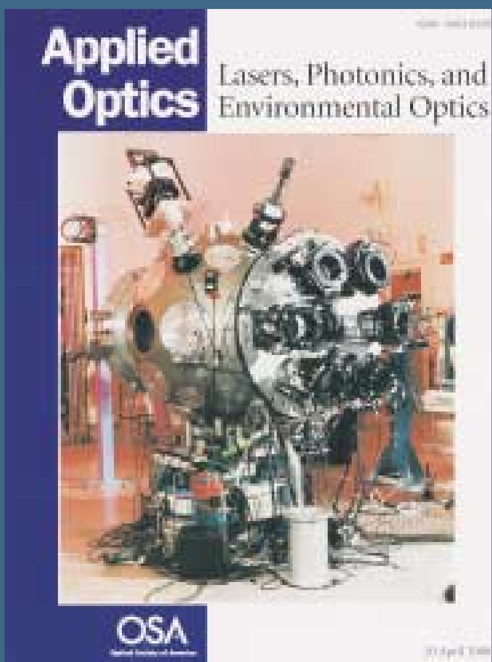
Freezing the secrets of life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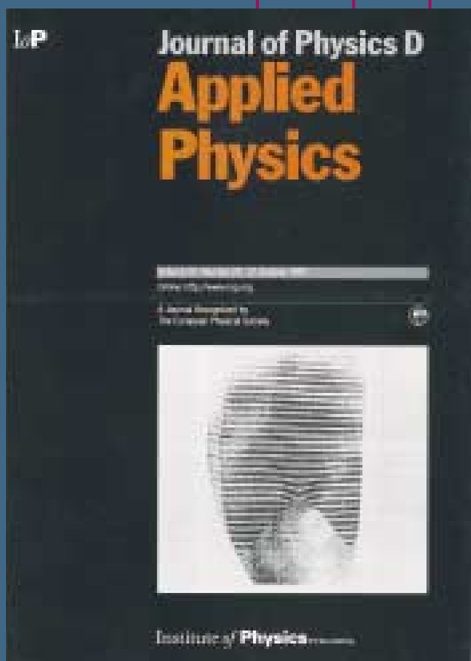
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Events

The Central Laser Facility has an important role in disseminating information to the public and the scientific community alike. The following section highlights some of the events which illustrate these activities.

As part of their visit the students toured the CLF and are seen being shown a target positioning assembly in the Vulcan target areas and taking a keen interest in Vulcan beam diagnostic data and optics.

2nd year optical engineering students being shown facilities by Lisa Coffey.

London International Youth Science Forum touring Vulcan with Rob Clarke, Vulcan Target Areas.

Engineering students visit the CLF

RAL hosted a visit from 36 students participating in a project organized by The Engineering Education Scheme, EES. The EES is one of the national providers giving high ability sixth-form students the opportunity to see engineering in action at a very formative stage of their lives. The Project Phase of the Engineering Scheme involves a professional engineer from a company liaising with and advising a team of students and their teacher over a period of four to five months. They work as a team on a real industrial problem for which the company needs a solution.

French science students visit CLF

Sixty 2nd year optical engineering students from the Institut d'Optique Théorique et Appliquée, France visited the Central Laser Facility. This annual science trip is a regular event for the students and has been regarded as beneficial to their course. The students received introductory talks on the work of the CLF from Henry Hutchinson, Chris Edwards, Steve Rose and Mike Towrie. They then visited Vulcan, Astra and the Lasers *for* Science Facility.

Participants from the London International Youth Science Forum visit RAL

Participants from the London International Youth Science Forum visited RAL as part of the two week long Forum. The Forum, which was organised and sponsored by a variety of organisations from academia to industry, gave 300 students from 50 countries the opportunity:

> *"to meet, to discuss, to exchange opinions and ideas and perhaps develop an understanding of the common responsibilities and challenges that will face all the worlds people"*
>
> *George McGowan,*
> *Director London International Youth Science Forum*

The Forum included lectures and demonstrations by a number of distinguished professionals and visits to some of the UK's world class research institutions and leading industrial facilities. Twenty participants chose to visit RAL and were shown around ISIS, the Space Environment Test Facility and the Vulcan Laser Facility.

Sir Michael Scholar, Permanent Secretary, DTI with
Dr Gordon Walker and Prof. Steve Rose, CLF Associate Director, Physics.

Members of the House of Lords Select Committee on Science and Technology accompanied by Professor David Cope, Director POST,and Professor Justin Wark, Oxford University.

Members of the LEA (Dr Gabriel Wild, 'Charge de Mission' Engineering Science Dept., CNRS; Mme Michele Glass, Vice-President of University Paris 6; Dr Jean-Claude Gauthier, Directeur-Adjoint du LULI) being shown round the Vulcan and Astra facilities by Professor Henry Hutchinson, Director, CLF.

Sir Michael Scholar, DTI visits RAL

Sir Michael Scholar, Permanent Secretary, DTI visited RAL on the 14th June 2000. As part of his visit he was shown around ISIS and the CLF by Dr Gordon Walker. He is pictured in the photograph being shown one of the main Vulcan target areas by Prof. Steve Rose, CLF Associate Director, Physics.

House of Lords Select Committee visit RAL

Members of the House of Lords Select Committee on Science and Technology visited RAL on the 25th May 2000. Lord Haskel, Lord Winston, and Lord Jenkin of Roding were accompanied by Professor David Cope, Director POST. As part of their visit, they toured ISIS, SSTD and the CLF. Members of the Select Committee are pictured being shown an on-going experiment in Vulcan's Target Area East by Professor Justin Wark, Oxford University.

LEA collaboration

The LEA (Laboratoire Européen Associé) is a collaboration agreement between the Central Laser Facility and the LULI laboratory, Palaiseau, France, which formalises a productive pooling of expertise to cover a whole spectrum of research in high power lasers. Members of the LEA met at the Rutherford Appleton Laboratory to discuss past LEA activity and the prospects for future collaborations.





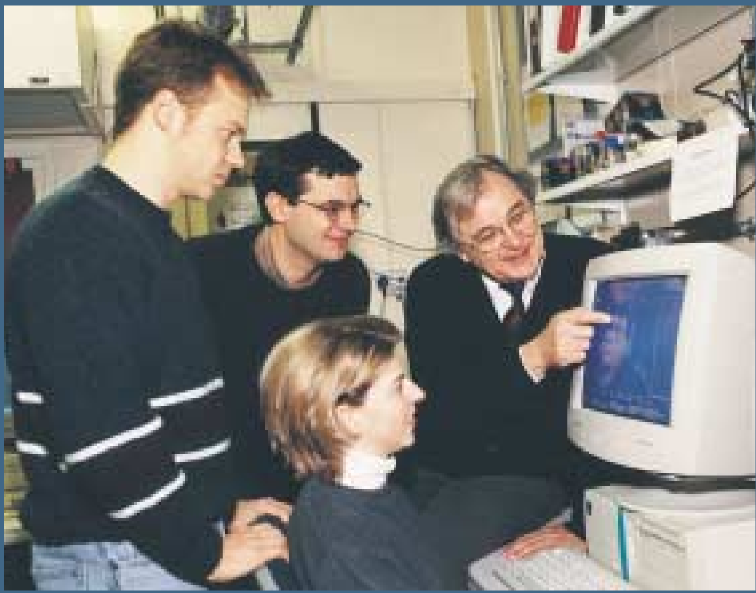


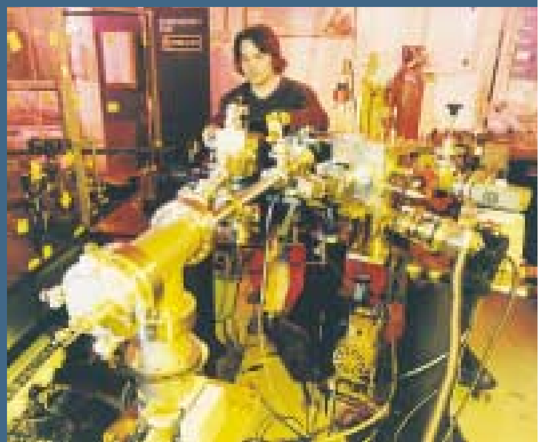
Training at the Central Laser Facility

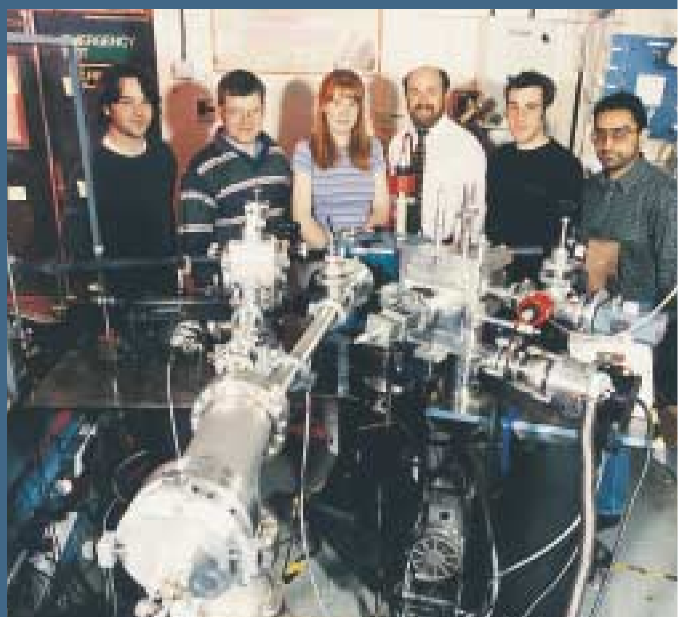
The Central Laser Facility has hosted highly successful two week courses to provide training for PhD students in using the Vulcan high-power laser. The courses involved a mixture of classes and practical work. The training was funded by the Engineering and Physical Sciences Research Council to enable a higher level of contribution in highly complex Vulcan experiments from new researchers. The images show activities on the first two courses where twenty seven students took part in the training representing many of the research groups that regularly use Vulcan.

Topics covered within the courses included: safety training; plasma diagnostics; clean handling of optics; fast electronics and data capture; target preparation and characterization; and numerical simulation techniques. The course members had many opportunities for hands-on experience. One of the Vulcan target chambers was available and full power shots were delivered to target to teach the course members target alignment and the use of plasma diagnostic instruments, including an optical spectrometer, x-ray camera, a flat-field XUV spectrometer and a streak camera.

The courses are open to all, although they are designed around postgraduates, especially those at the beginning of their PhD studies who would benefit most from this style of course.



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EU access to the CLF

The CLF has been host to a large number of researchers under the HCM, TMR & IHP Large Scale Facility access schemes operated under Frameworks III, IV & V of the European Union. The experiments have covered a broad spectrum of research from the investigations of damage mechanisms in yeast cells, using the x-ray source, to the measurement of the shortest recorded soft x-ray laser using the Vulcan laser facility. A number of these experiments are presented in the highlights section of these pages. The experiments performed under this scheme have increased collaboration between research groups across Europe, and have introduced researchers to state of the art facilities not available in their home institutions.

The pictures indicate some of the activity under the Framework IV Large Scale Facility Access Contract.

On Vulcan:
Dr A Klisnick, University Paris-Sud, France developed ultra-short pulse x-ray lasers in collaboration with Dr P Nickles, Max Borne Institute, Germany and UK researchers from Queens University Belfast and the University of York. In addition Dr F Amiranoff of LULI, France studied electron acceleration schemes in Vulcan's TAW in collaboration with researchers from Imperial College, London and RAL.

In the Lasers For Science Facility:
Dr S Schneider and his team from the University Erlangen-Nurnberg, Germany used the Ultra-fast laboratory to study electron transfer processes within molecules; Prof. Dr D Oelkrug of the Institute for Physical Chemistry, University of Tubingen, Germany used the Ultra-fast Laboratory to study compounds important for future electro-luminescent devices; and Dr J Costello of Dublin City University conducted experiments in the Laser Plasma X-ray Laboratory to study the absorption of ultra violet light in laser generated plasmas.

Acknowledgements

I would like to thank the large number of users and CLF staff who have generously contributed.
My appreciation also goes to Phase II Creative Associates, Simon Hadlington - Science Writer, EPSRC, CLRC Press and Public Relations and Photographic and Reprographic Services who have all played a key role in the production of this report.

Colin Danson, Editor

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