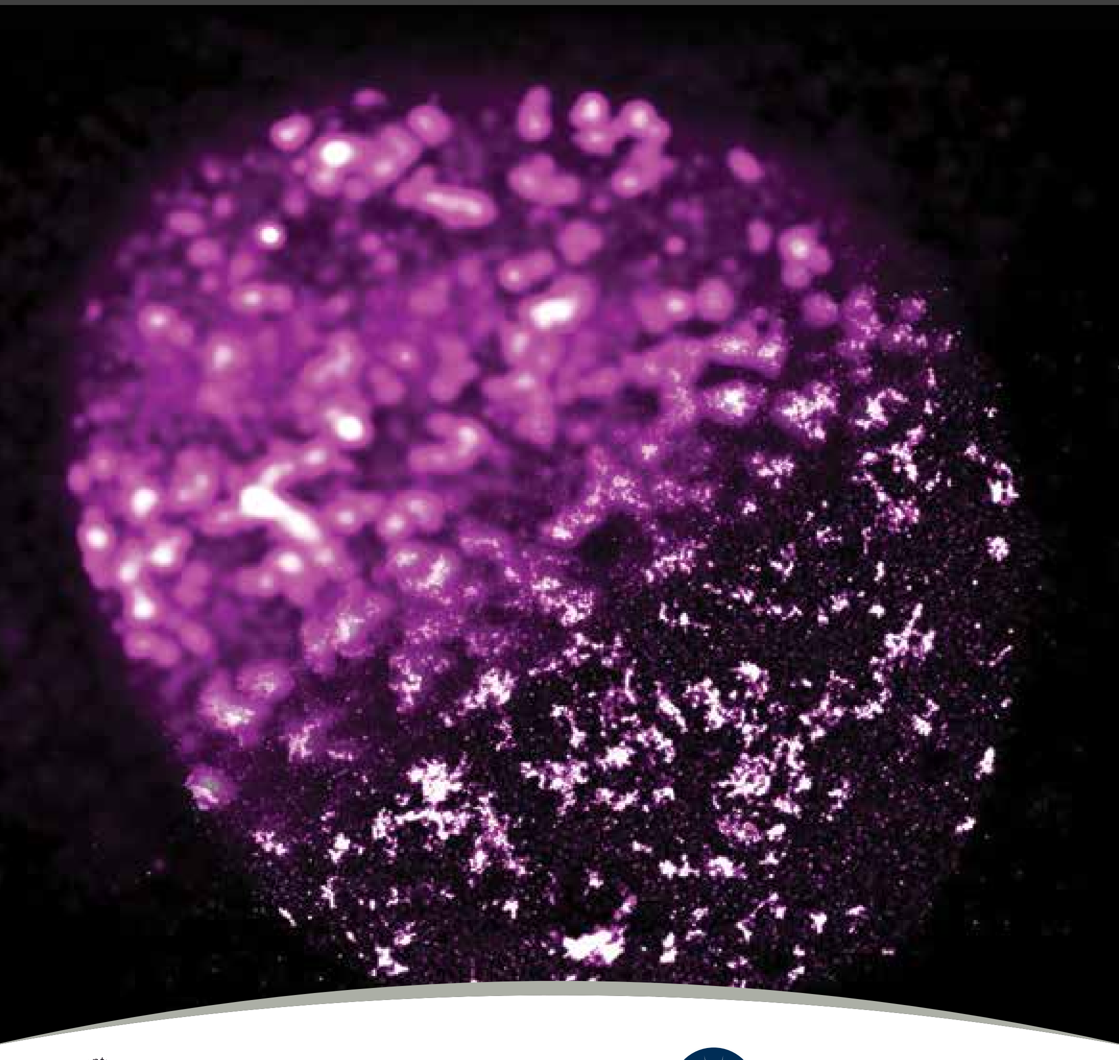
Central Laser Facility

making light work



central laser facility

Science & Technology Facilities Council

innovative DiPOLE laser gain media *(see page 22)*

The language of extreme measurements

10^{-18} atto, a, quintillionth	10^{3} kilo, k, thousand
10^{-15} femto, f, quadrillionth	10^{6} mega, M, million
10^{-12} pico, p, trillionth	10^{9} giga, G, billion
10^{-9} nano, n, billionth	10^{12} tera, T, trillion
10^{-6} micro, μ, millionth	10^{15} peta, P, quadrillion
10^{-3} milli, m, thousandth	10^{18} exa, E, quintillion

Front cover image: super-resolution microscopy at the CLF

Introduction

At the Central Laser Facility our work is helping to inspire solutions to everyday problems; from developing future energy sources and security technologies, to finding new ways to see beneath the skin to diagnose cancer and bone disease.

We are innovating within laser science itself, developing the technology that will lead to the next generation of high-powered lasers, doing ground-breaking work in sample and target engineering, and spinning-out award-winning technology into the commercial sector. And we're illuminating the world of fundamental science, exploring the extremes of the Universe through high energy plasmas, recreating plasma jets and even mimicking the aftermath of a supernova explosion.

The stories you read in this brochure are just a slice of the ones we could tell you, selected to showcase the amazing power of lasers, and the breadth of the science that they enable. None of this would be possible without the highly-trained staff here at the CLF, and our close links with the laser community. We're committed to training the next generation of scientists to use and develop lasers, and to sharing our ongoing work with you. To keep up-to-date, visit our website at: www.clf.stfc.ac.uk/CLF/

Contents

Inspiring

Our work in laser science is providing novel solutions to some of the greatest challenges facing the global community. From developing new energy sources to help us meet our energy needs -without adding to our greenhouse gas emissions and climate change, to new technologies that keep us safe in an uncertain world: increasing our understanding of the dynamics of life, inventing new methods of treating and diagnosing disease.

SEE PAGE 4

Innovating

We're developing new laser techniques, and new generations of laser, so that laser science can continue to bring benefits to the people of the UK, and beyond. We're delivering extreme engineering, extreme laser intensities and ensuring that important new developments make their way into the commercial sector.

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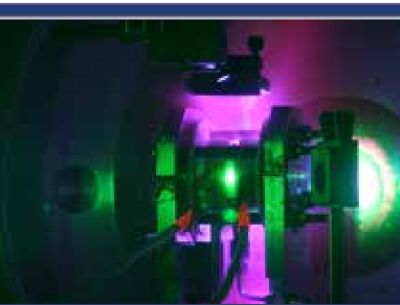
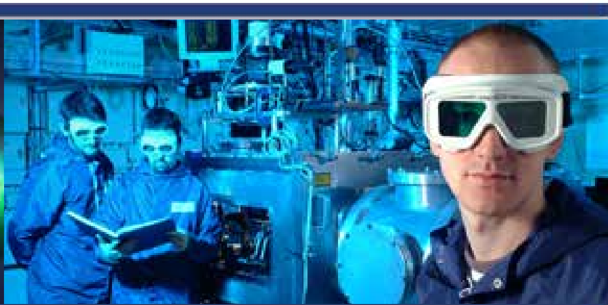




Illuminating

Our lasers are being used to make big steps in a wide range of research areas. From watching molecules moving in real time to mimicking the most extreme and distant corners of the Universe, lasers are exploring areas of fundamental science, and lighting up the technologies of tomorrow.

→ SEE PAGE 30

Our lasers

The CLF has a unique collection of cutting-edge lasers, each one specialising in different types of scientific research. From the petawatt power of Vulcan and laser-microscopy facilities of Octopus, to the specialist 'movie' cameras of ULTRA and Artemis, and the twin high-intensity beams of Gemini, the CLF is a shining example of a modern science facility.

→ SEE PAGE 38

Our community

The CLF doesn't exist in a vacuum, but within a vibrant and diverse scientific community. Our facilities are built, maintained and upgraded to offer our community of users the best possible facilities. And it's not only facilities we're building – our work in engaging the public and training the next generation of scientists and engineers ensures a sustainable future.

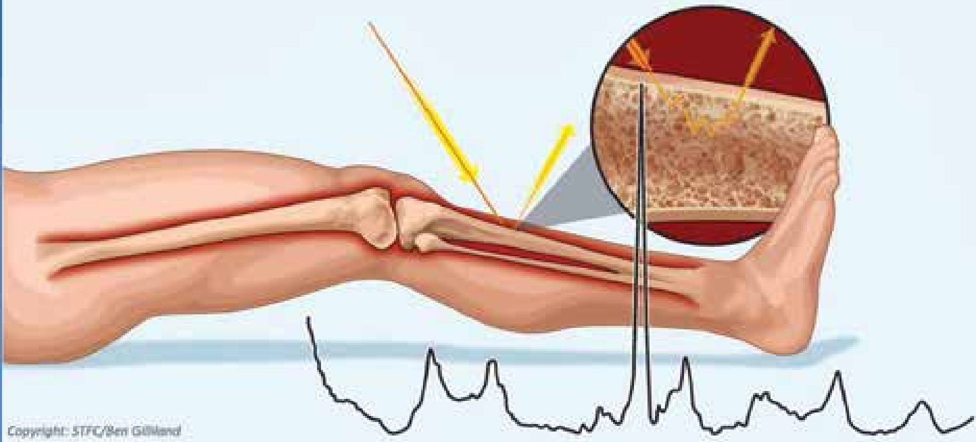
→ SEE PAGE 40

Aligning the Spatially Offset Raman Spectroscopy (SORS) instrument

Seeing beneath the skin

Spatially offset raman spectroscopy (SORS), a technique invented at the CLF, allows us to 'see' beneath the surface of non-transparent objects. SORS works by shining a laser through the object and measuring the colours of light reflected back. It has a wide range of potential applications, including security scanning (see page 10), analysing art (see page 19) diagnosing disease (see page 5).

SORS does this by shining a laser in one part of the sample and collecting the scattered light from a point close by. The distance from the collection point to the laser determines roughly the depth into the sample that is monitored. The Raman spectrum obtained shows a series of peaks, a unique 'fingerprint' of the chemicals present.



Detecting bone disease

A major research effort is underway to develop new technology to diagnose bone disease from a scan of the patient's limbs. Bone is a complex material made from minerals (calcium carbonates and phosphates) and cross-linked strands of protein in the form of collagen. Changes in the proportions and chemical make-up of these components lead to bone disease. X-rays can only detect the mineral components of bone, but SORS sees both the minerals and the collagen, and does not use ionising radiation.

Careful analysis is beginning to identify differences between healthy and diseased bone. SORS has enabled detection of a genetic 'brittle bone' disease known as osteogenesis imperfecta. Further clinical trials will verify whether the technique also works for osteoporosis (weak or fragile bones) and osteoarthritis (stiff joints). The goal is to design better treatments for people with osteoporosis, a major illness in the Western world estimated to affect a third of women over the age of 50. SORS has also revealed evidence of bone disease amongst the Mary Rose sailors (see page 19).

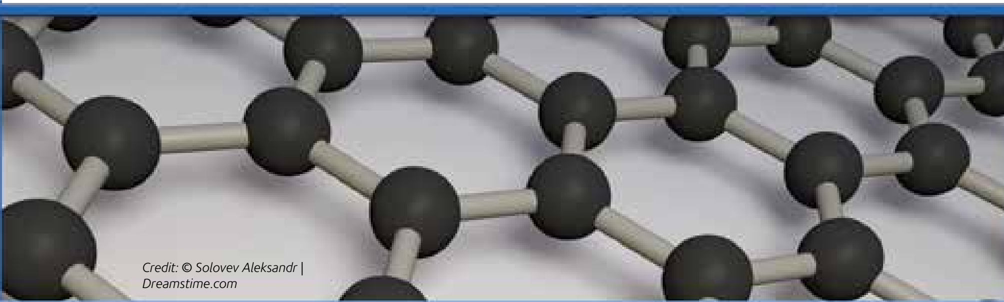
Detecting breast cancer

An exciting new application of SORS could cut down on patient anxiety (and costs to the National Health Service) by offering instant results for breast cancer screening. SORS analyses signatures obtained as light from the laser passes through the small bone-like crystals (calcifications) found in breast tissue. These show whether the tissue is benign or cancerous.

In March 2013, the Engineering and Physical Sciences Research Council (EPSRC) awarded a grant to test this technique on human tissue. Although promising, the use of SORS in breast cancer diagnosis is in the early stages of development. It may be a decade or more before it could be routinely used in hospitals.

"…we are very excited about our collaboration with the CLF trying to develop SORS as a diagnostic modality for human bone disease. There is no doubt that SORS, being a non-invasive and safe technique, as opposed to most existing imaging modalities, will revolutionise the way we diagnose and treat bone disorders providing a huge improvement on patient care. Moreover, we hope that SORS, by differentiating between normal and cancerous tissue, can be used as an intraoperative tool to help us plan surgical excision of bone tumours, allowing great benefits for patients by improving outcome and function after major oncological surgery…."

Panagiotis Gikas, Royal North Orthopaedic Hospital.



Credit: © Solovev Aleksandr | Dreamstime.com

Future materials: graphene

Graphene is a carbon crystal that is just one atom thick. Stronger than steel, lightweight, transparent and flexible, graphene is a 'wonder material' expected to revolutionise technology. Researchers are exploring its potential in optoelectronic systems such as solar cells, faster transistors, flexible displays and lasers.

Fast computer chips

The modern world relies on silicon chips – they're an essential part of computers and mobile phones, cars and even smart fridges. The reason that we use silicon in these devices is that it is a semiconductor. Semiconductors have small 'band gaps', the energy required to free up an electron to conduct electricity, and are used to build field effect transistors (FETs) that can be switched on and off, ensuring low power consumption when they're in 'stand by' mode.

Graphene has remarkable strength and is an efficient conductor of heat and electricity. These two properties make it an ideal candidate to replace silicon for building electronic devices that are smaller, faster and use less energy. But graphene doesn't have a band gap, and isn't a semiconductor.

Professor Philip Hofmann from Aarhus University in Denmark led the collaboration with researchers from Trieste, Chemnitz and St Andrews .

Experiments using the Artemis laser facility explored the potential of bilayer graphene – a new material made from two layers of graphene, which is predicted to behave as a semiconductor. The researchers fired ultra-short laser pulses at the sample, boosting electrons into the conduction band. They followed this with a short, extreme ultraviolet wavelength pulse, which ejects electrons from the sample. The scientists collected these electrons and analysed their energies and movement.

Their results showed that it may be possible to improve the performance of bilayer graphene to the point where it could challenge silicon-based devices.

"The exploration of novel materials for the next generation of electronics is at the heart of our activities. We routinely use photoemission technique to explore the physical mechanisms involved in such materials. Access to the CLF gives us a unique opportunity to understand our systems under very different conditions. In particular using short laser pulses, the electrons dynamics is directly observed on ultrafast time scale."

Prof Philip Hofmann, Aarus University

Terahertz laser

Theoretical studies and light absorption measurements suggested that graphene could lase (give off coherent light) in the terahertz (long wavelength) region of the spectrum. A laser amplifies light by 'cloning' photons, a process that needs more electrons in the laser material to be in a higher energy state than a lower one. This is a population inversion.

Scientists thought that a semiconductor material with a band gap was essential for producing a population inversion, and graphene does not have a band gap. But using ultra-short flashes of extreme ultraviolet light on Artemis, researchers investigated the electron dynamics of graphene and found they could create a population inversion using an infrared laser pulse.

The absence of the bandgap means that the population inversion in graphene is short-lived, and graphene can't be used for continuous lasers. It could potentially produce ultrashort laser pulses, and graphene could be used to amplify terahertz light, which is currently produced using inefficient processes. As well as having security scanning applications, a terahertz graphene laser would be useful for research into condensed matter physics.

A team from the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg and the Max Planck Institute for Solid State Research in Stuttgart is developing these ideas.

"As a scientist on Artemis I develop experiments for the user community. This involves preparing the experiment and working with the users to make sure that they get the best out of their time at the CLF. I do my own research on magnetic materials and keep up-to-date with developments in this area internationally. My work at the CLF is really interesting and I work with a great team. The structure of the CLF is efficient and productive, and I like it because it lets people contribute and allows you to be creative."

Dr Cephise Cacho, Senior Experimental Scientist, CLF

Future energy sources

Plastic solar panels

To build more cost-effective solar panels, and make renewable energy more accessible, we need a better understanding of how 'plastic' solar panels work. They use plastic-based photovoltaic diodes, semiconductor devices that convert light into electricity. When the diodes absorb a photon of light, they release an electron.

These electrons must rapidly move away, or they recombine with a positive ion and do not produce electricity. The efficiency of solar devices compares how many electrons recombine and how many separate.

An international group of collaborators studied the chemistry at work in the reactions that underpin solar energy conversion devices. For their research, published in Nature Communications, the team used ultra-short laser pulses less than a millionth of a millionth of a second long. This shows how chemical bonds change during these extremely fast chemical reactions, and enables researchers to seek out the most efficient materials.

The research team includes members from the University of Cyprus, the University of Montreal, Imperial College, London and the CLF.

Artificial photosynthesis

Green plants use the energy of sunlight to grow, using a complicated chemical process called photosynthesis. Photosynthesis converts solar energy into fuels, which store energy in the form of chemical bonds. We can grow crops to turn into biofuels, but we need our farm land to grow food, and burning plants for fuel is a wasteful process and can cause air pollution. Artificial photosynthesis has the potential to be much more efficient, and environmentally friendly.

Scientists are working on the challenge of developing a method of artificial photosynthesis that would work as well as plants and would enable us to produce clean, renewable, carbon-free fuels.

Researchers using Ultra are looking for molecules that efficiently absorb light and form a "charge separated state", where a positive and negative charge separate and can take part in independent chemical reactions. One new molecule could do just that and has a lifetime long enough for artificial photosynthesis applications. ULTRA's time-resolved infrared laser capability allows us to understand how these molecules respond to light.

The Ultra team is working with Sheffield University and the University of Nottingham on this challenge.

Laser-driven fusion

Fusion is the process that keeps our Sun and every star in the Universe shining. If we could harness this energy release mechanism, we could use it to generate clean electricity, using hydrogen as fuel.

The idea of using lasers to ignite the fusion process is over 50 years old. Powerful lasers could create the necessary conditions, by superheating and compressing a small pellet of heavy hydrogen to millions of degrees Celsius and a density ten times that of lead. Many of the experiments carried out on the CLF's Vulcan laser have contributed to the world-wide effort to solve this challenge.

The fast ignition (FI) approach, first considered at the CLF, uses one set of lasers to compress the fuel pellet and a single high-intensity laser pulse to generate a beam of energetic particles that heats the compressed fuel. A collaboration united under the HiPER project used the Vulcan petawatt laser to achieve a 15% conversion of laser energy into protons, a world record for laser-driven proton beams, and above the minimum efficiency required for a fusion power plant.

The National Ignition Facility (NIF) in the USA is also working to reach the coveted goal of ignition – getting more energy out than the laser beams use to get the fusion process going. One of their main problems is uneven pellet compression, however a collaborative study between NIF and CLF plasma physicists has been able to explain the origin of the asymmetry. The NIF team have used this information, published in Physical Review Letters in 2014, to reconfigure the laser beams, and initial results indicate a significant improvement.

Credit: © George Tsartsianidis | Dreamstime.com

Detecting liquid explosives

SORS in airports

Airports around the world are using spinout CLF technology to prove that liquids taken onto planes are safe.

CLF spinout, Cobalt Light Systems, have developed scanners based on patented SORS technology (See page 4), capable of rapid and accurate chemical analysis of substances in unopened non-metallic containers.

Cobalt's systems screen a range of materials including liquids, powders and gels. They have the highest detection capability and lowest false alarm rates of any European Civil Aviation Conference (ECAC)-approved scanner.

Detecting landmines

Landmines kill 15,000 to 20,000 people each year – many of them women, children and the elderly. They provide a terrifying reminder of conflict in around 78 countries, and continue to be used as weapons of war.

Remote delivery methods mean that there are no maps of minefields. Each mine has to be cleared individually, but modern plastic mines are smaller and harder to detect.

X-ray backscatter imaging is used in a range of scanning technologies, from portal security (scanning airline passengers, vehicles and containers) to industrial inspection (studying the internal structure of low density materials). This technique is not used to detect landmines, as the X-rays do not travel deep enough into the surrounding soil.

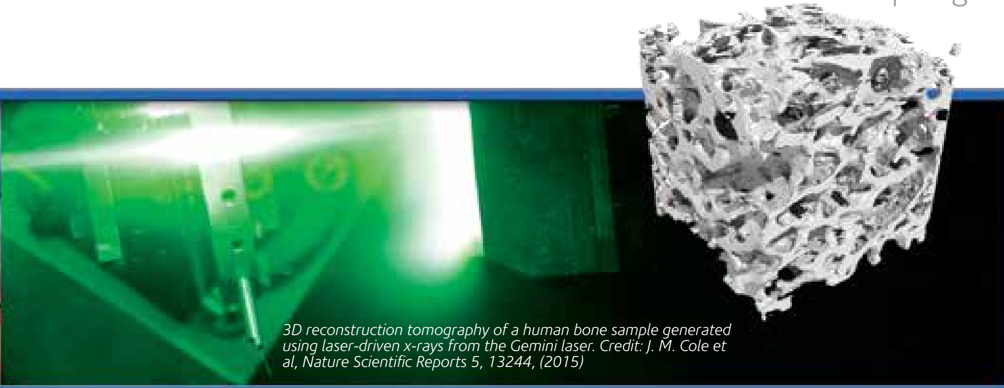
A new approach uses a high-energy electron beam, generated by laser-driven acceleration. High-energy electrons can penetrate deeper into the soil. Once under the surface they produce X-rays that backscatter back through the soil to a detector. X-rays returning from deeper in the soil take longer to reach the detectors, which creates a depth profile and allows the identification of hidden or buried objects.

This technique can produce clearer images, as the X-rays only have to make a 'one-way trip' up through the soil to the detector. Another benefit is that it doesn't scan the surface of the soil, as the X-rays are only produced beneath it.

An experiment on Gemini used an electron beam generated by focusing a laser pulse in a supersonic gas jet. This was the first time a backscatter image was produced using a laser-generated electron beam to generate X-ray emission for this application.

Although this research is in its early stages, it is hoped that it will lead to a deployable system that can be used to help clear landmines and save lives.

The CLF has been collaborating with the UK's Defence Science and Technology Laboratory on this project.



3D reconstruction tomography of a human bone sample generated using laser-driven x-rays from the Gemini laser. Credit: J. M. Cole et al, Nature Scientific Reports 5, 13244, (2015)

Future accelerators

Electron and ion acceleration and X-ray generation

Work carried out on the Gemini laser over 10 years ago showed that the interaction of an ultra-short laser pulse with a gas jet generates high-quality beams of high-energy electrons.

This concept could lead to much smaller accelerators in the future, making advanced medical imaging and treatment methods available in compact machines. Groups from around the world have been using the Gemini facility to develop this technique. Recent research, led by Imperial College, showed that the coherent X-ray flash that accompanies laser-driven electron acceleration can be used to produce high-resolution medical images, such as the bone image above.

Directing laser-accelerated electrons at the surface of a solid, rather than a gas, produces ultra-short and bright flashes of gamma rays, protons, ions and neutrons. Applications for these gamma and neutron flashes include the non-destructive imaging and inspection of large engineering components.

Laser-accelerated protons could help meet the global demand for radionuclides used in PET imaging. These medical isotopes are produced using proton beams generated by cyclotrons, large machines which are expensive to build and run. Lasers can now produce the necessary protons more cheaply and easily.

The CLF is working with the aerospace, defence, nuclear and advanced manufacturing sectors to develop these laser-driven sources, collaborating with STFC technology.

" We have enjoyed working with collaborators at the CLF - bringing together our interests in genetics and biological imaging with their cutting edge approach to high resolution tomography, utilising an extremely bright compact x-ray source. The exciting results that have come out of this demonstrate the potential of laser-based sources to dramatically increase imaging capabilities without the need to travel to large scale facilities."

Dr Dominic Norris and Dr Henrik Westerberg, MRC Harwell

Credit: © Lculig | Dreamstime.com

Dynamics of life

Proteins

Life depends on the ability of complex molecules (such as proteins and DNA) to respond to external stimuli.

Researchers used Ultra to study light-sensitive flavoproteins (molecules involved in a wide range of biological processes, including photosynthesis and DNA repair). The unique capabilities of a new instrument, TRMPS (time-resolved multiple probe spectroscopy) allowed them to see the proteins 'in action', exploring their response to light stimulation over a vast timescale, from less than a trillionth to a thousandth of a second. Their work studied directly how the chemical bonds of a protein change over time, and showed how the response of the protein structure cascaded away from the initially activated area. Their most interesting discovery was that the relaxation pathway is short-circuited for mutant versions, suppressing the changes that occur far away from the stimulated region, whilst accelerating dynamics close to it.

This research was carried out by Stony Brook University in New York and University of East Anglia, and published in the Journal of the American Chemical Society.

Another tool being developed using the ultrafast lasers is two-dimensional infrared spectroscopy (2D-IR). 2D-IR represents a new way to study the role played by fast motions and the energetics of biological molecules. Protein structures constantly change shape, and studying these dynamic processes provides a means to understand their biological activity in relation to their structure and biological function.

The goal for 2D-IR technology is to provide real-time measurements that complement static X-ray crystal studies and may lead to new ways to investigate drug binding in DNA and proteins, and provide a new tool for developing and designing new drugs.

2D-IR is being developed as a collaboration between the University of Strathclyde and the CLF.

DNA

Our DNA is under constant attack, by foreign chemicals inside our cells as well as external factors such as natural background radiation and the ultraviolet component of sunlight. Estimates suggest that the DNA in a cell is damaged 10,000 times every day, but has evolved natural processes to protect itself and ensure that we survive.

Ultraviolet light can damage DNA and lead to skin cancer. When DNA absorbs an ultraviolet photon, it acquires enough energy to break chemical bonds or start dangerous chemical reactions. This may lead to mutation, and the onset of cancer.

However, research using Ultra shows that DNA rapidly dissipates the energy it receives from a photon. Using ultrafast infrared spectroscopy provides a deeper understanding of DNA by tracking the structural changes, energy loss and reactions that occur million-millionths of a second after the photon has been absorbed.

The CLF has been investigating DNA in collaboration with Trinity College and the University of Dublin.

"Shining a light on protein dynamics".

Journal of the American Chemical Society's Spotlight feature on work carried out on the Ultra system

Water droplet held in a laser trap.

Environment

Climate science from cloud to droplets

The relationship between cloud formation and our climate is complex and not well understood. Clouds form when a large mass of air moves upwards in the atmosphere, and cools. Water vapour condenses around particles (known as 'icks') to form droplets.

Cloud dynamics can depend on what is in these droplets. Researchers in the Indian Ocean realised that clouds drifting downwind of cities had a different level of reflectivity. Air pollution may affect how reflective clouds are, enclosing water droplets in an oily layer and preventing them growing to form rain droplets or shrinking to evaporate.

However, everything released into the atmosphere is oxidised. The atmosphere acts like a cool fire, and the pollutant casings (called surfactant films) are short-lived. They oxidise with ozone in the atmosphere, freeing the cloud droplet to expand or contract according to local conditions.

A team from Royal Holloway University of London, working with CLF scientists, has been investigating the rates of different chemical reactions that remove these surfactant films, studying the chemistry that is so important in the atmosphere.

To do so they used complementary studies at the CLF and the ISIS neutron and muon source.

Technology developed by a collaboration between CLF, Diamond Light Source and STFC technology allows lasers to be used like tweezers, holding and manipulating micron-sized particles with a focused laser beam. The team used the laser trap system to hold a water droplet in the focus of a laser, as shown above. This allowed analysis of the surface chemistry of the droplet, using spectroscopy techniques.

They exposed the droplets, doped with a small amount of pollutant material, to ozone to model atmospheric reaction processes, measuring changes in their surface chemistry during the reaction. Neutron investigations allowed the team to measure the rate of loss of the surfactant film by monitoring the reflectivity of the droplet during chemical reactions.

Determination of these properties provides a greater understanding of cloud droplet behaviour in the atmosphere, and its impact on the climate.

Sample preparation in the Octopus laser microscopy laboratory

Plant defence

A discovery about how plants defend themselves in the face of pathogen attacks could hold the key to making crops more disease-resistant.

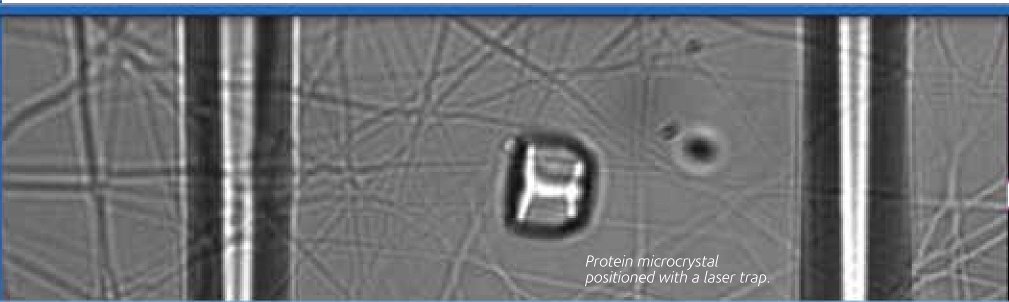
The Octopus laser microscopes have developed a unique technique that has answered a question that has puzzled scientists for many years. Why do certain proteins in plant cells move around less than their counterparts in animal cells?

By showing the movement of individual molecules in living plant cells in real time for the first time, the new technique has revealed that the cell wall plays a crucial role in limiting the movement of proteins produced when a plant comes under attack.

The cell wall allows these proteins to stabilise in the plasma membrane (a 'skin' covering the inside of the cell wall). This restricts their ability to move around and fight invading pathogens and so increases the plant's vulnerability.

Increasing our understanding in this area could help to boost food production and improve global food security.

"'Access to the microscopes in Octopus allows us to perform cutting edge imaging which is only available to a few labs around the world. This allows us to study proteins in the plasma-membrane at unprecedented detail. Our work is applicable to a wide range of fields within plant biology from plant development to plant-pathogen interactions."
Dr Joseph McKenna, Oxford Brookes University.



Protein microcrystal positioned with a laser trap.

Future Health

Protein crystallography with Diamond

Studying protein microcrystals with X-ray crystallography at the Diamond Light Source enables researchers to understand the structure and function of a molecule. This can be essential for understanding biological functions and disease, and lead to medical breakthroughs.

This technique uses crystals of proteins (rather than single molecules). For many proteins, the crystals formed are so small (less than 10 microns) that they are difficult to handle and to mount onto standard sample holders.

The CLF's laser traps provide a novel solution to this problem. Using a laser as 'tweezers' allows the minute crystals to be precisely placed into position on a special microfiber web that acts as a 'net'. The use of laser traps to streamline the process of selecting and mounting microcrystals saves precious research days and resources, and should lead to faster discoveries.

Asthma inhalers

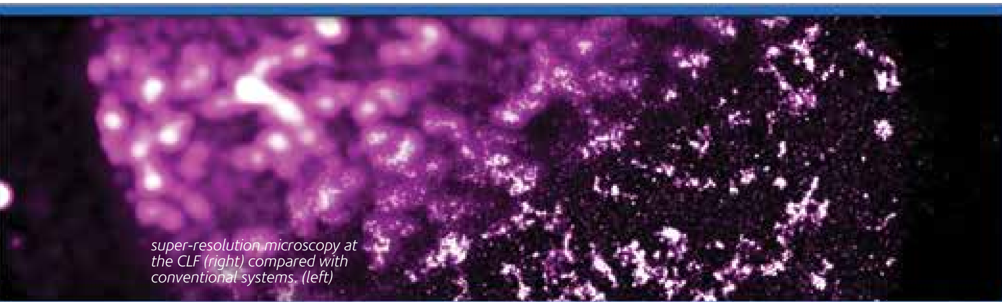
Over five million people in the UK suffer from asthma, and many of them rely on inhalers to deliver their treatment. More than 73 million inhalers are used in the UK every year.

Our lungs have natural defences against the inhalation of particles. Inhalers are pressurised devices which deliver a measured dose of a drug in a way that tries to overcome these defences. Water clinging to the drug particles as they travel from the inhaler into the lung is likely to affect where the drug particles are deposited. This could cause the treatment to be less effective, and give rise to more side-effects.

Until recently, investigations into how the microscopic drug particles behave outside the inhaler were done on glass slides.

Pioneering research using Octopus has been able to investigate airborne drug particles, and the results of these - and future - experiments could help to develop better inhalers, and more effective treatments. Researchers used a laser trap to test how individual particles of the asthma drug salbutamol sulphate behave in conditions simulating the human respiratory system.

Using Raman spectroscopy techniques to measure the vibration and wavelength of light from the molecules, the tests showed how water is adsorbed following changes in chemical bond vibrations, at different temperatures and levels of humidity.



super-resolution microscopy at the CLF (right) compared with conventional systems. (left)

An eye on disease

The treatment of disease is often hampered by a lack of understanding of the way in which complex biological processes influence the development of disease in individual patients.

Being able to predict and monitor the progression of major diseases, and to use this information to develop 'personalised medicine', could offer improved outcomes for patients, whilst reducing costs for health services.

A £1.7 million grant from the Medical Research Council (MRC) is bringing together the CLF, the Research Complex at Harwell (RCaH) and MRC Harwell to improve our understanding of diseases such as cancer, and other medical concerns such as deafness and ageing.

The UK Astronomy Centre (UK ATC) in Edinburgh is also a collaborator, aiding in the development of adaptive optics for super-resolution microscopes. The development of adaptive optics solved a problem in astronomy research, where the 'twinkling' of stars (caused by atmospheric distortion) makes it hard to get a clear image. The murky environment within cells causes similar problems, and adaptive optics can help get a clear picture here as well.

Super-resolution microscopy

Visible light is well-suited for microscopy of biological systems. It is relatively harmless to the samples, has no special requirements on sample environment, and a large range of fluorescent molecules is available for labelling molecules of interest. For these reasons optical microscopy, and particularly fluorescence microscopy, is an indispensable tool in biological research.

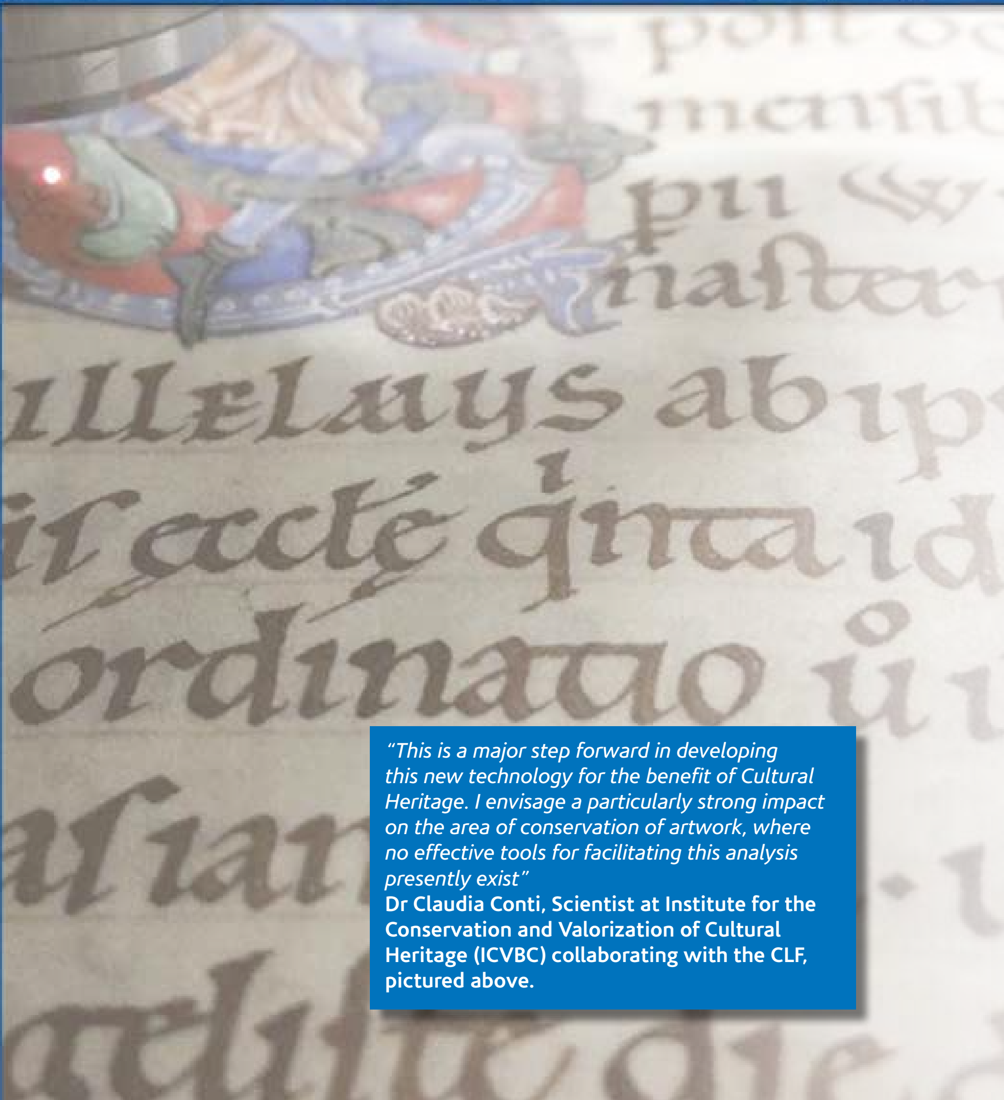
Yet conventional optical microscopy is unable to see many of the structures that are important for biological processes as they are just too small.

Super-resolution imaging techniques available in the Octopus facility allow us to see features ten times smaller than with conventional microscopy. This allows us to see how molecules position and orient themselves to cling on to cell walls, for example.

"I'm a post-doctoral research scientist but also conducted my PhD studies at the CLF. I'm involved in biological investigations of complex systems, making use of the unique technical capabilities of Octopus laser cluster. I work in a multidisciplinary team made up of everyone from biologists to astrophysicists.

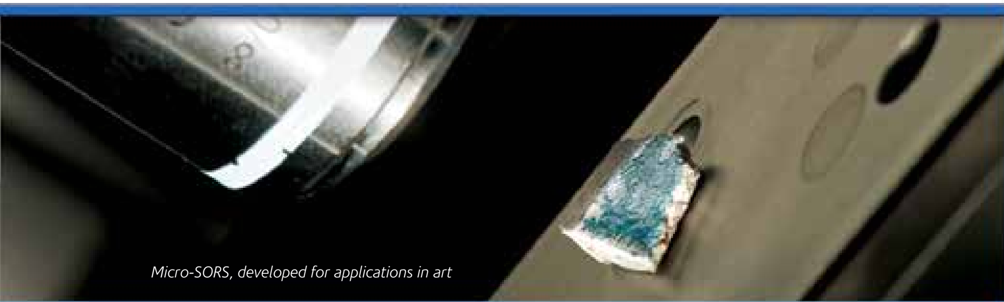
Day-to-day I prepare biological samples and analyse them with the different fluorescent microscopy techniques available on the cluster. I like working in the CLF because it provides opportunities for students to work with scientists from different backgrounds, and to contribute scientific discoveries and technological development." **Dr Laura Zanetti-Domingues, Post-doctoral Researcher**

Micro-SORS, developed for applications in art



"This is a major step forward in developing this new technology for the benefit of Cultural Heritage. I envisage a particularly strong impact on the area of conservation of artwork, where no effective tools for facilitating this analysis presently exist"

Dr Claudia Conti, Scientist at Institute for the Conservation and Valorization of Cultural Heritage (ICVBC) collaborating with the CLF, pictured above.



Micro-SORS, developed for applications in art

Revealing history

Lasers support our cultural heritage

Raman spectroscopy can provide a chemical fingerprint for the identification of pigments in artworks and manuscripts, and the composition of archaeological finds. Using lasers to identify the chemical makeup of materials reduces the risk of damage to precious paintings during conservation and restoration work.

Researchers tested this technique on an artificial surface of painted layers, prepared to mimic a real painting. They were able to assess the chemical make-up of each individual layer.

The next step is to optimise the sensitivity and depth penetration, and apply the technique to real artwork. The ultimate goal is to develop a portable scanner.

In collaboration with University of Durham, the CLF has supported investigations on the pigments used in Northumbrian manuscripts dating from as early as the mid-seventh century.

The Durham Gospels is thought to be one of the precious books made on the Holy Island of Lindisfarne around 650 AD. The Raman analysis characterises the wide range of pigments used in the decorated illuminations found on its pages.

Raman spectroscopy has also analysed the bones of sailors who sailed on Henry VIII's flagship. The Mary Rose sank in battle in the Solent on the 19 July 1545 and was preserved under layers of silt.

Researchers tested two sets of shin bones from the ship. One set appeared anatomically healthy, whilst the other bones were abnormal in shape.

The results of the Raman study confirmed that the abnormal bones have chemical abnormalities associated with rickets. Rickets is a metabolic bone disease that was common in Tudor times due to the poor diet of the average person.

"I was surprised to see the quality of the results that can be obtained with a simple and clever adaptation of standard instrumentation. This approach has enormous potential in our field"
Dr Marco Leona, David H. Koch Scientist in Charge at the Metropolitan Museum of Art in New York.

This work was performed by the Royal National Orthopaedic Hospital (RNOH), University College London (UCL), the CLF and The Mary Rose Trust.

DiPOLE innovative laser design (see page 22)

Enabling technology transfer

The CLF is constantly developing new ideas, technologies and processes. By protecting this knowledge and exploiting it through licenses, patents and spin-out companies, we can ensure that our work is of maximum benefit to UK society.

CALTA

STFC set up the Centre for Advanced Laser Technology and Applications (CALTA) in 2011, with a primary mission to develop new laser technology. CALTA has won projects, worth around £20M, to supply technology to leading research institutes in Germany and the Czech Republic. The technology we are developing will keep the CLF at the forefront of international laser capability. CALTA is also commercialising innovations from the CLF, such as a revolutionary electronic control unit for electric motors.

By bringing together scientists and engineers from the CLF with experts from our Business and Innovation Department, CALTA allows new ideas like these to be developed and exploited for the UK's economic benefit.

Licensing

The Universal Motor Controller, developed through STFC proof of concept funding, allows 'plug and play' control of any motor through an easy-to-use web-based interface, bringing technology developed in the CLF to new users from heavy industry to electronic hobbyists.

"Rolls-Royce recognise the considerable potential of new laser technology to all areas of our products life cycle. This includes research on current topics such as laser peening through to advanced high energy short duration imaging techniques. They have provided a highly constructive and stimulating framework to identify areas for exploitation both near and long term"

Prof. David Rugg, Materials specialist and engineering fellow, Rolls-Royce plc

Credit: © Jakub Jirsák | Dreamstime.com

Intellectual property

The CLF has a strong background in innovation - our current patent portfolio represents a third of STFC's active patents. STFC's top two inventors work in the CLF.

We recently filed a new patent concerning the use of transmission gratings to significantly enhance pulse contrast in high-power laser systems. This provides the CLF with protected intellectual property, allowing us to exploit this technology commercially in the future.

Scanning for new intellectual property is an ongoing activity. Several new inventions, from diverse fields such as adaptive optics, micro-target manipulation and molecular imaging are currently under review.

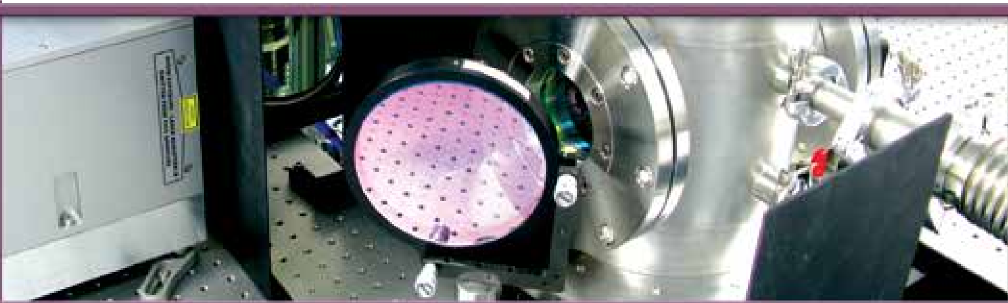
Industry engagement

Over the last two years, more than 20 companies have engaged with the CLF, across sectors including aerospace, automotive, defence and security, pharmaceuticals and consumer goods.

Recent funding made available through our business and innovations directorate enabled Evotec to use Octopus to investigate the effectiveness of their cancer treatment drugs. The ability to conduct single-cell imaging of inhibitor drugs binding their target in cancer cells is a critical step towards developing novel anti-cancer drugs. This work will contribute to the eventual development of personalised cancer treatment options.

"The facilities at RAL, such as Diamond, the Central Laser Facility and ISIS, are world-class. Coupled with the presence of many high-impact researchers at the site and the commitment of STFC management to foster collaboration, the site is very attractive to industry. The key to engagement has been the opportunity to be located on the site combined with a commitment from Johnson Matthey to participate. Spaces such as RCaH are particularly beneficial for collaboration and its future growth is supported along with an increased number of RAL-industry fellowships."

Dr Paul Collier, Johnson Matthey Senior Research Fellow,
Johnson Matthey Technology Centre



Next-generation lasers

Delivering DiPOLE

Diode Pumped Optical Laser for Experiments (DiPOLE) is a pulsed laser delivering a unique combination of high pulse energy plus a rapid pulse repetition rate. It exploits patented cryogenic cooling techniques and recent advances in laser diode technology and advanced ceramic manufacturing.

DiPOLE 10 (with 10 Joules pulse energy and a 10 Hz repetition rate) was the first project for CALTA and demonstrated that this technology is more efficient that the current generation of high power lasers. Early in 2014, CALTA delivered its first major project to ELI, the Extreme Light Infrastructure, in Prague.

CALTA has recently delivered DiPOLE 100 (100 Joules) to the applications-focused HiLASE facility. EPSRC and STFC are also supporting the delivery of a DiPOLE 100 to the European XFEL laboratory in Germany.

CALTA's next major project will see the technology mature into a solid feature within the global high power laser community.

The DiPOLE technology has industrial applications, including materials surface treatment. Shining a DiPOLE laser onto a suitable target produces X-rays, electron beams, and other radiation types, which also have applications in a variety of medical and commercial settings (see page 11).

"I am truly delighted to confirm that the 100 J DPSSL system was safely delivered to the HiLASE facility in Dolni Brezany, Czech Republic. It is currently the most advanced high power laser of this kind in the world and our dream became reality. I would like to express my big thanks to our colleagues at STFC for their hard, professional, and fully devoted work on this challenging project. The best part of this success story is that HiLASE and STFC shall continue over the next years in strategic collaboration and in building solid academic and industrial user community for the 100 J laser"

Dr Tomas Mocek, Director of HiLASE facility.

Lasers in industry

Cobalt Light Systems

Spinout company Cobalt Light Systems is marketing technology using Spatially Offset Raman Spectroscopy (SORS), a technique invented at the CLF.

SORS provides a method for identifying the chemical composition underneath the surface of materials, including beneath the skin (see page 4) and liquids in bottles (see page 10).

A recent addition to the Cobalt product range is the RapID system (pictured above), a handheld "point-and-shoot" device for regulation testing of raw materials for the pharmaceutical industry. These new machines provide accurate quality control, and removing the need to open packaging saves time.

As a leading new company, Cobalt won the prestigious 2014 MacRobert Award for engineering innovation for its unique liquids scanner. Cobalt were up against engineering giant, Rolls Royce, and the fast-growing QuinetiQ spin-out, OptaSense, but won the prize for their pioneering technique that identified liquids in non-metallic containers in seconds.

In 2014,Cobalt Light Systems entered at number ten in the Tech Track 100 league table, which ranks Britain's fastest-growing private technology, media and telecoms companies. The 14th annual Sunday Times Hiscox Tech Track 100 placed Cobalt Light Systems in the top ten of a prestigious list of technology firms in the UK. Cobalt was also presented with the Tech Track 100 high-tech manufacturing award. These awards reflect Cobalt's rapid growth since 2011, with innovative technology enabling the development of successful products in key markets.

And Cobalt has been awarded the 2015 Queen's Award for Enterprise, the UK's highest accolade for business success, in the international trade category.

"We are continually investing in R&D to develop innovative technologies, and our dramatic revenue and export growth over the last three years is testament to how well our products have been received both in the UK and around the world."

Dr Paul Loeffen, CEO of Cobalt Light Systems.

Complex target
with needle to scale

Scitech Precision Ltd

The CLF benefits from a dedicated team of scientists that produces high-quality microtargets for experiments on Vulcan and Astra Gemini. This capability, almost unique among high power laser facilities, allows the user community to maximise the science it can achieve.

As the relationship between the target fabrication group and the user community evolved, demand grew for the group's capabilities to be used in support of experiments on laser systems throughout the world. A spin-out company was set up to supply these facilities, providing extra staff resources and exploiting the economic opportunity provided.

Starting with no external funding in 2009, Scitech Precision has grown to support more than 50 experiments per year, employing five full time members of staff.

The company has also developed exciting, new production technologies that are available for use by STFC. Its work has enabled leading-edge science to be carried out at international facilities such as LULI in France, Gekko in Japan and LCLS in the USA. Experiments at the NIF (see page 9) have used Scitech components.

Scitech's recent acquisition of Colsicoat, an optical coatings company, has added phase plates and anti-reflection coatings to its portfolio. The unique linking of targets and optical components has led to the growth of the customer base, with the number of contracts increasing year on year. The ongoing development of novel technologies is allowing Scitech to enter other markets in precision engineering and science, in addition to its core business aim of supplying the world's best precision microtargets.

"My role involves collaborating with visiting scientists to develop their ideas into achievable designs of targets for intense lasers to irradiate, and developing techniques to bring their ideas into reality. Day-to-day this involves microassembly, metrology, thin film coating and bringing together novel techniques in micromachining and micro-electromechanical system (MEMS) manufacturing.

Between the CLF and spin-out Scitech Precision Ltd, we work on a huge variety of science – we've supplied targets to facilities in the UK, Europe, Japan and the USA. Working on the cutting-edge of high power laser science and being involved with this broad range of projects keeps my job interesting."

Chris Spindloe, Chief Scientific Officer, Scitech Precision

Delivering extreme engineering

A world-class laser facility is more than just excellent laser systems, and one of the factors that enables the CLF to conduct cutting-edge scientific experiments is its embedded engineering department.

The CLF engineers are a highly-skilled team with expertise in mechanical, electrical and control engineering, focused on building and running the laser facilities, supporting user experiments and research and development activities within the CLF.

Each experiment and project is unique, and the engineering team work in close collaboration with internal groups and the external scientific community to ensure safety, success and maximum scientific delivery.

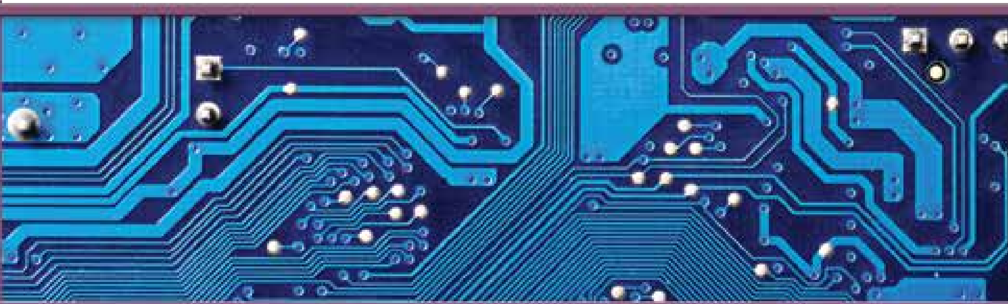
Engineers can join the CLF at all stages of their career, from apprentices to skilled technicians and designers.

"STFC has provided me with a diverse and inspiring career in mechanical engineering, as a I have been able manage the full life-cycle of engineering projects from specification to commissioning.

The DiPOLE-100 project has been a fantastic opportunity, allowing me to demonstrate and develop my skills and knowledge in project management and engineering. An unexpected privilege has been to learn a lot about applied optics and laser science, thanks to the generosity and patience of the scientific team.

It has been highly rewarding to see the system grow from the concepts in my mind to a fully populated lab with commissioning well underway in such a short timescale."

Steph Tomlinson, DiPOLE Project Engineer



Automated laser control systems

CLF engineers are working on fully automated control systems for the DiPOLE lasers. EPICS (Experimental Physics and Industrial Control System), an open source system used in many large scale science facilities such as accelerators, has been chosen as the backbone of the system for the HiLASE project. Work on various sub-systems has already started, including automatic laser beam steering, imaging of laser beam profiles via camera diagnostic integration and the development of a bespoke user interface development environment. A new web-based graphical user interface allows flexible display options, including the use of touch screens, tablets and other mobile devices

Laser technology

The Vulcan laser is charged and fired using a large bank of capacitors to energise flash lamps. A new capacitor charger has been developed to charge and control the firing of the laser. A solid state high voltage switch is being tested as a potential ignitron replacement, and offers a far more compact design. The switch and charger will enable the capacitors to be fired at higher repetition rate and will be used for repetition rate tests of the laser amplifiers.

"One of the best things about CLF is working with users from around the world, helping them to carry out a range of experiments using cutting-edge scientific and engineering equipment. I enjoy the variety of work that is done in the workshop and alongside the laser target area technicians."

Rob Pocock, Fourth Year Mechanical Apprentice

Image above credit: © Alexey Buhantsoff | Dreamstime.com

Sample and target engineering

We're developing software for positioning laser targets that will decrease the time between laser shots. This is essential to make the most of a high repetition rate laser system. The technical challenge is to position targets, which can be too small to see, to a precision of a few microns in the centre of a few-meter vacuum chamber.

CLF engineers have developed a system that produces solid hydrogen targets using a condensation method. It will enable laser scientists to shoot pure droplets of solid hydrogen or deuterium – a unique capability for the CLF. The droplets need to be kept at a temperature of just a few Kelvin to remain solid.

We are building a dedicated small-scale flexible mixing system for the Gemini facility remote controlled gas system.

The remote controlled gas system allows users to change pressures and fire gas jets from the control room. Precise control of the mixing ratio is essential to allow detailed parameter scans - for example, to optimise the quality of electron beams generated by the laser interacting with the gas.

Several experiments require gas targets at pressures much higher than can be delivered with bottled gas. A high-precision, electronically-operated piezo valve capable of 500 bar with hydrogen is under development with Imperial College, London and an external specialist. The technical challenge here is to design a valve that can open and close rapidly under these high pressures, releasing a precise quantity of gas into the target chamber.

Extreme intensities

Increasing the power of lasers opens up new avenues of research in particle physics, nuclear physics, gravitational physics, astrophysics and cosmology. With ten laser beams at 200 petawatts (PW) each, focused to a small point, we would be able to produce a light intensity greater than that at the centre of the Sun. This would be an order of magnitude more powerful than any lasers currently being built.

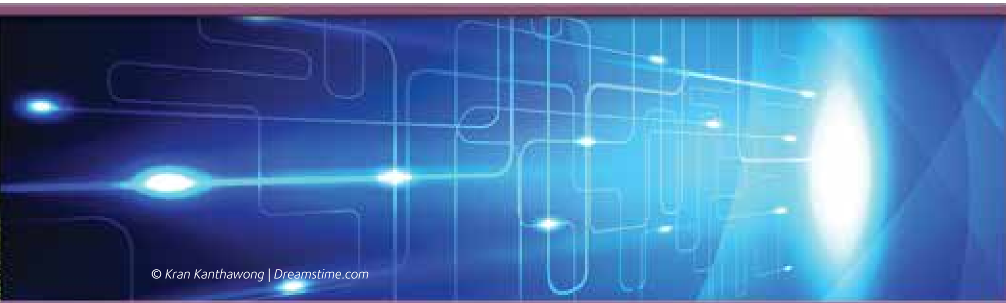
The aim would be to 'break the vacuum', by pulling apart pairs of matter-antimatter particles, which pop into existence but then instantly annihilate. By doing so we would learn more about the fundamental particles in the Universe, and possibly learn the secrets of dark matter. Different scientific measurements suggests that there is more matter in the Universe than we can see, with the rest being dark matter that has yet to be detected by any experiment.

Reaching higher powers

The CLF has been pioneering the development of technologies for ultra-short pulse duration laser systems. We have developed a novel seed source for a laser system capable of supporting clean laser pulses of less than 20 femtoseconds in duration, which with further amplification could deliver peak powers of 20 petawatts and above. This will give access to unprecedented focused intensities of light, enabling new scientific discoveries. This technology could be combined with others under development in the CLF to lead to new and exciting applications of lasers.

New laser concepts

Our ability to amplify laser pulses is limited by the laser intensities that can be sustained without damaging solid-state amplifiers. Amplification within plasmas would avoid this limitation. The CLF's plasma group has been investigating theoretical methods of transferring energy to a laser via waves in a plasma, using advanced numerical simulations. They have shown that this could be highly effective with the right conditions.



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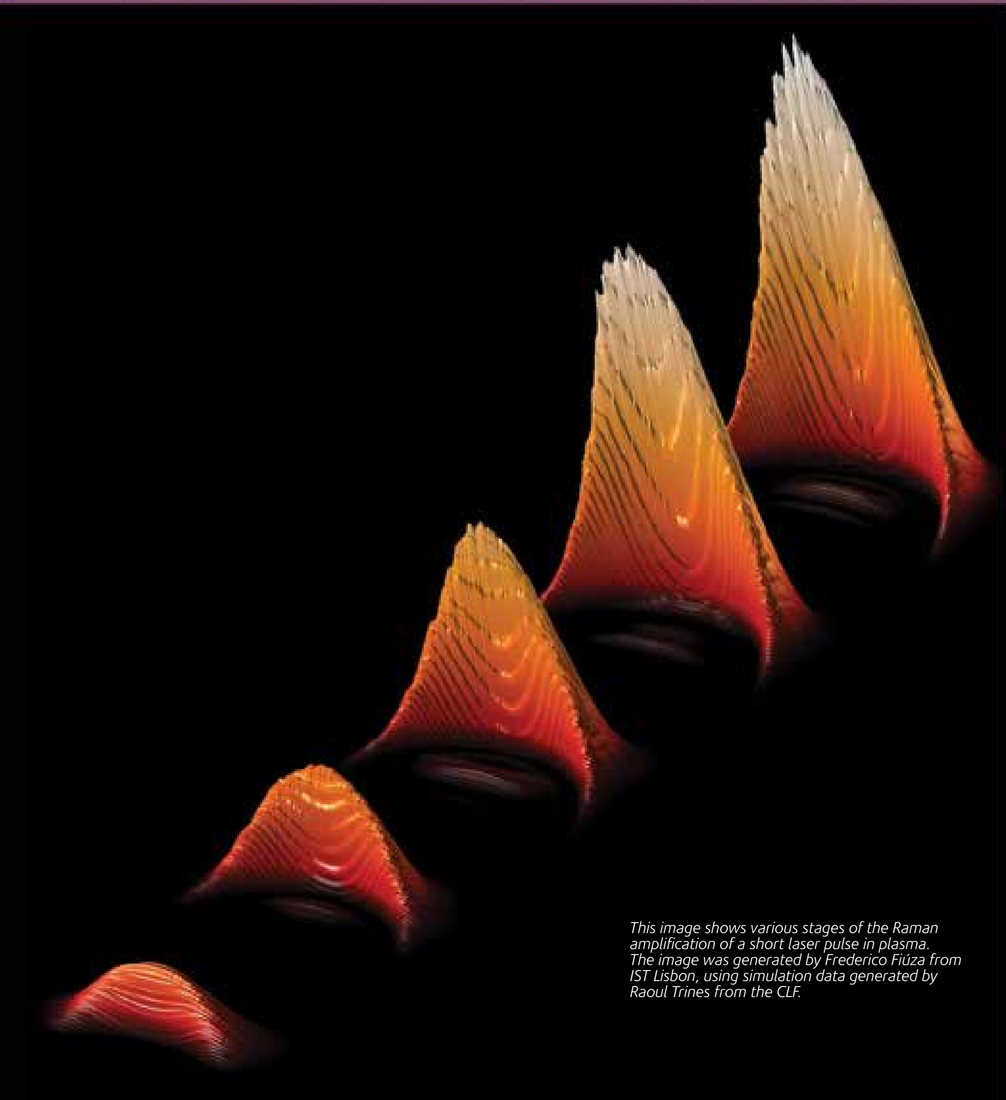


This image shows various stages of the Raman amplification of a short laser pulse in plasma. The image was generated by Frederico Fiúza from IST Lisbon, using simulation data generated by Raoul Trines from the CLF.

Lasers in space

Supernova in a lab

Vulcan's nanosecond beamlines were able to mimick the turbulent blast wave that occurs following a supernova explosion, a world first that could explain how the Universe developed magnetic fields. Researchers from the University of Oxford focused three laser beams onto a carbon rod target in a gas-filled chamber. The rod exploded, causing a shock wave that expanded out through the gas –recreating what happens in the aftermath of a supernova explosion.

The scientists introduced turbulence into the shock wave, and showed that this produces a stronger magnetic field. Their results could help explain why some supernova explosions show irregular knots and twists in their radio synchrotron radiation emissions.

High-powered lasers allow us to recreate, in minutes, events that take hundreds of years to unfold in the Universe, and mean we can investigate astrophysical phenomena right here on Earth.

Simulating plasma jets

Powerful jets emanating from small (or compact) objects are a common occurrence in astrophysics. For example, powerful jets come from what may be immense black holes in the centres of galaxies, and from new-born stars. Questions remain about the origin of these jets, and physicists have created reproductions driven by intense laser beams.

The CLF plasma group investigated a situation that was driven by a single, spherical exploding shockwave crashing into a region of denser material. 3D numerical simulations showed that this can create a strong and well-defined jet under certain conditions.

This opens up the possibility of using laser experiments to investigate theories that have been hard to test experimentally.

"…for using one of the world's most powerful laser facilities to create tiny versions of supernova explosions in the laboratory."

Extract from Top 10 Physics World Breakthroughs of the Year 2014

Image above: Jena Meinecke, University of Oxford, sets up the experiment for generating supernova blast waves in the Vulcan target chamber.

Singing stars

A team of researchers using a laser technique similar to a police speed camera has made the unexpected discovery that suggests stars can 'sing'.

The study of fluids in motion, hydrodynamics, goes back to crop irrigation in Ancient Egypt, and so new discoveries are rare. A team of researchers from the York Plasma Institute at the University of York and the Tata Institute of Fundamental Research in Mumbai, aided by theory from the CLF, noticed something unusual when they were investigating the interaction of an ultra-intense laser with a plasma target.

A trillionth of a second after the laser strikes the target, plasma flows from areas of high density to areas of lower density. This rapid movement causes plasma to 'pile up' at the boundaries between different densities, generating a series of pressure pulses – sound waves.

Sound waves could be generated in a similar manner at the surface of stars that are accumulating material. But we won't be able to listen to the stars singing. The vacuum of space stops sound waves from travelling, and at a frequency of almost a trillion hertz, these are well beyond our range of hearing.

Accessing the atomic world

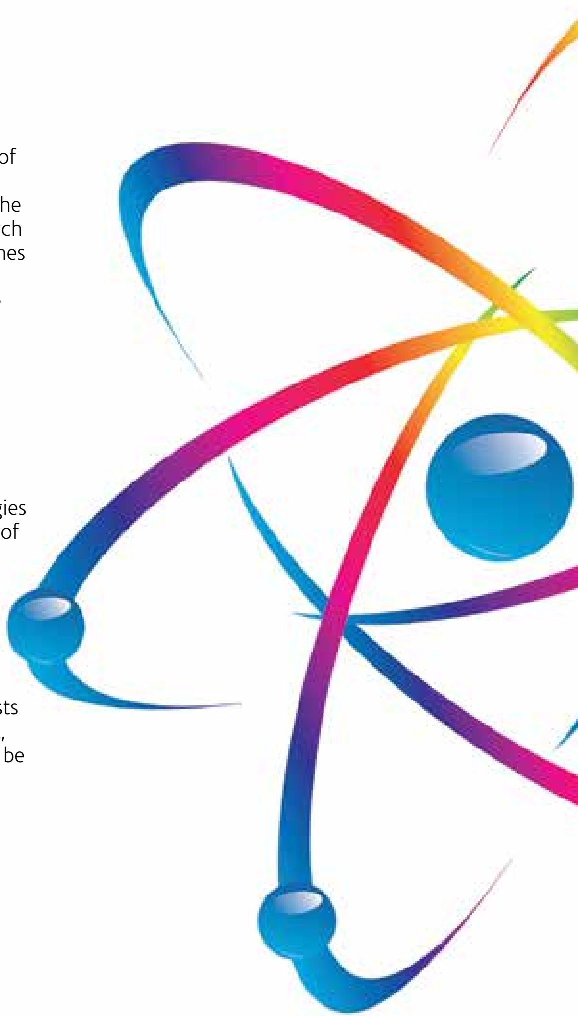
Attosecond pulses

Attosecond science – the creation and use of x-ray pulses a few millionths of a millionth of a millionth of a second long - is one of the most exciting fields at the frontier of research with lasers. These pulses are a thousand times shorter than the shortest possible visible light pulse, and so are short enough to take unblurred snapshots of electrons moving in atoms and molecules.

A recent discovery shows that focusing an intense laser on to a solid creates dense electron bunches travelling at close to the speed of light. These can generate periodic trains of attosecond pulses.

This new technique makes high pulse energies possible, important to enable a wide range of experiments.

A critical step in the development of this technique is to isolate a single attosecond pulse from the pulse trains. A recent experiment on Gemini showed that it is possible to do this by manipulating the polarisation of the driving laser. This suggests that current technology can produce bright, isolated attosecond pulses, and could soon be used to study the dynamics of electrons.



Gemini laser amplifier

Einstein flying mirror

We're all familiar with reflections from mirrors or still water – but what happens if the mirror moves at the speed of light?

In 1905, Albert Einstein formulated a thought experiment in which he predicted that a reflection from a mirror moving close to the speed of light could produce bright light pulses with short wavelengths.

In 2014, a group of scientists using the Gemini laser were the first to demonstrate this effect. They explored the interaction of intense laser light with a surface of densely-packed electrons moving at close to the speed of light (which acted as the 'mirror').

An exchange of momentum between the light and the electrons can result in a big increase in the peak power of the light. This is because the pulse is compressed in time and the reflected wave has a shorter wavelength (and hence a higher energy).

Creating the experimental conditions required to show this effect is tricky. It needs one super-intense laser to ionise a target and accelerate a dense packet of electrons, and another to meet the electron packet head-on during the fraction of second when the mirror exists.

The success of this experiment paves the way for a new technique for generating intense, attosecond pulses of light. These pulses can be used to study the dynamics of electron motion and expand our understanding of fundamental physics.

A collaboration of scientists from the Max-Planck-Institute of Quantum Optics in Garching, the Ludwig-Maximillians-Universität München, the Queens University Belfast and the CLF, used the dual-beam capability of Gemini to test Einstein's theory.

Molecules in motion

Lasers control chemistry

A collaboration between the University of Sheffield and the Ultra team has been looking at what is often deemed the "holy grail" of chemistry - using light to not only trigger a chemical reaction (for example photosynthesis), but also to control which products that reaction creates.

Their results, published in the journal *Science* in 2015, offer a step towards "quantum control" of chemical reactivity using infrared light. This may have fundamental implications, leading to better understanding and manipulation of light-driven chemistry.

A single product is usually the result of a chemical reaction, but that reaction can involve several intermediate steps. At these "road crossing points" or "junctions", the reaction path has to decide which route to follow.

The researchers have shown that using low energy infrared light can change which products form during an elementary reaction. The next step is to be able to block or unblock any chemical pathway at will.

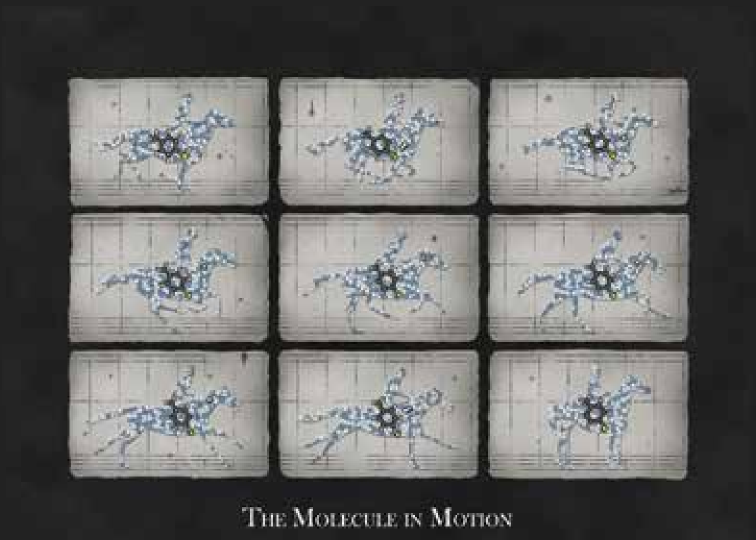
Chemistry in action

Absorption of light can often cause a chemical bond within a molecule to break, a process known as molecular dissociation.

Researchers used state-of-the-art time-resolved absorption spectroscopy at Ultra to study molecular dissociation in a solution. The study explored the similarities and differences introduced by the presence of the solvent, comparing the new experimental results with those from previous studies involving isolated molecules.

The experiment captured the evolution of a molecular dissociation process "in real time", offering previously unobtainable detail about how the dissociation and subsequent processes in the solution proceed. The results of this study featured on the front cover of the prestigious journal *Physical Chemistry Chemical Physics*.

This study was a collaborative effort between the University of Bristol, the University of Southern California and the Central Laser Facility.



Dr Stephanie Harris, University of Bristol
Front cover image of Physical Chemistry Chemical Physics journal. Credit: Physical Chemistry Chemical Physics journal 2013

"Time-resolved absorption spectroscopy methods allow one to capture the evolution of a molecular dissociation process 'in real time'. Such studies provide hitherto unobtainable detail about how the dissociation and subsequent processes in the solution proceed – much like how Eadweard Muybridge's iconic 1878 study entitled 'Horse in Motion,' on which the cover art is based, used the time-resolved capability of photography to unravel the mechanics of a horse's gallop"
Dr Stephanie Harris, University of Bristol

Lighting up tomorrow

Computational plasma physics

A plasma is a state of matter, behaving differently to the more familiar liquid, gas and solid states. Plasmas form when extreme conditions (eg high temperatures, electricity, particle collisions, strong electric fields) rip apart the building blocks of matter. Powerful lasers produce some of the most extreme conditions in the universe, and so create plasma.

Plasma dynamics are complex, due to the interactions between electric currents and magnetic fields. Being able to simulate plasma dynamics would allow physicists to predict what will happen in laser experiments.

The development of a new 3D simulation program called Odin will help with experiment design, interpretation of experiment results, and the design of multi-beam systems, as well as theoretical predictions.

"The UK laser-plasma community would benefit greatly from access to an UK developed radiation-hydrodynamics code. The EPSRC funded Odin project aims to deliver such a code. This project is a collaboration between the Universities of Warwick, Imperial, York and the STFC Central Laser Facility and aims to have an initial user release version of the code by April 2018. Support from the CLF will be essential in testing this code against both analytic and observational results."

Prof. Tony Arber, University of Warwick

Magnetic guidance systems on a microscopic scale

When ultra-intense lasers hit solid targets, they produce a spray of high-energy electrons that are travelling at close to the speed of light. If we could control the direction and flow of these electrons, this would open up a number of exciting applications. It could, for example, radically change laser fusion concepts (see page 9) and laser accelerators (see page 11).

Electron beams from conventional accelerators are guided by complex and well-engineered magnetic guidance systems. For laser-plasma interactions, a guidance system would need to be miniaturised – a task that has so far seemed impossible.

The CLF's plasma group have used computer simulations to show that it is possible to exploit the magnetic fields generated as the beam flows through the solid target, and to develop miniature guiding magnetic field structures. Their results were published in a series of papers, including one in *Physical Review Letters* in 2012.


Credit: © Razvan Ionut Dragomirescu | Dreamstime.com

New laser instruments

In 2014, the Biotechnology and Biological Sciences Research Council (BBSRC) provided two grants, totalling £1.5 million, to invest in new and world-leading instruments for the CLF and the life science user community.

The first grant is to develop the unique LIFEtime instrument, which makes use of ultrafast lasers that can 'hit' a sample a hundred thousand times a second.

When conducting experiments with precious or sensitive samples, there is a risk of damaging the sample. With something as delicate as a DNA base, or a protein, you want to limit the damage as much as possible, but some researchers need to repeat some experiments to gather information at both fast and slow timescales.

The LIFEtime instrument uses its ultrafast lasers to record molecular level changes on different timescales at the same time on the same instrument. From the fast initial reaction that occurs when the laser hits the target, to the slow, follow-on reactions, LIFEtime can reveal processes that would otherwise be undetectable.

This could uncover crucial information, for example how bacteria and plants respond to light and how DNA is damaged in ways that can lead to cancer. Big data is the key to making LIFEtime a useable tool – it is driving the development of computational capabilities that can analyse and interpret the high-volume, highly-complex datasets it generates.

The second grant is funding a Stimulated Emission Depletion (STED) microscope.

This super-resolution microscope will enable scientists to study, in real time, almost any organelle (sub-unit within living cell) to see how it is functioning.

One use for the new microscope will be investigating 'nerve guidance conduits' (NGC), used to bridge the gap in nerve injuries that are too severe for the nerves to grow back. Scientists will be able to produce high resolution images of the interaction between the NGC and nerve cells, and use this information to make NGCs more effective.

Researchers will also be able to use STED to monitor the behaviour of receptor molecules in plants as they respond to bacteria attacks, which will help us to develop plant varieties that are more resistant, and to reduce the need for pesticides.

LIFEtime is a collaboration with the universities of East Anglia, Nottingham, Reading, Sheffield, Manchester and Strathclyde, Queen Mary, London, Trinity College Dublin, University College Dublin, Ècole polytechnique fédérale de Lausanne and Stony Brook.

Our Lasers

Vulcan

The Vulcan laser system delivers pulses of light, containing up to one petawatt of power, that are so extreme in intensity that they are able to instantly rip apart and super heat matter to millions of degrees, forming a plasma. Each Vulcan pulse is compressed to last only half-a-trillionth of a second and focused down to a spot that is ten times smaller than the width of a human hair, generating extreme powers and intensities.

The Vulcan laser supports a wide-ranging programme of research, encompassing both fundamental and applied aspects of plasma physics. Its ability to simultaneously compress and heat matter makes it ideal to study many aspects of laser fusion and to recreate conditions only found "off planet", such as extreme temperatures (found in the cores of stars), extreme magnetic fields (found in neutron stars) or extreme pressures (found in planetary cores).

Gemini

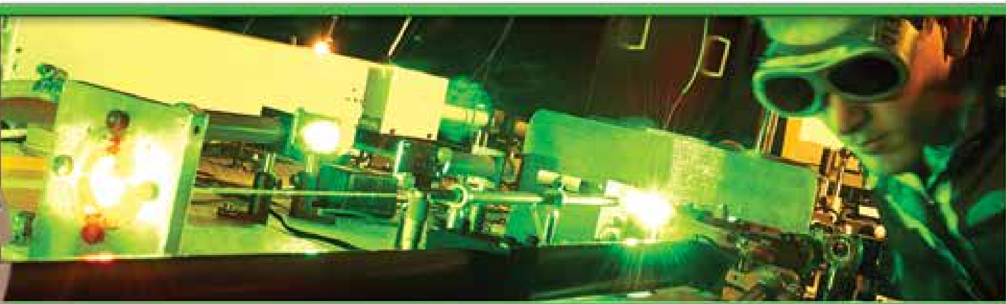
The Gemini laser system was the first facility in the world to provide two beams of high-power, super-intense laser light. The pulses are focused down to a spot that is smaller than the width of human hair and contain almost one petawatt of power. Gemini pulses are more than ten times shorter in duration than the Vulcan laser, enabling the exploration of ultrafast plasma science.

Experiments on Gemini have shown that lasers can produce super-bright, high quality X-ray and gamma ray sources that are ideal for seeing through and probing very dense or concealed objects, and for medical applications. Gemini has also shown that lasers can be used as super-compact particle accelerators with revolutionary potential for science and technology in general.

Artemis

The Artemis system produces pulses of extreme ultraviolet light (between UV and X-ray) so short that they are able to probe and take snapshots of the way electrons move within matter. Artemis experiments adapt techniques used on synchrotrons, but produce ultrafast movies rather than static images. They use one laser pulse to energise electrons in a sample and start them moving, followed by an extreme ultraviolet pulse to freeze-frame the electron motion. A series of snapshots are then sequenced into ultrafast movies of electron behaviour. For maximum flexibility, the laser colour can be tuned across the spectrum from the UV to the infrared.

Experiments on Artemis are revealing, for example, how novel materials such as



graphene could be used in lasers, solar cells and electronics and exactly how molecules move as they make and break bonds in chemical reactions.

Ultra

The Ultra system has multiple laser beams of different colours and a suite of specialist cameras that take super high speed "movies" of molecules during chemical and biological reactions. The structures of molecules are measured by the most sensitive instrument in the world for detecting tiny colour changes, from which scientists can infer the structure changes that are taking place.

Researchers use Ultra for example, to study how well DNA is able to repair itself after damage and how problems with this may lead to cancer. It can also be used to investigate how proteins interact and arrange themselves in nature, and to assist the development of new molecules that can generate energy from sunlight or form part of novel electronic devices.

Octopus

The Octopus system is a laser-based microscopy facility that offers a set of advanced imaging stations, used to investigate biological systems from single molecules to whole cells and tissues.

Specialist techniques allow scientists to see objects up to 50 times smaller than is possible with conventional microscopes. This allows, for example, the observation and tracking of many molecule interactions in complex biological systems, inside living cells, in real time.

The Fluorescence Resonance Energy Transfer technique labels biological molecules and watches how the timescale of the fluorescent emission changes. It is used to explore cell signalling pathways that control life-sustaining processes.

Recent work on Octopus aims to discover why certain anti-cancer drugs lose their efficiency over time, and to help in the development of personalised drugs and treatments.

"I'm responsible for making sure Gemini remains a world-leading facility, producing cutting-edge science. To do this, we need to find innovative solutions for challenging problems. Recently, we have been exploring novel solutions for improving the temporal contrast of high power laser pulses, and collaborating with scientists at Imperial College on finding new media for accelerating electrons to GeV energies.
Working in CLF provides a unique opportunity to work at the forefront of intense field science, with some of the best minds around. The atmosphere here makes it easy to focus on the outstanding science we do."
Dr Rajeev Pattathil, Gemini Group Leader

CLF user career profile: Stuart Mangles

Stuart Mangles (pictured above) is a lecturer at Imperial College London and works within the laser-plasma physics group. He is the lead author of one of the three 'dream beam' papers, (see page 11) that were published by the journal *Nature* in 2004. This work, carried out on the Gemini laser, has become the most highly-cited work to come out of the CLF, with over 1000 citations.

"My first experience of the CLF was an EU experiment, trying to accelerate electrons in a glass capillary using Vulcan TAW. It was exciting to work on an international experiment and within a big team.

During that time I went on training weeks, which I found very useful - both for what I was taught and for getting to know people at RAL and other universities.

During the 'dream beam' experiment in 2004 we were all obviously very excited by the results, but I think that it was really the senior people on the experimentwho realised quite how significant the result was.

My first role post-PhD was an experiment in Lund, and my experience at the CLF helped me to design and build an experiment in an unfamiliar laboratory in quite a tight time frame.

Now I hold a University Research Fellowship from the Royal Society, I get funding through STFC through the John Adams Institute for Accelerator Science and I'm on an EPSRC grant about the effects of QED in very high intensity laser plasma interactions. I supervise or co-supervise three PhD students at various stages; we are regular users, particularly of Gemini.

The CLF is a major part of my research. For me the next things include a move to high repetition rate lasers, so that the electrons and X-rays we have developed can be used for a wide range of applications including imaging, and a move to ever-higher intensities where we can probe new physics.

One nice thing I have seen over the last few years is that people now want to use the electron beams and X-rays we've been developing - and that has led us to really appreciate the demands of supplying a beam to a group of users!"

Training the next generation

A core value of the CLF is in training the next generation of scientists and engineers through work experience programmes, undergraduate placements and engineering apprenticeships. We also run training courses for early career members of the user community to equip them with the knowledge and experience required to run productive, safe and successful experiments.

In an initiative announced by the Business Secretary in October 2014, BBSRC has awarded funding to leading universities and scientific institutions through their

Doctoral Training Programme. The strategic investment will ensure that PhD researchers are trained in areas that benefit the UK and help to develop new industries, products and services.

STFC and the Harwell campus are partnering with the University of Oxford to form an Interdisciplinary Bioscience Doctoral Training Programme. Staff and scientists at the CLF, ISIS neutron and muon source, Diamond Light Source and the RCaH, will run training courses and provide expert mentoring for the students at these facilities. The £12.5 million Oxford programme will train 125 students over the next five years.

Outreach and public engagement

Our new CLF visitor centre provides an educational space that tells the story of the CLF by describing the laser systems, engineering and science, alongside the global and societal impact and technology spin-offs of our work.

We host visits, work experience placements and facility tours. A 3-month residency provided an opportunity for an artist to develop work in close cooperation with leading scientists. We act as STEM (science, technology, engineering and mathematics) ambassadors, visiting schools and giving public talks. We have a passion for enthusing, inspiring and exciting the public with the research, applications and technology enabled by our lasers.

Several thousand visitors pass through our door each year, from members of Parliament and international delegations, to school students and industry and representatives.

The bang of a Gemini laser amplifier has been heard on BBC Radio 4's Inside Science programme. The Discovery Channel filmed the Vulcan experimental area where we replicated a supernova blast wave (see page 30) for their 'How the Universe Works' series. When CLF spinout Cobalt Light Systems won the MacRobert Award (see page 21), the news reached more than five million people across the world.

Throughout 2015, our Incredible Power of Light roadshow travelled to meet people across the country, to coincide with the International Year of Light.

Community involvement

The CLF is assisting the new University of Oxford/Imperial College London/University of Warwick Centre for Postgraduate Training in Plasma Physics and High Energy Density Science , hosting the first autumn school - Introduction to Plasma Physics.

The Plasma Physics Group trains graduate students and post-doctoral researchers in high performance computing and provides access to computing facilities.

The popular CLF annual User Meetings provide a friendly environment in which students can present research to audiences outside of their institutions.'

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