Science & Technology Facilities Council

CLF Annual Report 2016-2017

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Central Laser Facility
Science & Technology Facilities Council
Rutherford Appleton Laboratory
Harwell Campus
Didcot, Oxfordshire OX11 0QX
T: +44 (0)1235 445603
E: clfenquiries@stfc.ac.uk
W: www.clf.stfc.ac.uk

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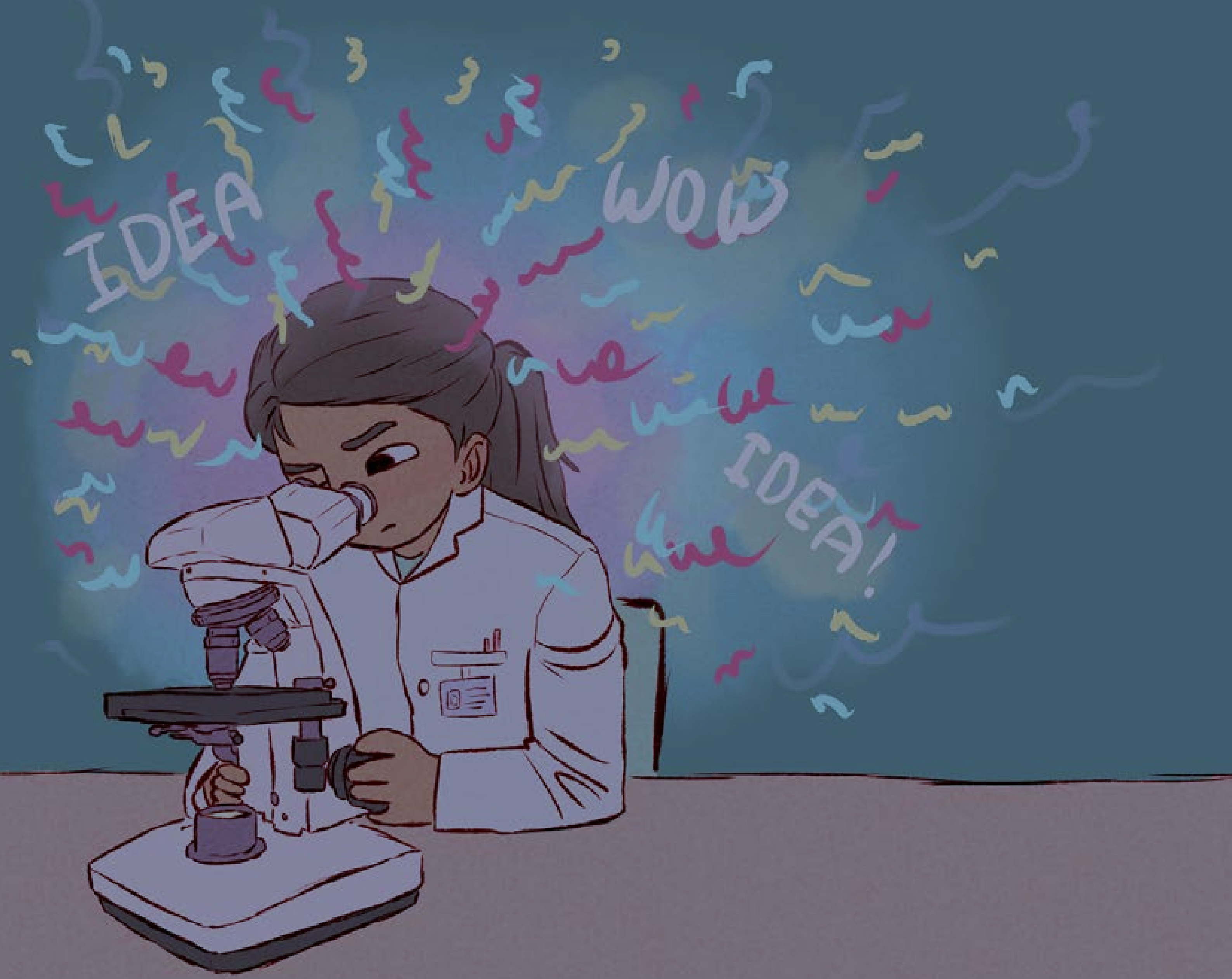

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Editor: Raoul Trines

Production: Raoul Trines, Tracey Burge and Lizzie Henderson

Section Editors: David Carroll, Richard Chapman, Ian Clark, Dave Clarke, James Green, Chris Hooker, Ian Musgrave, Rajeev Pattahil, Jonathan Phillips, Dan Symes, Martin Tolley, Raoul Trines, Adam Wyatt

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Thanks to all of the above for their contribution towards producing this report and, of course, to all of the authors for their submissions.

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Foreword

John Collier
Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
Email address: john.collier@stfc.ac.uk Website: www.clf.stfc.ac.uk

This annual report for the Central Laser Facility (CLF) at the STFC Rutherford Appleton Laboratory provides highlights of scientific and technical research that has been carried out by users of the Facility and its staff over the financial year 2016-17.

This year has seen an uplift in funding and consequently an uplift in the volume of user access we are able to offer, with the CLF's facilities remaining heavily oversubscribed. The CLF and its community have continued to deliver scientific output and technical development of the highest order.

Vulcan – One of the main highlights from this period was in the first imaging campaign for the x-ray radiography of nuclear waste. This feasibility study successfully demonstrated the ability to image a uranium penny encased in grout, and led to a successful grant and further experiments to continue this area of study. The successful imaging via electronic detectors on this experiment led to the further development of high-energy imaging cameras, and also underpins the concept for imaging at higher repetition rates.

Gemini continued to maintain its preeminent stature as a driver for secondary sources for applications as well as fundamental science, yielding several high-impact papers this year. These include two publications in Nature group journals (Nature Physics and Nature Communications) on the demonstration of relativistic-induced transparency that creates an instantaneous pinhole in an otherwise opaque plasma, providing a new way of controlling laser-driven proton beams. An experiment in Astra also demonstrated feedback control of high-energy electron beams employing genetic algorithms for the first time.

Artemis received funding for a laser upgrade – a mid-IR system running at 100 kHz – which is a joint purchase with Ultra. The laser will arrive in 2018. Artemis expanded the range of experiments it can offer with its first demonstration of XUV lensless imaging, using ptychography to image a biological sample (mouse neurons) with 100 nm resolution. The team also demonstrated UV-pump XUV-probe photoelectron spectroscopy from molecular gases for the first time.

Target Fabrication – Scitech Precision Ltd (the CLF spin-out specialising in microtargetry) continued to supply microtargets for use on an increasing number of international facilities including FELs.

The CLF's facilities in the Research Complex at Harwell, Ultra and Octopus, continue to serve a multidisciplinary community, with user programmes in areas ranging from fundamental chemistry and materials science, to biomedical and environmental research.

Ultra continued to deliver 60 weeks of access to the academic community. It also supported an increased volume of access by industrial users. Of note has been the application of a range of ultrafast techniques to catalysis research, including *in operando* Kerr-gate Raman studies of zeolites. The commissioning of an IR pulse shaper on the Ultra B station has enabled the first broadband 2DIR experiments on highly scattering zeolite samples. Two new programmes were awarded, both focusing on homogeneous solution phase catalysis.

Octopus is now running routinely with parallel operation for multiple user groups. As part of its programme of continuous development, two older microscopes were decommissioned to make way for new instruments. Development work has focused on cryo-super resolution and correlative microscopy, building on technology patented by the CLF. As part of its drive to maximise the potential of multiple microscopy techniques available on the Harwell Campus, collaborations in correlative imaging have been established with both eBIC and the Rosalind Franklin Institute.

The CLF's **Centre for Advanced Laser Technology and Applications (CALTA**) demonstrated world leading performance from its "DiPOLE 100" laser in December 2016, with an output of 107 J at 10 Hz for an extended period. This is the first time that a system of this type has demonstrated kW-level average power operation and marks the successful completion of the £10M contract with the Institute of Physics in the Czech Republic. The laser is now fully commissioned in the HiLASE Centre, close to Prague.

Following this outstanding result, the CLF and HiLASE teams have been awarded €50M as part of a Horizon 2020 Widespread Teaming project to enhance the HiLASE Centre and to develop diode pumped solid state laser technology. As part of the project, the CALTA team will design and construct a 100 Hz version of the DiPOLE 10J laser. This system will be unique, extending STFC's lead at the forefront of DPSSL laser technology.

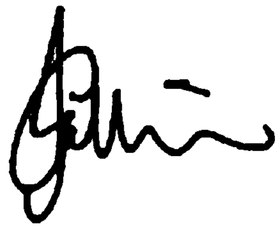
Construction of a second DiPOLE 100 laser (D-100X), a UK contribution to the HIBEF consortium at the European XFEL facility, is well advanced. The laser will be commissioned at RAL with delivery to Hamburg scheduled for December 2018. Funding is being provided jointly by STFC and EPSRC. When installed at the high energy density instrument, users will be able to access new states of matter, using the D-100X laser beam to shock-compress targets to high pressure followed by diagnosis using the XFEL beam. The 10 Hz repetition rate of D-100X will give users the ability to optimise the interactions in "real time" and to gather data at an unprecedented rate.

Economic Impact – CLF continues to build strong relationships with industry, resulting this year in five new commercial contracts with companies to gain access to our facilities (Ultra, Octopus and Gemini). Additionally two major contracts have been awarded: one with DSTL for the preparation of the PULSAR TDR; and a second through the H2020 Widespread and Teaming programme with the HiLASE facility in the Czech Republic, to develop DiPOLE technology further and to provide support for innovation activities.

We have continued to build on our Intellectual Property (IP) portfolio, with two new patent applications filed and two patents granted. CLF continues to take the lead in terms of invention disclosures and patent ideas submitted for review.

Work on developing Laser Driven Sources for industrial applications has progressed, and the CLF was awarded a grant through the STFC IPS scheme to work alongside Bristol University and Sellafield in developing laser driven x-rays and neutrons for inspection of nuclear waste containers. This is a big opportunity and further broadens the applications space for these rapidly developing sources.

Finally, at the CLF, the close partnership we have with our User Community has been central to our past success. As we look forward, it is imperative that we collectively draw on that partnership to promote our collective success that is, in part, represented in this publication. I hope that you enjoy reading it!



Professor John Collier FLSW
Director, Central Laser Facility

Overview of the Central Laser Facility (CLF)

Cristina Hernandez-Gomez
Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
Email address: cristina.hernandez-gomez@stfc.ac.uk Website: www.clf.stfc.ac.uk

The CLF is a world leading centre for research using lasers in a wide range of scientific disciplines. This section provides an overview of the capabilities offered to our international academic and industrial community.

Vulcan

Vulcan is a highly versatile 8 beam Nd:glass laser facility that operates to two independent target areas. The 8 beams can be configured in a number of combinations of long (>500ps) and short (<30ps) pulse arrangements.

Target Area Petawatt is Vulcan's highest intensity area, capable of 500 J / 500 fs pulses focused to 10^{21} W/cm^2. The ps OPCPA front end ensures that the ASE contrast of the PW system is better than 10^{10} at 1 ns. To complement the short pulse beamline, an additional 250 J long pulse beam line, as well as a variety of possible probe beams, can be configured in the area. A compressor has been installed in the Vulcan front-end to help with characterising the contrast and for the development of new short-pulse diagnostics.

Target Area West is Vulcan's most flexible target area, offering up to 8 long pulse beams or 2 short and 6 long pulse beams. The two short pulse beams operate independently and can be configured so that one operates at 80-100 J / 1 ps (10^{20} W/cm^2) and the other one at either at 80-100 J / 1 ps or at 300 J / 10 ps in flexible geometries. TAW can be also be configured with all 8 beams in long pulse mode by using a compressor by-pass arrangement delivering a maximum of 2.5 kJ with all beams. Temporal pulse shaping is available for long pulse operation and there are a number of focusing, beam smoothing, probe beam and harmonic conversion options. This year there has been an upgrade to the Vulcan timing system, to reduce the temporal jitter between the long and short pulses by an order of magnitude to 20 ps RMS.

Gemini

Gemini is a Titanium-Sapphire based dual-beam high power laser system with the unique capability of 2 synchronised Petawatt-class beams, enabling interactions at extreme light intensities (~10^{22} W/cm^2). Gemini's dual-beam capability enables cutting-edge experiments that are difficult to perform in other facilities around the world. This year, Gemini performed several experiments - ranging from Thomson scattering to investigate Quantum corrections to gravity and demonstrating radiation reaction as near-light-speed electrons are slowed down in intense light fields, to investigating novel injection mechanisms for laser wakefield acceleration - utilising this capability. In recent years, Gemini has established itself as one of the preeminent centres for laser-driven wakefield acceleration and applications. An experiment in Gemini's Astra Target area last year demonstrated feedback-control of high-energy laser-driven electrons at high-repetition rate for the first time, while another experiment in Gemini investigated novel injection mechanisms to improve laser-driven electron acceleration.

Artemis

Artemis is the CLF's facility for ultrafast laser and XUV science. It offers ultrashort pulses at high repetition-rate, spanning the spectral range from the XUV to the far-infrared. The facility is configured flexibly for pump-probe experiments. Tuneable or few-cycle pulses can be used as pump and probe pulses, or to generate ultrafast, coherent XUV pulses through harmonic generation. Two XUV beamlines lead to end-stations for time-resolved photoelectron spectroscopy (for both gas-phase and condensed matter experiments) and coherent lensless XUV imaging. This year saw Artemis's first demonstrations of UV-pump XUV-probe photoelectron spectroscopy from gaseous molecules, and also its first demonstration of XUV lensless imaging from biological molecules.

Artemis has received funding for a 100 kHz laser system operating at 1700 nm and 3000 nm, in a joint purchase with Ultra. The laser system will be installed and commissioned in 2018.

Octopus & Ultra (Research Complex)

The CLF operates two facilities in the Research Complex at Harwell: Ultra, for ultrafast molecular dynamics measurements in chemistry and biology, and Octopus, a cluster of advanced laser microscopes for life science research.

In the dynamics area, Ultra offers a state-of-the-art high power 10 kHz fsec / psec system combined with OPAs to generate pulses for a range of unique pump and probe spectroscopy techniques. It provides spectral coverage from 200-12,000 nm and temporal resolution down to 50 fs. This is used in the investigations of fast photodynamic processes in solids, solutions and gases. Its time resolved resonance Raman (TR^3) capability enables highly fluorescent samples to be studied using a 4 ps optical Kerr shutter. The Time-Resolved Multiple-Probe Spectroscopy (TRMPS) facility links Ultra with a 1 kHz ultrafast laser spectroscopy system, giving a femtosecond to millisecond pump-multiple probe spectrometer. The BBSRC funded Ultra station, LIFEtime, is a high repetition rate system (100 kHz) offering TRMPS capability for the investigation of biological systems. 2DIR spectroscopy capability is also available. An IR pulse shaper on the Ultra B station enables broadband 2DIR experiments on highly scattering samples.

In the imaging area, the Octopus cluster offers a range of microscopy stations linked to a central core of pulsed and CW lasers offering "tailor-made" illumination for imaging. Microscopy techniques offered include total internal reflection (TIRF) and multi-wavelength single-molecule imaging, confocal microscopy (including multiphoton), fluorescence energy transfer (FRET) and fluorescence lifetime imaging (FLIM). Super-resolution techniques available are Stochastic Optical Reconstruction Microscopy (STORM) with adaptive optics, Photoactivated Localization Microscopy (PALM), Structured Illumination Microscopy (SIM), Stimulated Emission Depletion (STED) Microscopy, and Light Sheet Microscopy. Laser tweezers are available for combined manipulation/trapping and imaging with other Octopus stations, and can also be used to study Raman spectra and pico-Newton forces between particles in solution for bioscience and environmental research. A new facility offering super-resolution microscopy at cryogenic temperatures has recently been commissioned and is now available for users.

Chemistry, biology, and spectroscopy laboratories support the laser facilities, and the CLF offers access to a multidisciplinary team providing advice to users on all aspects of imaging and spectroscopy, including specialised biological sample preparation, data acquisition, and advanced data analysis techniques. Access is also available to shared facilities in the Research Complex, including cell culture, scanning and transmission electron microscopy, NMR, and x-ray diffraction.

Engineering Services

Mechanical, electrical and computing support is provided for the operation of the laser facilities at the CLF, for the experimental programmes on these facilities and for the CLF's research and development activities. Mechanical and electrical CAD tools and workshop facilities enable a rapid response.

Theory and Modelling

The Plasma Physics Group supports scheduled experiments throughout the design, analysis and interpretation phases, as well as users who need theoretical support in matters relating to CLF science. We support principal investigators using radiation hydrodynamics, particle-in-cell, hybrid and Vlasov-Fokker-Planck codes, as well as by providing access to large-scale computing. Access to the PRISM suite has been renewed for a further year, as endorsed by the CLF User Forum. Support for student training in plasma physics, computational methods and opportunities for networking with colleagues will continue to be provided. Extended collaborative placements within the group are particularly encouraged.

Target Fabrication

The Target Fabrication Group makes almost all of the solid targets shot on the CLF's high power lasers. A wide variety of microtarget types are produced in collaboration with the user community to enable the exploration of many experimental regimes. The integrated range of fabrication techniques includes thin film coating, precision micro assembly, laser micromachining, and chemistry processes, all verified by sophisticated characterisation. Additionally the advanced capabilities within STFC in both high precision micro machining and MEMS microfabrication are utilised. The Target Fabrication Group is ISO9001 accredited and consequently provides a high level of traceability for all supplied microtargets. The Group is also responsible for the production of targets for academic access shots on the Orion facility at AWE. Commercial access to target fabrication capabilities is available to external laboratories and experimentalists via the spin-out company Scitech Precision Ltd.

In the reporting year the Target Fabrication chemistry laboratory was commissioned and began production of low density foam and aerogel microtarget components. To address the opportunities for high repetition rate solid targets on Gemini, the high accuracy target wheel system was proven to be compatible with MEMS-produced targets under experimental conditions. The design of the CLF cryogenic hydrogen target was refined to enable operation at lower temperatures.

Centre for Advanced Laser Technology and Applications (CALTA)

The CLF's Centre for Advanced Laser Technology and Applications was established in 2012 to develop diode pumped solid state lasers (DPSSLs), capable of delivering high energy pulses at high repetition rate, and to exploit this new technology in applications including advanced imaging, materials processing, non-destructive testing and fundamental science.

CALTA has already won contracts and grants in excess of £26M and is currently constructing its second 1 kW laser based on its proprietary "DiPOLE" laser architecture. The first has been delivered to the HiLASE Centre in the Czech Republic, where it is being used for materials studies and laser peening. The second will be supplied to the European XFEL Facility in Hamburg for integration within the high energy density (HED) end station. It will be used to compress material to high density and the extreme states produced will be diagnosed by the synchronised XFEL x-ray beam.

Delivery of the system to HiLASE was completed in early 2016, followed by installation and commissioning by a joint STFC / HiLASE team. In December 2016 the DiPOLE100 system was demonstrated at full capacity, becoming the first system of its kind in the world to operate at 1 kW. The build of the second DiPOLE100 system for the European XFEL laser is well advanced, with the optical tables and front end system already installed. Final commissioning of the system will take place at RAL, prior to packaging and delivery to Hamburg at the end of 2018.

2017 saw the start of a Horizon 2020 Widespread Teaming Project, a collaboration between STFC and the Czech Institute of Physics to establish a laser applications "Centre of Excellence" at HiLASE. The €50M project is jointly funded by the European Commission and the Czech Ministry of Science. STFC will assist with the establishment of the Centre and play a leading role in the development of advanced DPSSL technology. This includes the design and construction of a 100 Hz version of the DiPOLE 10J laser. This will extend STFC's lead at the forefront of DPSSL laser technology.

Access to Facilities

Calls for access are made twice annually, with applications peer reviewed by external Facility Access Panels.

The CLF operates "free at the point of access", available to any UK academic or industrial group engaged in open scientific research, subject to external peer review. European collaboration is fully open for the high power lasers, whilst European and International collaborations are also encouraged across the CLF suite for significant fractions of the time. Dedicated access to CLF facilities is awarded to European researchers via the LaserLab-Europe initiative (www.laserlab-europe.net) funded by the European Commission.

Hiring of the facilities and access to CLF expertise is also available on a commercial basis for proprietary or urgent industrial research and development.

Please visit www.clf.stfc.ac.uk for more details on all aspects of the CLF.

Economic impact

A major aspect of our Economic Impact work this year was in the establishment of a contract with DSTL for a full and detailed Technical Design Review for the PULSAR project. This involved significant negotiation and planning. The PULSAR TDR was successfully completed and delivered during this reporting year.

Relationships with industry continue to be built, and in total five new commercial contracts were established for access to Ultra, Octopus and Gemini. Importantly we have identified three new areas for engagement with Rolls Royce: laser peening, laser driven sources for Non Destructive Evaluation and fluid inspection within large and complex gear box and engine systems.

An important international highlight was the phase 2 proposal submitted to the European Commission under the H2020 Widespread and Teaming initiative with HiLASE in the Czech Republic. This proposal was successful and will allow CALTA to develop the DiPOLE technology to higher energy and higher repetition rates. The CLF also leads on the Innovation work package and has formed an innovation task force for the project to support the industrial take up and exploitation of high power lasers and their applications. This is a circa €50M programme funded jointly by the European Commission and the Czech Ministry, with 20% of the funds allocated directly to CLF.

Economic Impact

Ric Allott
Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK
Email address: ric.allott@stfc.ac.uk Website: www.clf.stfc.ac.uk

Introduction

This article highlights some of the key economic impact activities of the Central Laser Facility over the year 2016-17.

Enhancing and Demonstrating Capability

A major aspect of our work this year was in the establishment of a contract with DSTL for a full and detailed Technical Design Review for the PULSAR project. This involved significant negotiation and planning. The PULSAR TDR was successfully completed and delivered during this reporting year.

Funding for the construction and commissioning of a new Laser Peening Laboratory based on CALTA's DiPOLE laser technology was secured, and a materials scientist recruited into post for the two years of the project. This enabled the project to proceed at pace and a portfolio of academic and industrial collaborators has been built over the year. Laser peening allows the fatigue strength and lifetime of materials to be significantly increased (>3x) via the inducement of significant sub-surface compressive residual stress. Proving the use of our DiPOLE technology in this critical area for sectors such as high value manufacturing, aerospace and automotive is an important step forward in building the commercial case for DiPOLE.

Work on developing Laser Driven Sources for industrial applications has progressed, and the CLF was awarded a grant through the STFC IPS scheme to work alongside Bristol University and Sellafield in developing laser driven x-rays and neutrons for inspection of nuclear waste containers. Again this is a very exciting step forward in realising some key industrial applications of high power lasers.

Industry Engagement

We continued to build on and strengthen our relationships with Johnson Matthey, Innovate UK and the High Value Manufacturing Catapult Centres. This year saw approximately £350k of income derived through contracts for facility access. In total five different contracts were established for access to Ultra, Octopus and Gemini. Importantly we have identified three new areas for engagement with Rolls Royce; laser peening, laser driven sources for Non Destructive Evaluation and fluid inspection within large and complex gear box and engine systems. These will be investigated and taken forward over the coming year.

A number of new companies from the aerospace and solar energy sectors have been engaged, with the aim of establishing new contracts for facility access in the future.

International Engagement

We submitted a phase 2 proposal to the EC under the H2020 Widespread and Teaming initiative with HiLASE in the Czech Republic. This proposal was successful and allows CALTA to develop DiPOLE technology to higher energy and higher repetition rates. We also lead on the Innovation work package and have formed an innovation task force for the project to support the industrial take up and exploitation of high power lasers and their applications. This is a circa €50M programme funded jointly by the EC and the Czech Ministry with approximately 20% of the funds allocated directly to CLF.

Our projects funded through the Newton programme with India, China and South Africa continue and have started to bear fruit this year with a number of successful collaborations and scientific publications.

Intellectual Property and Technology Transfer

This year two new patents were filed and two patents have now been granted.

Conclusions

Overall this has been a very successful year for the CLF in terms of economic impact, industry engagement and development of CLF's capabilities. We will continue to build on this in the coming years.

Acknowledgements

I would like to thank all the CLF and CALTA staff involved in delivering the industrial access, the laser driven sources and the laser peening work.

Communication and outreach activities within the CLF

Ceri Brenner, Emma Springate

Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK

Email address: ceri.brenner@stfc.ac.uk, emma.springate@stfc.ac.uk Website: www.clf.stfc.ac.uk

Introduction

Public engagement encompasses outreach activities that inspire the next generation and raise the profile of our world-class research, as well as communication activities that offer a platform on which to demonstrate the high-impact and inspiring science that the Central Laser Facility (CLF) delivers. Opportunities for communication and engagement in the reporting period 2016-2017 have been diverse, reaching across the UK and around the world. Here we highlight a selection of those activities.

CLF in government

Part of the *Incredible Power of Light* roadshow (shown in full above at the Big Bang Fair) was installed in the foyer of government offices to engage with staff and policy makers. The objective of the UK government's Business Innovation and Skills (BIS) 'Hands on Science' programme, led by Professor Tim Dafforn, Chief Scientific Adviser, is to demonstrate how BIS science partner organisations spend over £7 billion a year of investment in UK universities and research institutes on beneficial applications. The events tap into a real desire for BIS staff to find out more about new applications for UK science research. Colleagues from BIS, UK Trade and Investment, the Department of Energy and Climate Change (DECC), and the Ministry of Defence (MoD) took part in an interactive exhibition focused on the CLF, which demonstrated how laser technology is applied in day-to-day life. The visitors had the opportunity to hear from CLF staff about the science, technology and engineering of the CLF, as well as the impact and innovation of the work that we do. They saw a demonstration of the technology behind award-winning Cobalt Light Systems, a spinout company of the CLF. Their leading product, the Insight100, was on display; this uses laser spectroscopy to detect hidden liquid explosives and identify the contents within opaque bottles. BIS staff enjoyed testing sample liquids in sealed shampoo bottles, to determine whether the contents were safe or dangerous - the same technology that is currently deployed in eight of the top 10 airport hubs in Europe, and in 65 airports across Europe. The exhibition attracted a real mix of BIS staff from various policy and other teams, plus people from GO Science, UK Trade and Investment, Digital, BIS Local, BIS Sheffield, MoD and DECC, all of whom were very positive about the event. Visitor comments included:

"*Very interesting and informative session. We should bring the Rutherford Appleton Lab to 1VS for a seminar*"

"*Thank you to the team who put the exhibition together, fascinating stuff!*"

"*I was impressed by the Hands on Science event, I've persuaded the Engineering and Innovation team here to do an energy version for DECC staff.*"

Martin Donnelly (Permanent Secretary to BIS) also stopped by en route to an evidence session with the Public Accounts Committee on the National Audit Office's report on BIS's capital investment in science projects. As a result, Martin mentioned what an important contribution lasers are making and that STFC was running a laser demonstration at BIS:

"*It is clear that looking at a lot of these projects just one year after they are in place is far too early. We have to move that back, and we will do that. The other question is how we go on checking years later. In classic areas like lasers - we had some work on that being shown off in the Department today - they are still producing new medical research innovations from research that took place 20-odd years ago and has come through. We need to make sure that we do not stop at an arbitrary point. What we must not do is do it too quickly. We must also make sure we are picking up the full range of social, health and other related benefits - not just narrowly economic, if I can put it that way.*"

Laserlab and ELI Training Weeks held at CLF

The Training Weeks event, jointly organised by the CLF and Laserlab Networking, provided a unique opportunity for the participants to learn the key skills required to run experiments on HPL facilities, such as Vulcan or Gemini.

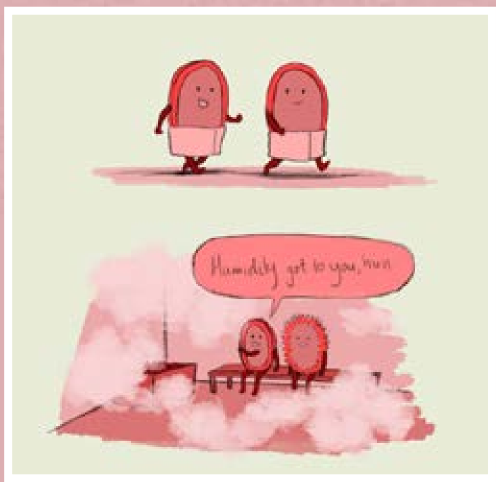
The broad range of topics covered in the course included laser and plasma diagnostics, optics characterisation, laser safety, vacuum and cryogenic systems, targetry, and overall project management of a typical experiment. In addition the participants had the opportunity to put their skills to the test by setting up and performing their own experiment in the Vulcan Petawatt target area. With many new to the field, this was an extremely useful exercise in working collaboratively with experimenters from other laboratories and universities.

12 scientists from eight different European institutions (including ELI-NP) attended the course, which also featured guest talks and tutorials from leading academics in the field of laser-plasma interactions from the UK and Europe. As well as hands-on and classroom learning provided by the CLF, the Training Weeks also provided an excellent opportunity for the participants to network with other members of the EU HPL community.

International collaboration with Newton funding

The first Newton-Bhabha workshop was jointly organised by the CLF and the Tata Institute of Fundamental Research, and was held in India.

The Newton Fund is part of the UK's official development assistance programme. It supports the UK to use its strengths in scientific research to promote economic development and social welfare in emerging science nations, while building long-term collaborations. Teams from UK universities and Indian institutes are exploring laser-based plasma-accelerators for cancer therapies, and training a new generation of Indian researchers, in a joint collaboration supported by the Newton Fund. Professor G. Ravindra Kumar, based at the Tata Institute of Fundamental Research in Mumbai, India, is one of the collaborators in this programme. *"Personally, it has been very fruitful as we can now hope to strengthen existing links, improve research infrastructure in India with the participation of the UK teams, and innovate together with them right here,"* he says.



Illustrator joins as CLF outreach officer

Helen Towrie has taken up a three-month placement as the CLF's Illustration and Outreach Officer. Illustration is a powerful form of visual communication – it is an all-inclusive tool which, by its very design, tells a story for any and all to enjoy. An example of one of her pieces is shown opposite in the doodle created to summarise the main messages of a symposium and workshop on correlative light, electron and x-ray microscopy held in STFC's Pickavance Lecture Theatre. The event aimed to discuss the developments of these complex fields, and how scientists have been using them to get accurate results in their experiments.

The monster under each moat symbolises the hidden, difficult to analyse sample, and the people atop the castles are scientists trying to identify the monster.

The CLF hopes to use images like this, aimed at older children, to strengthen the general awareness of analytical processes such as spectroscopy, and to portray them in a dynamic, exciting and, most importantly, understandable way.

Other examples of Helen's work include her 'engineers are like bees' project, which engages people with the wide-ranging impact of engineers, and her coverage of science highlights, such as the work carried out on Ultra about condensation in asthma inhalers.

Light Microscopy
+ Produces a very clear image
- Only a magnified version of what the eye can see.
All clear!
CLEM:
- Combo of light and electron.
+ Gives a very clear image
- very destructive
- Very slow
Electron:
+ Great detail
- But only on very small target areas.
FIB
+ Can pick up certain substances
- Lots of the same substance can ruin the image.
STEM:
+ Gives very accurate image
- very destructive.
Raman:
+ Can see what things are made of
- only gives 2D image.
Combined, The many different types of spectroscopy can create a clear, reliable image.
We know what it is now!
X-Ray CT:
+ Gives a full, 3D picture.
+ Non destructive
- Low resolution.

High Energy Density & High Intensity Physics

High fidelity parameter scans in a 5 Hz plasma wakefield accelerator

S.J.D. Dann, J.D.E. Scott, M.J.V. Streeter *(The Cockcroft Institute, Keckwick Lane, Daresbury,UK)*
J. Hah, K. Krushelnick, J. Nees, A.G.R. Thomas *(Center for Ultrafast Optical Science, University of Michigan, USA)*
J. Osterhoff, P. Pourmoussavi *(Deutsches Elektronen-Synchrotron DESY, Germany)*
C.D. Baird, C.D. Murphy *(York Plasma Institute, Department of Physics, University of York, UK)*
M. Krishnamurthy, S. Tata *(Tata Institute of Fundamental Research, India)*
N. Bourgeois, O. Chekhlov, C.D. Gregory, S.J. Hawkes, C.J. Hooker, V. Marshall, B. Parry, P.P. Rajeev, E. Springate, D.R. Symes, Y. Tang, C. Thornton *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
S. Eardley, R.A. Smith *(Blackett Laboratory, Imperial College London, UK)*
J.-N. Gruse, S.P.D. Mangles, Z. Najmudin, S. Rozario *(The John Adams Institute for Accelerator Science, Imperial College London, UK)*
S.V. Rahul *(TIFR Centre for Interdisciplinary Sciences, India)*
D. Hazra *(Laser Plasma Section, Raja Ramanna Centre for Advanced Technology, India)*

We present experimental data showing the beneficial effects of performing parameter scans with a high repetition rate laser. The transmitted laser and electron beam generated in a laser-driven plasma wakefield accelerator are clearly observed to depend on the gas jet backing pressure. The spectral properties of these beams are seen to be smooth functions of the input parameters, when averaging over a set 49 shots for each value and employing gradual changes in pressure. This allows for detailed examination of the interaction physics, and can better reveal threshold behaviour and highly localised optima. Extending high-repetition rate operation to higher power laser systems is expected to yield great benefits in performance, and will enable a range of new applications.

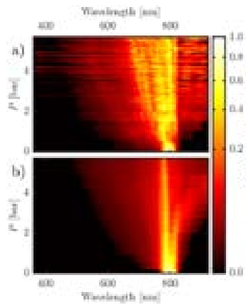


Figure 1

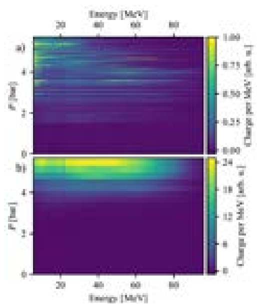


Figure 2

Figure 1: Transmitted laser spectra for a) the fully compressed laser pulse and b) a laser pulse shape which was optimised for electron beam generation, both as functions of backing pressure. For a) each row is a single shot, whereas in b) each row is the average of 49 shots. Note the non-linear colour mapping to make the low intensity regions visible.
Figure 2: Electron spectra for a) the fully compressed laser pulse and b) a laser pulse shape which was optimised for electron beam generation, both as functions of backing pressure. For a) each row is a single shot, whereas in b) each row is the average of 49 shots.

Contact: M.J.V. Streeter (m.streeter@lancaster.ac.uk)

Genetic algorithm optimization of x-ray emission from laser-cluster interactions

S. Eardley, R.A. Smith *(Blackett Laboratory, Imperial College London, UK)*
D.R. Symes, N. Bourgeois, C. Thornton, C.D. Gregory, C.J. Hooker, O. Chekhlov, S.J. Hawkes, B. Parry, V. Marshall, Y. Tang, E. Springate, P.P. Rajeev *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
M.J.V. Streeter, S.J.D. Dann, J.D.E. Scott *(The Cockcroft Institute, Keckwick Lane, Daresbury, UK)*
C.D. Murphy, C.D. Baird *(York Plasma Institute, Department of Physics, University of York, UK)*
S. Rozario, J.-N. Gruse, S.P.D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Imperial College London, UK)*
S. Tata, M. Krishnamurthy *(Tata Institute of Fundamental Research, India)*
S.V. Rahul *(TIFR Center for Interdisciplinary Sciences, India)*
D. Hazra *(Laser Plasma Section, Raja Ramanna Centre for Advanced Technology)*
P. Pourmoussavi, J. Osterhoff *(Deutsches Elektronen-Synchrotron DESY, Germany)*
J. Hah, A.G.R. Thomas *(Center for Ultrafast Optical Science, University of Michigan, USA)*

Using the front end of the Gemini laser with a repetition-rate of 5 Hz, a genetic algorithm was used to optimise x-ray emission from a clustered gas target driven by a 150 mJ pulse. This was achieved by allowing the algorithm to manipulate the temporal shape of the laser pulse using an acousto-optic dispersion filter (*Dazzler*) to modify the spectral phase of the pulse. The optimum pulse shape was found to have a slow rising edge followed by a sharp drop off. The shape of this optimum pulse provides insight into the physical processes involved in the laser-cluster interaction.

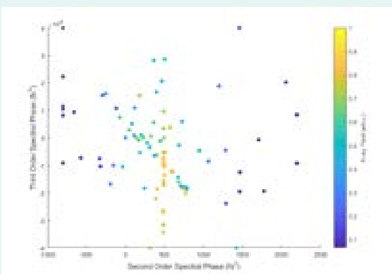


Figure 1: Every trial solution attempted by the genetic algorithm across all generations, with the colour representing the x-ray yield of each trial solution

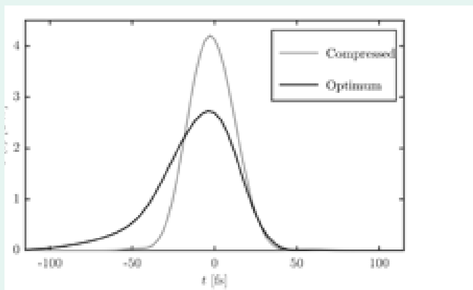


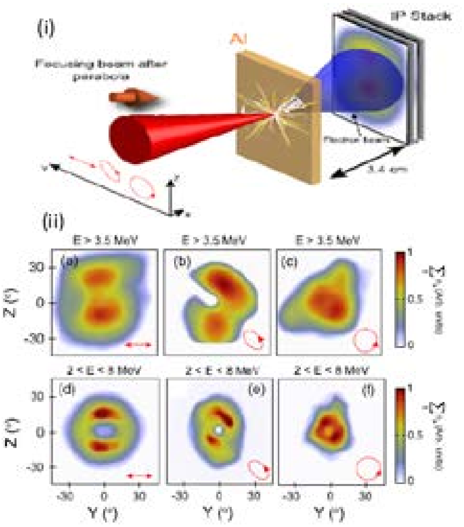
Figure 2: Temporal shape of the laser pulse that produced the highest x-ray yield

Contact: S. Eardley (sje15@ic.ac.uk)

Influence of laser polarization on collective electron dynamics in ultraintense laser-foil interactions

B. Gonzalez-Izquierdo, R.J. Gray, M. King, R. Wilson, R.J. Dance, H. Powell, D.A. Maclellan, J. McCreadie, N.M.H. Butler, P. McKenna *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*
S.J. Hawkes, J.S. Green, D.C. Carroll, N. Booth, G.G. Scott, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
C.D. Murphy *(Department of Physics, University of York, Heslington, York, UK)*
L.C. Stockhausen *(Centro de Láseres Pulsados (CLPU), M5 Parque Científico, Spain)*
M. Borghesi *(Centre for Plasma Physics, Queens University Belfast, UK)*

The collective response of electrons in an ultrathin foil target irradiated by an ultra-intense (~6 × 10^{20} W/cm^2) laser pulse is investigated experimentally and via 3D particle-in-cell simulations. It is shown that if the target is sufficiently thin that the laser induces significant radiation pressure, but not thin enough to become relativistically transparent to the laser light, the resulting relativistic electron beam is elliptical, with the major axis of the ellipse directed along the laser polarization axis. When the target thickness is decreased such that it becomes relativistically transparent early in the interaction with the laser pulse, diffraction of the transmitted laser light occurs through a so called 'relativistic plasma aperture', inducing structure in the spatial-intensity profile of the beam of energetic electrons. It is shown that the electron beam profile can be modified by variation of the target thickness and degree of ellipticity in the laser polarization.



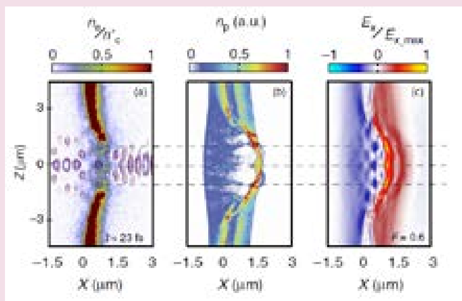
(i) Schematic illustrating the experimental setup, showing the position of the IP stack detector used to measure the electron spatial-intensity distribution; (ii) (a) Electron density for a l = 10 nm target as measured using IP for electrons with energy greater than 3.5 MeV for linear polarization. (b) Same for elliptical polarization. (c) Same for circular polarization; (d)–(f) 3D PIC simulation results for the electron density distribution from l = 10 nm and energies 2 < E < 8 MeV for linear, elliptical and circular polarization, respectively.

Contact: P. McKenna (paul.mckenna@strath.ac.uk)

Towards optical polarization control of laser-driven proton acceleration in foils undergoing relativistic transparency

B. Gonzalez-Izquierdo, M. King, R.J. Gray, R. Wilson, R.J. Dance, H. Powell, D.A. Maclellan, J. McCreadie, N.M.H. Butler, P. McKenna *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*
S.J. Hawkes, J.S. Green, D.C. Carroll, N. Booth, G.G. Scott, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
C.D. Murphy *(Department of Physics, University of York, Heslington, York, UK)*
L.C. Stockhausen *(Centro de Láseres Pulsados (CLPU), M5 Parque Científico, Spain)*
M. Borghesi *(Centre for Plasma Physics, Queens University Belfast, UK)*

Control of the collective response of plasma particles to intense laser light is intrinsic to relativistic optics, the development of compact laser-driven particle and radiation sources, as well as investigations of some laboratory astrophysics phenomena. We recently demonstrated that a relativistic plasma aperture produced in an ultra-thin foil at the focus of intense laser radiation can induce diffraction, enabling polarization-based control of the collective motion of plasma electrons. Here we show that under these conditions the electron dynamics are mapped into the beam of protons accelerated via strong charge-separation-induced electrostatic fields. It is demonstrated experimentally and numerically via 3D particle-in-cell simulations that the degree of ellipticity of the laser polarization strongly influences the spatial-intensity distribution of the beam of multi-MeV protons. The influence on both sheath-accelerated and radiationpressure-accelerated protons is investigated. This approach opens up a potential new route to control laser-driven ion sources.



Electrostatic field and particle density evolution for a 10 nm-thick Al foil target with a 6 nm-thick C^{6+} and H^{+} hydrocarbon contaminant layer defined on both the front and rear surfaces, at a time of 23 fs after the peak of the pulse. (a) Laser field contours and electron density in the X-Z plane at Y = 0; the onset of transparency and laser diffraction is observed. (b) Same for proton density, showing the front-surface protons being accelerated into the rear-surface population. (c) Same for the longitudinal electrostatic field component, demonstrating the onset of transverse modulations.

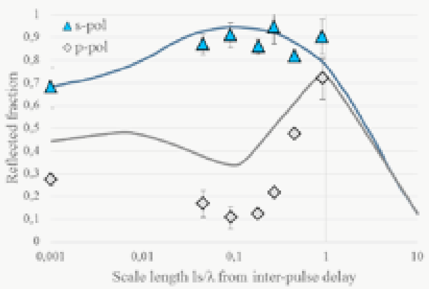
Contact: P. McKenna (paul.mckenna@strath.ac.uk)

Investigation on material and timing influences on high-reflective double-pulsed plasma mirrors with emphasis on scale length and absorption control

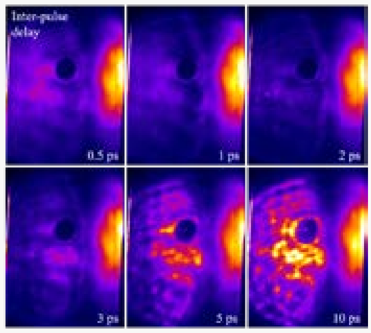
G.F.H. Indorf *(Carl von Ossietzky University of Oldenburg, Germany)*
M.A. Ennen, A. Andreev, U. Teubner *(Carl von Ossietzky University of Oldenburg, Germany; University of Applied Sciences Emden/Leer, Germany)*
G.G. Scott, L. Scaife, D. Haddock, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
P. Forestier-Colleoni *(University of California San Diego, USA)*

The characteristic absorption behaviour for radiation in laser-induced plasmas in the working intensity regime of plasma mirrors ($10^{14} – 10^{16}$ Wcm^{-2}) has been investigated as a function of polarisation, inter-pulse delay and angle of incidence. Resulting from the temperature of the plasma and the inter-pulse delay, the plasma scale length can be determined by applying a model from *Kieffer et al* [1] to the data, showing a distinct absorption minimum for a normalised plasma scale length of $l_s / \lambda = 0.1$ for p-polarisation at an angle of ~45 degree which appears to be material independent. This model can be utilised to infer to the prominent plasma parameters such as expansion velocity and electron temperature for scale lengths < 1.

[1] Kieffer et al, "Absorption of an ultrashort laser pulse in very steep plasma density gradients" IEEE Journal of Quantum Electronics, Vol 25, No 12, 1989



Double-pulse plasma mirror reflectivity as a function of inter-pulse delay/plasma scale length for s- & p-polarisation at 45 degree on glass showing a dominant absorption maximum for p-polarisation at $l_s / \lambda = 0.1$. The continuous curves correspond to the simulations of Kieffer et al with higher electron temperatures (in the collisional absorption regime), therefore lower absorption and a higher reflected signal.



Captured beam profiles, displaying the initial reduced and increasing reflected signal for higher inter-pulse delays/scale lengths at 45 degree (centre of the beam) for p-polarisation.

Contact: G.F.H. Indorf (g.indorf@gmx.de)

2D hydrodynamic simulations of a variable length gas target for density down-ramp injection of electrons into a laser wakefield accelerator

O. Kononenko, J. Osterhoff, C.A.J. Palmer *(Deutsches Elektronen-Synchrotron DESY, Germany)*
N.C. Lopes, J.M. Cole, C. Kamperidis, S.P.D. Mangles, Z. Najmudin, K. Poder, J.C. Wood *(The John Adams Institute for Accelerator Science, Imperial College London, UK)*
D. Rusby, D.R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
J. Warwick *(School of Mathematics and Physics, Queen's University Belfast, UK)*

In this work, two-dimensional (2D) hydrodynamic simulations of a variable length gas cell were performed using the open source fluid code OpenFOAM. The gas cell was designed to study controlled injection of electrons into a laser-driven wakefield at the Gemini laser facility. The target consists of two compartments: an accelerator and an injector section connected via an aperture. A sharp transition between the peak and plateau density regions in the injector and accelerator compartments, respectively, was observed in simulations with various inlet pressures. The fluid simulations indicate that the length of the down-ramp connecting the sections depends on the aperture diameter, as does the density drop outside the entrance and the exit cones. Further studies showed that increasing the inlet pressure leads to turbulence and strong fluctuations in density along the axial profile during target filling, and consequently, is expected to negatively impact the accelerator stability.

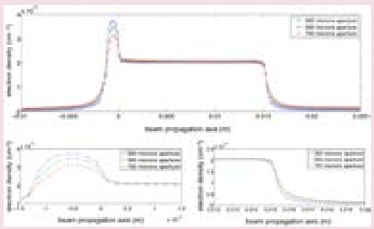


Figure 1: (a) Electron density distribution along the full gas cell, zero is the middle of the separation wall, depending on the aperture diameter; (b) density down-ramp between acceleration and injection stages; (c) density tail at the exit.

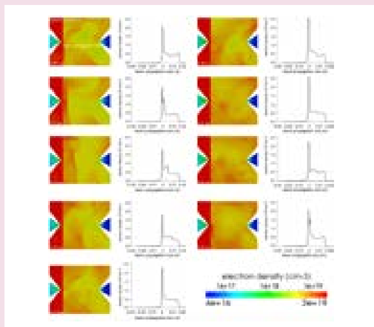


Figure 2: Density map and density plot at different time steps, which demonstrates the oscillations. The amplitude of the oscillation spike along the density profile reaches 35% of the plateau electron density for the high pressure and 20% for the medium pressure.

Contact: O. Kononenko (olena.kononenko@polytechnique.edu)

Absolute Calibration of Thomson Parabola Micro Channel Plate for multi-MeV carbon ions

A. McIlvenny, D. Doria, H. Ahmed, P. Martin, S. Kar, M. Borghesi *(Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, UK)*
L. Romagnani *(LULI, École Polytechnique, CNRS, Route de Saclay, 91128 Palaiseau Cedex, France)*
S. Williamson, P. McKenna
(SUPA, Department of Physics, University of Strathclyde Glasgow, UK)
E.J. Ditter, O. Ettlinger, G. Hicks, Z. Najmudin *(The John Adams Institute for Accelerator Science, Imperial College London, UK)*
D. Neely, N. Booth *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The Gemini North beam was used to explore ion acceleration from ultra-thin foils in an effort to produce high energy ion beams of potential medical interest. To make full use of the high repetition rate of Gemini, a Thomson Parabola Spectrometer –Micro Channel Plate (MCP) system was used to determine maximum energies and spectra per species. This was calibrated for absolute particle (carbon) number per steradian using CR-39 up to 21 MeV/nucleon and can be extended to higher energies using the same power law. The spectra show similar particle numbers to the well calibrated BAS-TR image plates for similar targets on Gemini showing the correctness of this technique. This is an important measurement when using these beams for radiobiological purposes but can also help improve our understanding of the underpinning physics of the interaction.

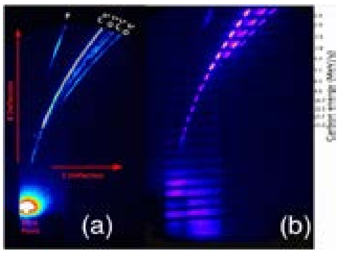


Figure 1 (a) MCP imaged on shot with Andor Neo CCD (false colour) (b) calibration shot using slotted CR-39 through which the carbon passes.

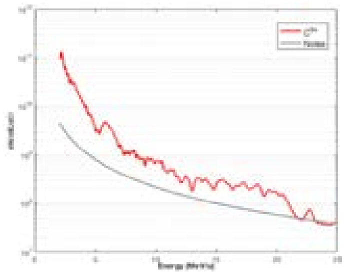


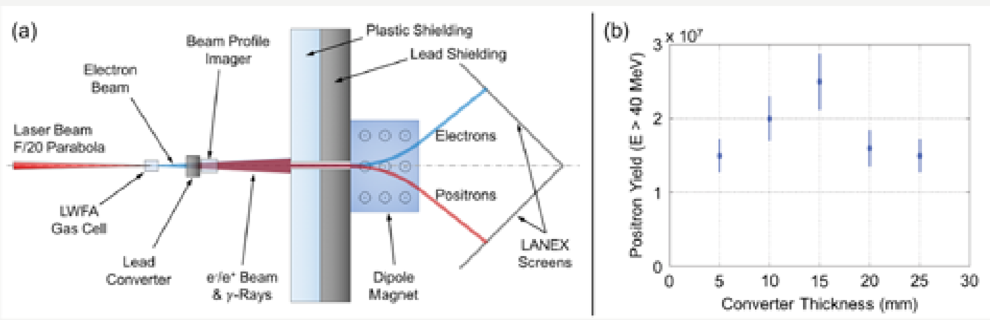
Figure 2: Spectra for a 15 nm foil with particle number/MeV/steradian plotted with the noise. Maximum energy is ~22 MeV/u.

Contact: A. McIlvenny (amcilvenny01@qub.ac.uk)

Spectral and spatial characterisation of laser-driven positron beams

G. Sarri, J. Warwick, D. Doria, T. Dzelzainis, G.M. Samarin, M. Yeung *(School of Mathematics and Physics, Queen's University Belfast, UK)*
W. Schumaker *(SLAC National Accelerator Laboratory, Menlo Park, CA, USA)*
K. Poder, J. Cole, S.P.D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
K. Krushelnick *(Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI, USA)*
S. Kuschel (Helmholtz Institute Jena, Germany)
L. Romagnani *(LULI, Ecole Polytechnique, CNRS, CEA, UPMC, France)*
D.R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
A.G.R. Thomas *(Lancaster University, Lancaster, UK)*
M. Zepf *(School of Mathematics and Physics, Queen's University Belfast, University Road, Belfast BT7 1NN, UK & Helmholtz Institute Jena, Germany)*

The generation of high-quality relativistic positron beams is a central area of research in experimental physics, due to their potential relevance in a wide range of scientific and engineering areas. There is now growing interest in developing hybrid accelerators, combining plasma-based and conventional radio-frequency technology, in order to minimise the size and cost of such machines. We report on recent experiments on laser-driven generation of high-quality positron beams using a relatively low energy and potentially table-top laser system. The results obtained indicate that current technology allows to create, in a compact setup, positron beams suitable for injection in radio-frequency accelerators.

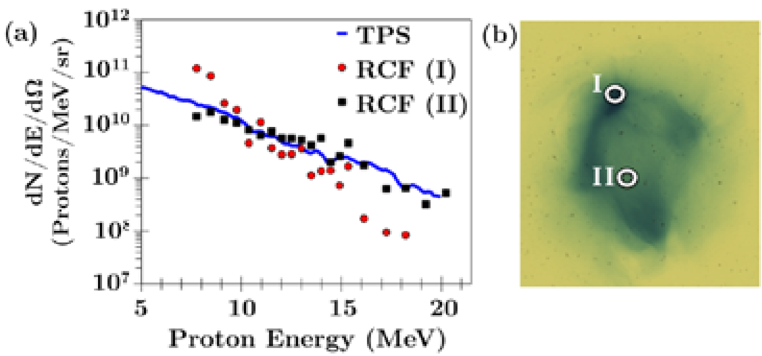


A diagram of the experimental setup is shown in (a). The measured number of positrons with energy > 40 MeV escaping the converter target is plotted in (b), with error bars representing shot-to-shot fluctuations.

Contact: G. Sarri (g.sarri@qub.ac.uk)

Angularly resolved characterization of ion beams from laser-ultrathin foil interactions

C. Scullion, D. Doria, H. Ahmed, A. Alejo, D. Jung, K. Naughton, S. Kar, M. Zepf, M. Borghesi *(Centre for Plasma Physics, Queen's University of Belfast, UK)*
L. Romagnani *(LULI, Ecole Polytechnique, CNRS, Route de Saclay, Palaiseau Cedex, France)*
O.C. Ettlinger, G.S. Hicks, K. Poder, Z. Najmudin *(The John Adams Institute for Accelerator Science, The Blackett Laboratory, Imperial College, London, UK)*
R.J.Gray, H. Padda, P. McKenna *(SUPA, Department of Physics, University of Strathclyde, Glasgow, UK)*
J. Green, G.G. Scott, D.R. Symes, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*



Methods and techniques used to capture and analyse beam profiles produced from the interaction of intense, ultrashort laser pulses and ultrathin foil targets using stacks of Radiochromic Film (RCF) and Columbia Resin #39 (CR-39) are presented. The identification of structure in the beam is particularly important in this regime, as it may be indicative of the dominance of specific acceleration mechanisms. Additionally, RCF can be used to deconvolve proton spectra with coarse energy resolution while maintaining angular information across the whole beam.

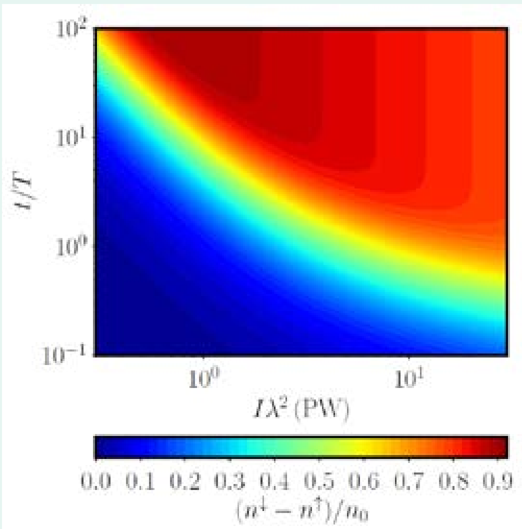
(a) Proton spectra from a RadioChromic Film stack and a Thomson Parabola Spectrometer (solid line) for 10 nm-thick carbon targets irradiated under similar conditions on the Gemini laser.

(b) The areas I and II marked on the RCF (HD-V2 layer 3) in (b) show where the spectra were taken from through the stack. Region I is aligned with the highest dose on layer 3. Region II is aligned with the axis of the high energy component of the proton beam.

Contact: Marco Borghesi (M.Borghesi@qub.ac.uk)

Spin polarization of electrons interacting with ultra-intense laser pulses

D. Seipt *(Department of Physics, Lancaster University, Lancaster, UK; The Cockcroft Institute, Daresbury Laboratory, Warrington, UK)*
D. Del Sorbo, C.P. Ridgers *(York Plasma Institute, University of York, UK)*
A.G.R. Thomas *(Center for Ultrafast Optical Science, University of Michigan, USA)*



Degree of electron spin polarization, as a function of laser intensity and time normalized to the laser period.

We have investigated the spin polarization of electrons interacting with ultra-intense laser pulses. It has been long known that electrons in a storage ring slowly self-polarize via the Sokolov-Ternov effect due to an asymmetry in the rate of spin flip transitions. We show that the self-polarization time is on the order of a few femtoseconds for electrons orbiting at the magnetic nodes of two counter propagating circularly polarized intense laser pulses with intensity 10^{23} W cm^{-2}. We discuss some immediate consequences of the spin polarization on QED plasma dynamics.

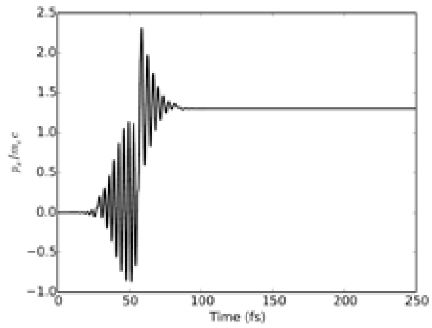
Contact: D. Seipt (d.seipt@lancaster.ac.uk)

Breaking of Dynamical Adiabaticity in Direct Laser Acceleration of Electrons

A.P.L. Robinson *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
A.V. Arefiev *(Center for High Energy Density Science, The University of Texas, Austin, Texas, USA)*

A key issue in fast electron generation in almost any aspect of ultra-intense laser-plasma interactions is what might be termed 'adiabaticity breaking', i.e. the irreversible transfer of energy from the electromagnetic (EM) field to the electrons. This is by no means a trivial matter: for example, a single electron oscillating in a plane EM wave with no other fields present cannot experience a net gain of energy once the interaction is complete (Lawson-Woodward Theorem). It is therefore vital that this problem is addressed, as without adiabaticity breaking there can be no absorption of the EM wave by the plasma electrons at all.

In this paper we address the question of adiabaticity breaking in the case of an electron undergoing motion in a plane wave and an ion channel, i.e. 'Direct Laser Acceleration' (DLA). The purpose of this paper is to point out that net energy transfer from a plane wave to an electron can occur due to a process that does not involve either betatron resonance or the parametric excitation of electron oscillations - these being the two main concepts that have previously been put forward to explain absorption in DLA. We show that if an electron is already undergoing strong relativistic oscillations then it can gain energy from a short, high frequency laser pulse due to the non-harmonic nature of the relativistic oscillations.



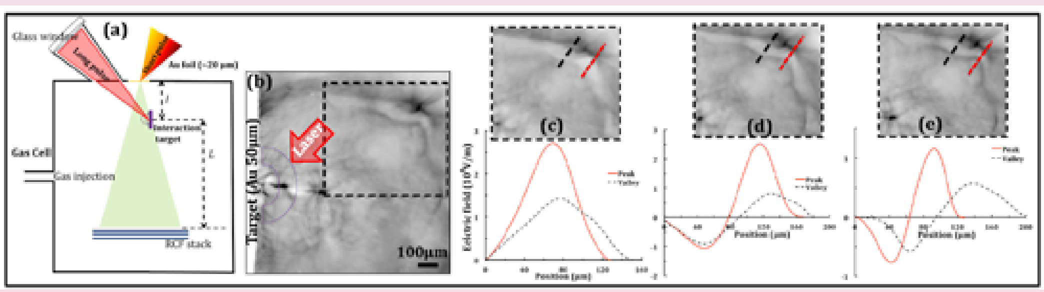
Plot of $p_x(t)$ from the baseline numerical calculation

Contact: A.P.L. Robinson (alex.robinson@stfc.ac.uk)

Experimental observation of thin-shell instability in a collisionless plasma

H. Ahmed, D. Doria, G. Sarri, E. Ianni, S. Kar, K. Quinn, M. Borghesi *(Centre for Plasma Physics, Queen's University of Belfast, UK)*
M. E. Dieckmann *(Department of Science and Technology, Linkoping University, Sweden)*
L. Romagnani *(LULI, École Polytechnique, CNRS, CEA, UPMC, Palaiseau, France)*
A. Bret *(ETSI Industriales, Universidad Castilla La Mancha, Spain)*
M. Cerchez, A.L. Giesecke, R. Prasad, O.Willi *(Institute for Laser and Plasma Physics, University of Düsseldorf, Germany)*
M. Notley *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

We report on the first experimental observation of a thin-shell instability in a collision-less plasma shell formed during the expansion of a laser ablated plasma into a rarefied ambient medium. By means of a proton radiography technique, the early stage evolution of the instability is temporally and spatially resolved on a time-scale much shorter than the typical hydrodynamic time-scales of the system. This is an effective indication of the collision-less nature of an instability previously considered to occur only in a hydrodynamic regime. Matching PIC simulations and simple analytical estimates support the experimental findings and it is envisaged that this kinetic stage of the instability might provide a seed for the hydrodynamic instability observed in astrophysical plasmas.



(a) Schematic of the experimental setup (top view). The experimental set up was enclosed in a gas cell, which was placed inside the vacuum chamber. (b) proton radiographs of the interaction of a nanosecond laser pulse (red arrow) with a 50 µm thick gold foil, correspond to time (t_0 + 6)ps from the start of interaction. The spatial scale shown in the image (b) corresponds to the object plane. (c-e) show the radiographs of the interested region (marked in the image (b)) and reconstructed electric field profiles at different positions across the plasma shell, corresponds to different probing times t_0, (t_0+2)ps, (t_0+6)ps.

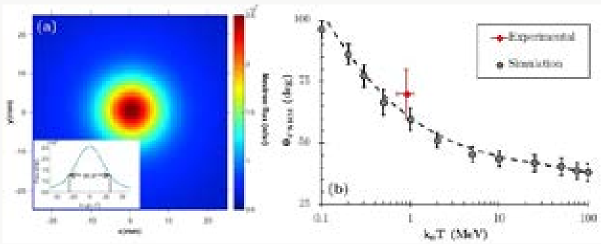
Contact: H. Ahmed (h.ahmed@qub.ac.uk)

Numerical study of neutron beam divergence in a beam-fusion scenario employing laser driven ions

A. Alejo, A. Green, H. Ahmed, D. Doria, S.R. Mirfayzi, M. Borghesi, S. Kar, K. Naughton *(Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, UK)*
A.P.L. Robinson, R. Clarke, S. Dorkings, J. Fernandez, D. Neely, P. Norreys *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
P. McKenna, H. Powell *(Department of Physics, SUPA, University of Strathclyde, Glasgow, UK)*
M. Cerchez, C. Peth, O. Willi *(Institut für Laser-und Plasmaphysik, Heinrich-Heine-Universität, Düsseldorf, Germany)*
J.A. Ruiz *(Colegio Los Naranjos, Fuenlabrada, Madrid, Spain)*
J. Swain *(Rudolf Peierls Centre for Theoretical Physics, University of Oxford, UK)*

The most established route to create a laser-based neutron source is by employing laser accelerated, low atomic-number ions in fusion reactions. In addition to the high reaction cross-sections at moderate energies of the projectile ions, the anisotropy in neutron emission is another important feature of beam-fusion reactions. Using a simple numerical model based on neutron generation in a pitcher–catcher scenario, anisotropy in neutron emission was studied for the deuterium–deuterium fusion reaction. Simulation results are consistent with the narrow-divergence (~70° full width at half maximum) neutron beam recently served in an experiment employing multi-MeV deuteron beams of narrow divergence (up to 30° FWHM, depending on the ion energy) accelerated by a sub-petawatt laser pulse from thin deuterated plastic foils via the Target Normal Sheath Acceleration mechanism. By varying the input ion beam parameters, simulations show that a further improvement in the neutron beam directionality (i.e. reduction in the beam divergence) can be obtained by increasing the projectile ion beam temperature and cut-off energy, as expected from interactions employing higher power lasers at upcoming facilities.

Contact: S. Kar (s.kar@qub.ac.uk)



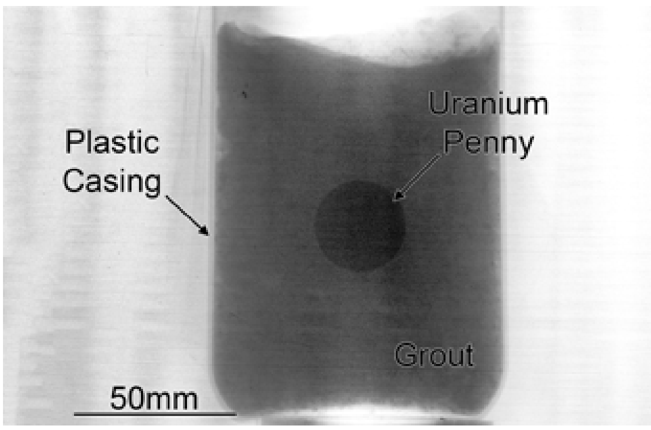
Simulated neutron beam. (a) Simulated profile of the neutron beam on a detector placed behind the catcher, as calculated considering the interaction of a deuteron beam with a deuterised plastic converter. Inset shows the lineout across the detector, indicating a neutron beam divergence of ~62 degree. (b) Neutron beam divergence as a function of the ion beam temperature [see A. Alejo et al. (NIM-A, 2016) for full details of the simulation]. The red point shows the experimentally experimental divergence of the neutron beam observed by Kar et al (NJP, 2016).

Evaluating laser-driven bremsstrahlung radiation sources for imaging and analysis of nuclear waste packages

C.P. Jones, C.A. Stitt, C. Paraskevoulakos, T.B. Scott *(Interface Analysis Centre, HH Wills Physics Laboratory, Tyndall Avenue, Bristol, UK)*
C.M. Brenner, L.A. Wilson, R. Allott, R.J. Clarke, D. Haddock, C. Hernandez-Gomez, M. Notley, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
C. Armstrong, D.R. Rusby *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Department of Physics, SUPA, University of Strathclyde, UK)*
S.R. Mirfayzi, H. Ahmed, A. Alejo, S. Kar *(Centre for Plasma Physics, Queen's University Belfast, UK)*
N.M.H. Butler, A. Higginson, P. McKenna *(Department of Physics, SUPA, University of Strathclyde, Glasgow, UK)*
C. Murphy *(Department of Physics, University of York, UK)*
J. Jowsey *(Ground Floor North B582, Sellafield Ltd, Seascale, Cumbria, UK)*

A small scale sample nuclear waste package consisting of a 28 mm diameter uranium penny encased in grout was imaged by absorption contrast radiography using a single pulse exposure from an x-ray source driven by a high-power laser. The Vulcan laser was used to deliver a focused pulse of photons to a tantalum foil, in order to generate a bright burst of highly penetrating x-rays (with energy > 500 keV) with a source size of < 0.5 mm. BAS-TR and BAS-SR image plates were used for image capture alongside a newly developed Thalium doped Caesium Iodide scintillator-based detector coupled to CCD chips. The uranium penny was clearly resolved to sub-mm accuracy over a 30 cm^2 scan area from a single pulse acquisition. In addition, neutron generation was demonstrated in situ with the x-ray beam, with a single shot, thus demonstrating the potential for multi-modal criticality testing of waste materials. This feasibility study successfully demonstrated non-destructive radiography of encapsulated, high density, nuclear material. With recent developments of high-power laser systems, to 10 Hz operation, a laser-driven multi-modal beamline for waste monitoring applications is envisioned.

Contact: C. M. Brenner (ceri.brenner@stfc.ac.uk)



Radiograph of uranium penny encased in grout obtained using single pulse of a laser-driven x-ray beam.

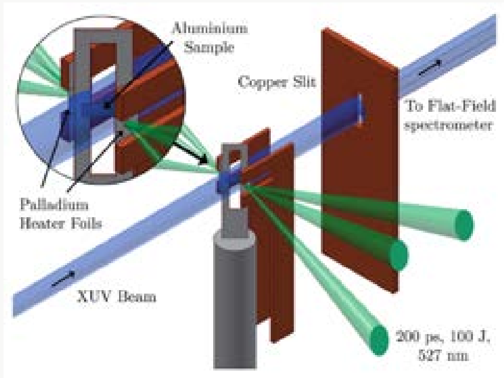
Credit: C.P. Jones et al, Journal of Hazardous Materials, 318, 694-701 (2016)

Experimental measurements of the collisional absorption of XUV radiation in warm dense aluminium

B. Kettle, T. Dzelzainis, S. White, L. Li, B. Dromey, M. Zepf, C.L.S. Lewis, D. Riley *(Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, UK)*
G. Williams, S. Kunzel, M. Fajardo, H. Dacasa *(Group of Lasers and Plasmas, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal)*
Ph. Zeitoun *(LOA, ENSTA ParisTech, CNRS, Ecole Polytechnique, Université Paris–Saclay, Palaiseau, France)*
A. Rigby, G. Gregori *(The University of Oxford, Clarendon Laboratory, Oxford, UK)*
C. Spindloe, R. Heathcote *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The collisional (or free-free) absorption of soft x-rays in warm dense aluminium remains an unsolved problem. Competing descriptions of the process exist, two of which we compare to our experimental data here. One of these is based on a weak scattering model, another uses a corrected classical approach. These two models show distinctly different behaviours with temperature. Here we describe experimental evidence for the absorption of 26-eV photons in solid density warm aluminium (Te ≈ 1 eV). Radiative x-ray heating from palladium-coated CH foils was used to create the warm dense aluminium samples and a laser-driven high-harmonic beam from an argon gas jet provided the probe. The results indicate little or no change in absorption upon heating. This behaviour is in agreement with the prediction of the corrected classical approach, although there is not agreement in absolute absorption value. Verifying the correct absorption mechanism is decisive in providing a better understanding of the complex behaviour of the warm dense state.

Contact: B. Kettle (b.kettle@imperial.ac.uk)

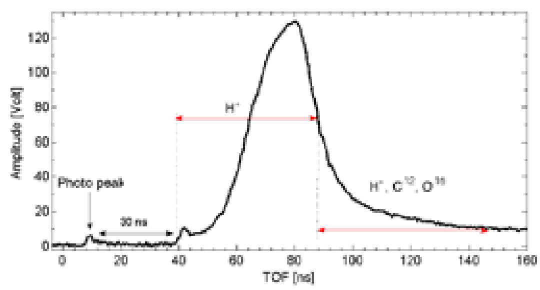


Experiment setup. Two palladium-coated CH foils surround a thin submicron aluminium sample (1 mm away). Three 527 nm laser pulses provide a total of ≈2 × 10^{15} W/cm^2 laser intensity onto each palladium foil (100 J in 200 ps full width at half maximum), which is converted into hard x-rays that bathe the sample, raising its temperature. An XUV probe propagates through the heated sample and onward to a spectrometer for analysis.

TOF-based diagnosis of high-energy laser-accelerated protons using diamond detectors

G. Milluzzo *(School of Mathematics and Physics, Queen's University Belfast, UK; INFN-LNS, Via Santa Sofia 62, Catania, Italy)*
V. Scuderi *(Institute of Physics ASCR, v.v.i (FZU), ELI-Beamlines project, Prague, Czech Republic; INFN-LNS, Via Santa Sofia 62, Catania, Italy)*
A. Alejo, M. Borghesi *(School of Mathematics and Physics, Queen's University Belfast, UK)*
N. Booth, J. Green *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
G.A.P. Cirrone, G. Cuttone *(INFN-LNS, Via Santa Sofia 62, Catania, Italy)*
D. Doria *(School of Mathematics and Physics, Queen's University Belfast, UK; National Institute for Physics and Nuclear Engineering, ELINP, Bucharest-Magurele, Romania)*
D. Margarone *(Institute of Physics ASCR, v.v.i (FZU), ELI-Beamlines project, Prague, Czech Republic)*
L. Romagnani *(LULI - CNRS, Ecole Polytechnique, CEA, Université Paris -Saclay, Palaiseau, France; School of Mathematics and Physics, Queen's University Belfast, UK)*

Time of Flight (TOF) measurements up to a proton energy cut-off around 30 MeV were performed for the first time, with a limited flight path, in the VULCAN Target Area Petawatt. Such results, together with the possibility of measuring the beam characteristics in real time, demonstrate how such a technique, coupled with the use of diamond as well as SiC detectors, represents a promising instrumentation for on-line measurement of higher (100 MeV) energy protons accelerated from high-repetition rate laser systems. This diagnostic approach is particularly attractive for the characterization of single species ion beams, e.g. as emerging from cryogenic hydrogen targets.



TOF signal acquired with a 100 μm thick diamond detector placed @ 2.35 m downstream from the target.

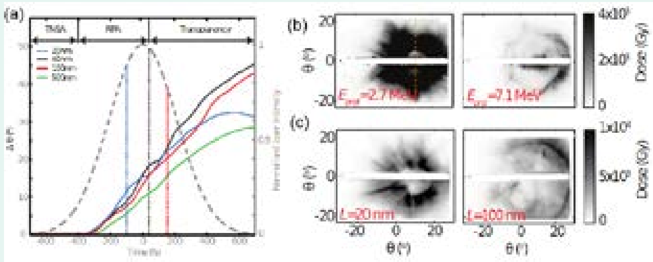
Contact: G. Milluzzo (g.milluzzo@qub.ac.uk)

Intra-pulse transition between ion acceleration mechanisms in intense laser-foil interactions

H. Padda, M. King, R.J. Gray, H.W. Powell, B. Gonzalez-Izquierdo, R. Wilson, R.J. Dance, D.A. Maclellan, N.M.H. Butler, R. Capdessus, P. McKenna *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*
L. C. Stockhausen (Centro de Laseres Pulsados *(CLPU), Parque Cientifico, Calle del Adaja s/n. 37185 Villamayor, Salamanca, Spain)*
D.C. Carroll *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
D. Neely *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK; Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
X. H. Yuan *(Key Laboratory for Laser Plasmas (Ministry of Education) and Department of Physics and Astronomy, Shanghai Jiao Tong University, China)*
M. Borghesi *(Centre for Plasma Physics, Queen's University Belfast, Belfast, UK)*

The Vulcan Petawatt laser was used to experimentally investigate ion acceleration from thin foils. A transition between ion acceleration mechanisms was observed over the duration of the pulse and characterised via measurements of the proton spatial-intensity distribution.

A low-energy, annular component of the proton beam is detected, indicating a transition from radiation-pressure acceleration to transparency-driven processes. Through variation of the target foil thickness, the opening angle of the ring is shown to be correlated to the point in time that transparency occurs during the interaction. It is shown that the divergence of the annular profile is maximised when transparency occurs at the peak of the laser intensity profile.



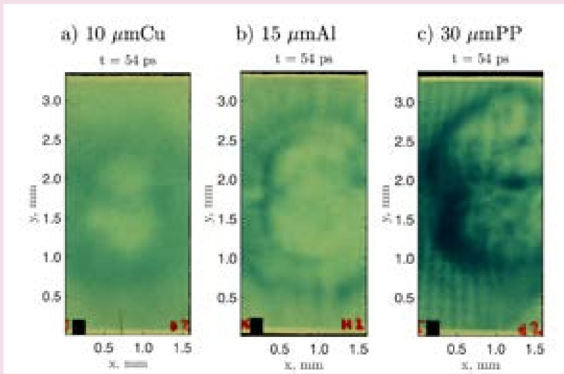
(a) Simulation results showing the temporal behaviour of the average ring divergence for given target thicknesses. The temporal profile of laser intensity is also shown, with dashed vertical lines indicating the onset of transparency for corresponding target thicknesses. (b)-(c) Measured proton spatial-intensity dose profiles for (b) given proton energies and (c) given target thickness.

Contact: P. McKenna (paul.mckenna@strath.ac.uk)

Proton probing of the reconnecting magnetic fields surrounding two adjacent, high-intensity laser interactions

C.A.J. Palmer, Y. Ma, M.J.V. Streeter *(The Cockcroft Institute, Keckwick Lane, Daresbury, UK/ Physics Department, Lancaster University, UK)*
P.T. Campbell, P. Kordell, K. Krushelnick, A.G.R. Thomas, L. Willingale *(Center for Ultrafast Optical Science, University of Michigan, USA)*
L. Antonelli, C.R. Ridgers, N. Woolsey *(Department of Physics, University of York, UK)*
J. Halliday, E. R. Tubman, S. Lebedev *(Department of Physics, The Blackett Laboratory, Imperial College London, UK)*
Y. Katzir, E. Montgomery, M. Notley
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)

Magnetic reconnection is a process that contributes significantly to plasma dynamics and energy transfer in a wide range of situations, including inertial confinement fusion experiments, stellar coronae and compact, highly magnetised objects like neutron stars. There are many different models to describe this phenomena and laboratory experiments are used to refine these models and assess their applicability. Magnetic fields can be generated using high power lasers through several mechanisms, most famously the Biermann battery associated with the formation of azimuthal magnetic fields around a laser focus due to non-parallel gradients in electron temperature and density. At high laser intensities ($I_L\lambda^2 > 10^{18}$ Wcm^{-2}μm^2), relativistic surface currents play a significant role in the generation of the azimuthal magnetic fields. Experiments exploring magnetic reconnection at moderate intensities ($I_L \sim 10^{14}$ Wcm^{-2}) have been performed at numerous international facilities. Here, we present on-going analysis of reconnection fields measured using proton probing during a recent experiment in Vulcan TAW that utilise laser intensities close to 10^{18} Wcm^{-2} to approach the relativistic regime.



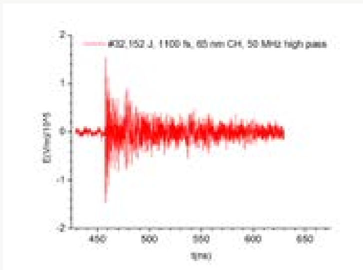
3.5 MeV proton flux distributions in the form of scanned radiochromic film for different target materials a) 10 μm Cu b) 15 μm Al c) 30 μm PP (Plastic). The point in time at which the proton probe crosses the main interaction is given above the images. In all cases the focal spot separation was set to 435 μm and a Cu mesh was included in the proton probing beam before the interaction. This is only visible in c) due to increased scattering in the metal targets.

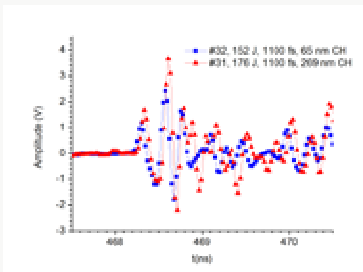
Contact: C. Palmer (charlotte.palmer@cockcroft.ac.uk)

Measurements of electromagnetic pulses generated from ultra-thin targets at Vulcan Petawatt

P. Rączka, J. Badziak *(Institute of Plasma Physics and Laser Microfusion, 01-497 Warsaw, Poland)*
P. McKenna, N.M.H. Butler, R. Wilson, S.D.R. Williamson *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*
S. Giltrap, R. Smith *(Blackett Laboratory, Imperial College London, UK)*
D. Carroll, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
Y. Zhang, Y. Li *(Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China; School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China)*

One of the effects accompanying the laser-target interaction at high laser intensities is the generation of strong electromagnetic pulses (EMP) with frequencies in the range of tens of MHz to few GHz. Such pulses may interfere with the electronics of the data acquisition systems and pose a threat to the safe and reliable operation of high-intensity laser facilities, it is therefore important to characterize them for various laser and target conditions and to develop a predictive model. To this end, measurements of EMP generated at Vulcan PW from ultra-thin (10s to 100s of nm) metal and plastic targets had been performed. Such targets undergo substantial deformation during the interaction, with the possibility of forming particle jets, resulting in conditions for which EMP generation had been rarely studied so far. Proper conditions were created to capture the multi-GHz component of the resulting electromagnetic pulses. Measurements were performed using conductive B-dot and D-dot probes placed inside and outside the experimental chamber. It was found that the spectrum of the generated pulses is quite wide and the multi-GHz component constitutes the bulk of the signal. It was also found that despite having a random and chaotic appearance such pulses are reproducible from shot to shot to a surprising degree. Electric fields of the order of 150 kV/m were measured behind a glass window just outside the experimental chamber.





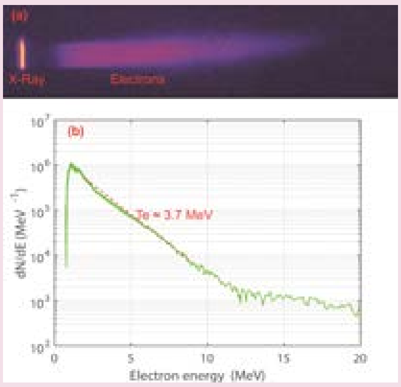
Top figure: The vertical component of the electric field intensity E as a function of time t, recorded with a D-dot probe placed just outside of the chamber in a glass window, as obtained after applying 50 MHz high pass filter.
Bottom figure: Comparison of the amplitude of the signal from the B-dot probe, corrected only for the attenuation at the oscilloscope terminal, for two shots employing CH targets, shown at fine time resolution, illustrating surprising reproducibility of the EMP field evolution from shot to shot.

Contact: P. Rączka (piotr.raczka@ifpilm.pl)

Escaping electron measurement in laser-solid interactions on Vulcan Target Area West

Y. Zhang *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Institute of Physics, Chinese Academy of Sciences, Beijing, China)*
D. Neely, G. Scott, G. Liao, D. Rusby, P. Brummitt *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
Y. Li, H. Liu *(Institute of Physics, Chinese Academy of Sciences, Beijing, China)*
C. Armstrong *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Department of Physics SUPA, University of Strathclyde, Glasgow, UK)*

An electron spectrometer has been employed in measuring escaping electrons from laser-solid interactions. Electron spectra have been obtained in different laser pulse conditions. Dependence of escaping electron numbers and temperature on the pulse energy, intensity and duration is shown in this report.



Typical results of electron signal on an image plate (a) and the relevant spectrum of a quasi-Boltzmann distribution with temperature of 3.7 MeV (b).

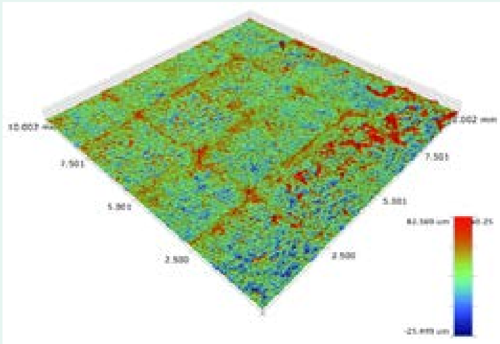
Contact: Y. Zhang (yihang.zhang@stfc.ac.uk)

Laser Science & Development

Laser shock peening of aluminium and titanium using the DiPOLE laser system

J. Nygaard, S. Banerjee, P.J. Phillips, K. Ertel, P.D. Mason, J.M. Smith, M. De Vido, S. Tomlinson, T.J. Butcher, A. Lintern, C.B. Edwards, R. Allott, C. Hernandez-Gomez, J.L. Collier
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, UK)

Successful laser shock peening (LSP) of aluminium and titanium was demonstrated using the DiPOLE laser system operating at 7 J, 10 ns. Peak compressive stress of 220 MPa and 170 MPa was measured in Al7075 and Ti6Al4V with a confinement medium (water). Both peak compressive stress as well as the depth of compression increased on the application of repeat laser shocks. Aluminium foil coating as an absorptive layer showed best results when no confinement condition (no water) was used for LSP.



Surface condition after laser peening with a roughness topography map

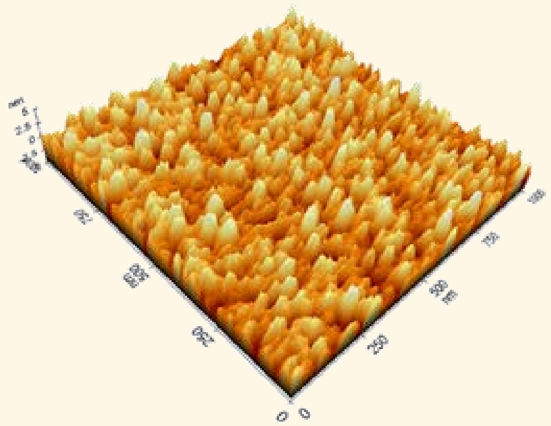
Contact: S. Banerjee (saumyabrata.banerjee@stfc.ac.uk)

Impact of gas cluster ion and accelerated neutral atom beam surface treatments on the LIDT of ceramic Yb:YAG

M. De Vido, K. Ertel, P.J. Phillips, P.D. Mason, S. Banerjee, J.M. Smith, T.J. Butcher, C.B. Edwards, C. Hernandez-Gomez, J.L. Collier *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

M.J. Walsh, S. Kirkpatrick, R. Svrluga *(Exogenesis Corporation, 20 Fortune Drive, Billerica, USA)*

We describe the application of the gas cluster ion beam (GCIB) and of the accelerated neutral atom beam (ANAB) surface treatments to ceramic Yb:YAG. We demonstrate that these techniques allow accurate control of ceramic Yb:YAG surface characteristics and constitute an alternative to conventional surface finishing techniques. In this study, we analyse the impact of angstrom level polishing and surface nano-texturing on laser induced damage threshold (LIDT) in the nanosecond pulsed regime of uncoated and antireflective coated ceramic Yb:YAG samples. We show that both techniques allow meeting the requirements on resilience to laser irradiation at fluence levels characterising high-energy laser systems. Moreover, we show that surface nano-texturing improves the LIDT of coated samples, possibly through an improvement in adherence of coatings to ceramic Yb:YAG substrates.



1 µm x 1 µm atomic force microscope 3D reconstruction of a GCIB nano-textured Yb:YAG sample surface.

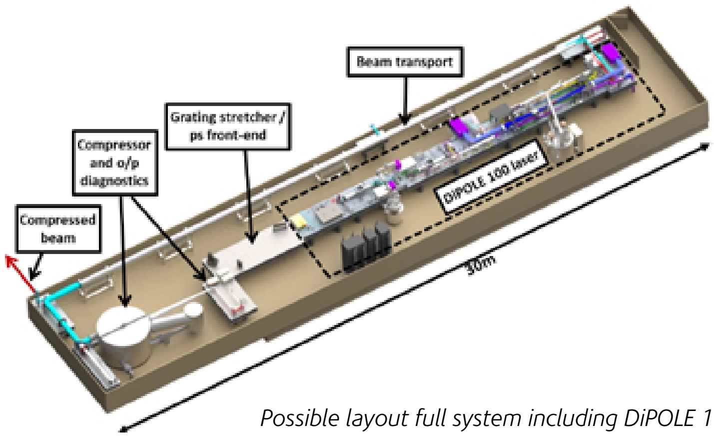
Contact: M. De Vido (mariastefania.de-vido@stfc.ac.uk)

The Prospect of a kW-Class, Multi-TW, ps Laser

K. Ertel, S. Banerjee, A. Boyle, I.O. Musgrave, W. Shaikh, S. Tomlinson, M. De Vido, T.B. Winstone, A.S. Wyatt, C. B. Edwards, C. Hernandez-Gomez, J.L. Collier
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)

We explore how DiPOLE-type laser systems, based on cryo-cooled, diode pumped, multi-slab Yb:YAG amplifier technology, can be adapted for direct-CPA ps-pulse generation. This adaption would open up the possibility of producing pulses with 10s of TW of peak power, 10s of J of energy, at the kW average power level, without having to resort to more complex and less efficient schemes like OPCPA or Ti:Sapphire amplifier chains. Initial calculations indicate that the narrow gain-bandwidth of cryo-cooled Yb:YAG is challenging in terms of stretching and recompression of the laser pulses, but nonetheless should allow the generation of 2 ps pulses at nearly the same energy and at the same repetition rate as in ns mode.

Contact: K. Ertel (klaus.ertel@stfc.ac.uk)



Possible layout full system including DiPOLE 100 laser, front-end with stretcher, compressor, and beam transport

Frequency conversion at 5.5 J, 10 Hz with an LBO Crystal in DiPOLE for greater than 4 hours operation

P. J. Phillips, S. Banerjee, K. Ertel, P.D. Mason, M. De Vido, J.M. Smith, T.J. Butcher, C.B. Edwards, C. Hernandez-Gomez, J.L. Collier
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)

We report on type-1 phase matched frequency conversion in LBO (X-Y Plane), of 5.5 J, 10 Hz cryogenic gas-cooled Yb:Yag laser operating at 1029.5 nm. LBO exhibited an efficiency of > 80% at a peak fundamental of 5.5 GW/cm^2 for 10 Hz operation at 10 ns. This was without any degradation or damage in the crystal.

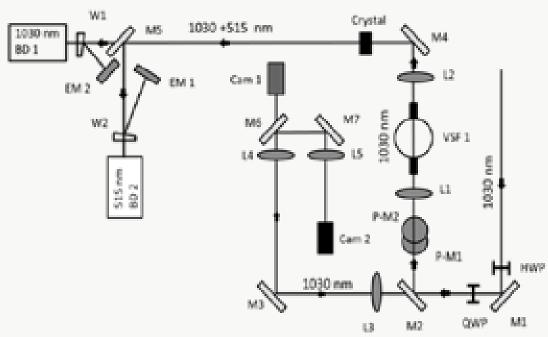


Figure 1 Schematic of the experimental setup to increase the fluence on LBO crystal. M1-M7: Mirrors; L1-L5: Lenses; HWP: Half-wave Plate; QWP: Quarter-wave plate; VSF1: Vacuum spatial filter; W1, W2: Wedges; Cam 1, Cam 2: Cameras, EM1, EM2: Energy meters; BD1, BD2: Beam dumps.

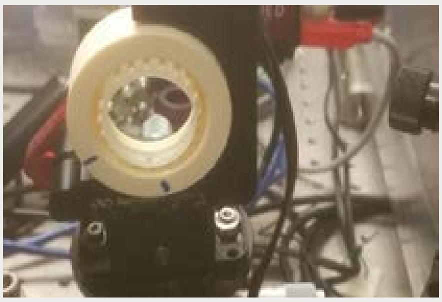


Figure 2 LBO crystal held in place by a laser printed holder which is fixed in a 50 mm mirror holder with electronic actuators for changing the angle of the crystal remotely.

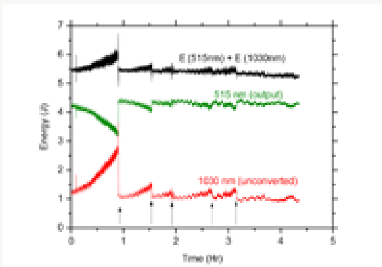


Figure 3 Long term energy stability for LBO crystal. The arrows indicate the time when the angle of the crystal is changed to recover the frequency conversion to the level at the start. The black line is the total energy, green line is the converted 515 nm and the red line is the unconverted 1030 nm.

Contact: J. Phillips (jonathan.phillips@stfc.ac.uk)

Engineering upgrades to the DiPOLE-100 laser system for the D100X project

S. Tomlinson, P.J. Phillips, K. Ertel, P.D. Mason, S. Banerjee, T.J. Butcher, J.M. Smith, M. De Vido, A. Lintern, B. Costello, I. Hollingham, B. Landowski, C. Edwards, C. Hernandez-Gomez, J.L. Collier
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot , UK)

J. Speedy
(Frazer Nash Consultancy, Stonebridge House, Dorking Business Park, Dorking, UK)

The 'state of the art' DIPOLE-100 laser system, commissioned at the HiLASE Facility in 2016, was 18 m long by 3 m wide. For the laser system being supplied to the European XFEL, available space in the HED Instrument laser hutch is severely constrained at 5 m x 11 m, posing an engineering challenge to reduce the footprint radically without major modification to the proven multi-pass architecture. In collaboration with European XFEL, the layout was reconfigured and developed to provide a seamless interface with existing and in-progress service designs for the laser hutch (see Figure 1).

The original amplifier head had a maximum allowable working pressure (MAWP) of 11 bar. An engineered increase in MAWP to 20 bar negates helium inventory depletion, a significant advantage in operation for the new design. To achieve this, the thickness of the main amplifier body has been increased, based on findings from complex technical models. This modification has resulted in a five-fold reduction in the deflection in critical regions of the amplifier head (Figures 2a and b).

Contact: S. Tomlinson (steph.tomlinson@stfc.ac.uk)

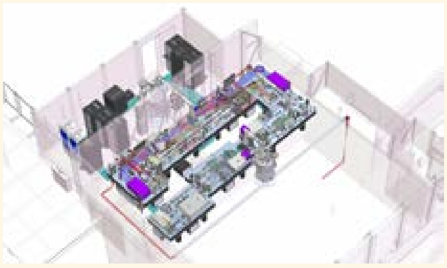


Figure 1: (left) CAD model of the DiPOLE-100X Laser System in the HED Instrument laser hutch at the European XFEL

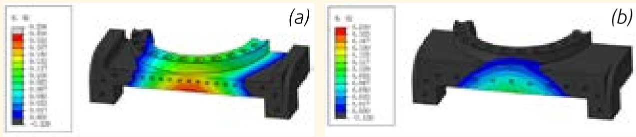


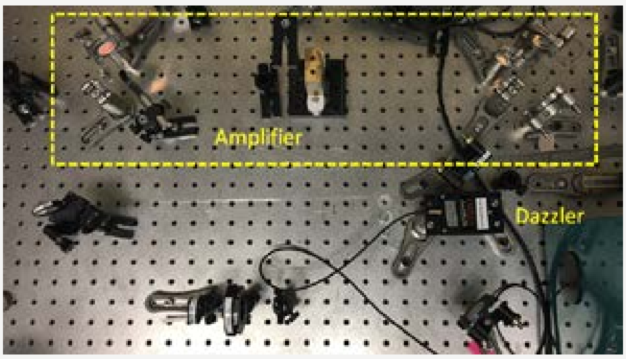
Figure 2: (above) Deformation (mm) outwards in the direction of the sapphire window for steady state operating conditions for (a) the original amplifier head design and (b) the revised amplifier head design

Progress on implementation of a cross-polarised wave generation temporal filter for the Gemini laser

O. Chekhlov, B. Parry, P.P. Rajeev *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot , UK)*

The implementation of the XPW pulse-cleaning technique on the Gemini laser is progressing, with the completion and testing of all the major components of the system. Pulses from the kHz front end amplifier are compressed by a transmission grating pair before the XPW stage itself. The cleaned output has greater bandwidth and improved spatial and spectral quality, but lower energy. The pulses are stretched again, using chirped mirrors and then a glass block, before amplification in a multi-pass Ti:sapphire amplifier to restore the pulse energy to the required level. The stretching has been characterised to show that the spectral and phase quality is maintained, and the performance of the amplifier has been verified. The next phase of the project will involve injecting the amplified beam into the input of the amplifier chain, and measuring the spectral and temporal characteristics of the amplified and compressed pulses at the output of Gemini.

Contact: O. Chekhlov (oleg.chekhlov@stfc.ac.uk)

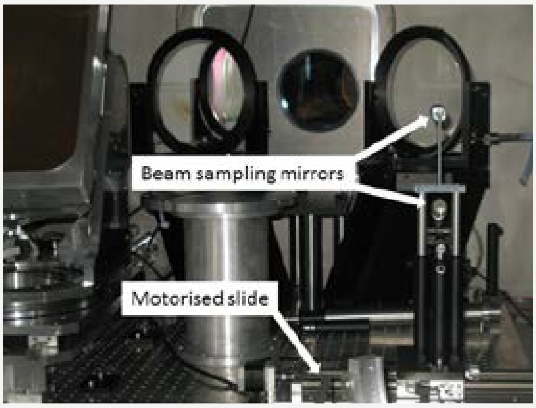


Booster amplifier, consisting of six folding mirrors and the Ti:Sapphire crystal in the middle of the amplifier

Gemini Facility Improvements

C.J. Hooker, O. Chekhlov, C.D. Gregory, S.J. Hawkes, B.T. Parry, Y. Tang, P.P. Rajeev, S. Hook, T. Zata *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

During the year, several new diagnostic capabilities have been implemented on the Gemini laser. A new suite of diagnostics, comprising near- and far-field images and a moiré collimation diagnostic, was installed after Amplifier 3 to allow better monitoring of its performance. In the Gemini pulse compressors, a drive-in periscope was installed for obtaining short pulse diagnostic beams. This was done at the request of the users, because the diffraction from the hole in the final mirror, previously used to obtain the diagnostic beam, was causing damage to optics in the target. The new setup does not provide pulse length information on every shot, but experience shows that there is no significant change in the pulse length during the day. Finally, new Glan-Thompson polarisers were installed in the pulse stretcher cavity to replace the polariser cubes, and eliminate some spectral losses that were adversely affecting the bandwidth of Gemini.



The new beam-sampling setup in the Gemini south compressor

Contact: C.J. Hooker (chris.hooker@stfc.ac.uk)

Software developments in Gemini

V.A. Marshall, O. Cheklov, C.D. Gregory *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

During the year, a number of software changes have been made as part of the continuing programme of upgrade work in Gemini. The main Control System was finally moved off its obsolete platform and onto a more up-to-date operating system. This move forced the replacement of some obsolete hardware controlling the energy delivered to the two target areas with more modern and reliable devices (see Figure 1). During this process, the opportunity was taken to revise the layout of the control system windows, bringing most functions into a single front-panel window.

In response to user requests, a new operating protocol was developed for TA2 to permit multiple-pulse 'burst' operation at 5 Hz repetition rate, and this has given the area a useful new capability.

New applications were written so that data from a new spectrometer system and the on-shot Dazzler settings could be integrated into the numerical sequence of shot data.

LA3 wave plate motion stage application

Contact: V.A. Marshall (victoria.marshall@stfc.ac.uk)

Operation of Gemini Target Area 2 at 5 Hz repetition rate

D.R. Symes, N. Bourgeois, P. Brummit, O. Chekhlov, C.D. Gregory, S.J. Hawkes, C.J. Hooker, V. Marshall, B. Parry, P.P. Rajeev, E. Springate, Y. Tang, C. Thornton *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
S.J.D. Dann, J.D.E. Scott, M.J.V. Streeter *(The Cockcroft Institute, Keckwick Lane, Daresbury, UK)*
C.D. Baird, C.D. Murphy *(York Plasma Institute, Department of Physics, University of York, UK)*
S. Eardley, R.A. Smith *(Blackett Laboratory, Imperial College London, London, UK)*
S. Rozario, J.-N. Gruse, S.P.D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Imperial College London, London, UK)*
S. Tata, M. Krishnamurthy *(Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, India)*
S.V. Rahul *(TIFR Centre for Interdisciplinary Sciences, Hyderabad, India)*
D. Hazra *(Laser Plasma Section, Raja Ramanna Centre for Advanced Technology, Indore, India)*
P. Pourmoussavi, J. Osterhoff *(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)*
J. Hah, A.G.R. Thomas *(Center for Ultrafast Optical Science, University of Michigan, USA)*

Modifications were made to the control and safety systems in Gemini TA2 to trial operations at the full repetition rate of 5 Hz. This allowed implementation of a feedback control code to optimise experimental parameters as shown in Figure 1. The laser performed well with 3% energy stability (see Figure 2) and no noticeable degradation in compressor performance during of order 100,000 shots. The main concerns with higher repetition rate of optic damage and radiological safety are discussed, with suggestions for fast response actions that will ensure safe facility operation.

Contact: D.R. Symes (dan.symes@stfc.ac.uk)

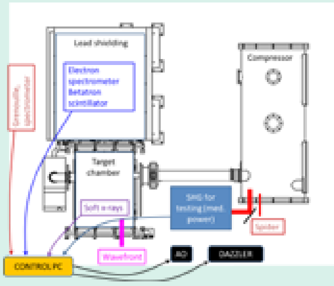


Figure 1: Layout for operating TA2 at high repetition rate. The gas jet is housed in an internal chamber directly connected to an Edwards iGX vacuum pump. Data from diagnostics are fed into a control code that can manipulate the pulse properties using the AO and Dazzler to improve experimental performance.

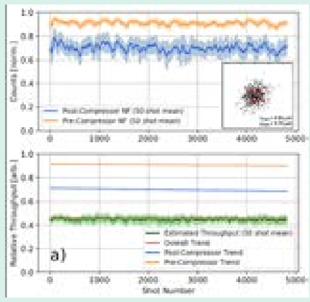


Figure 2: Pre- and post-compressor energy measurements and relative throughput for 4950 laser shots at 5 Hz. The inset shows the beam pointing variation relative to the 20 μm focal spot size.

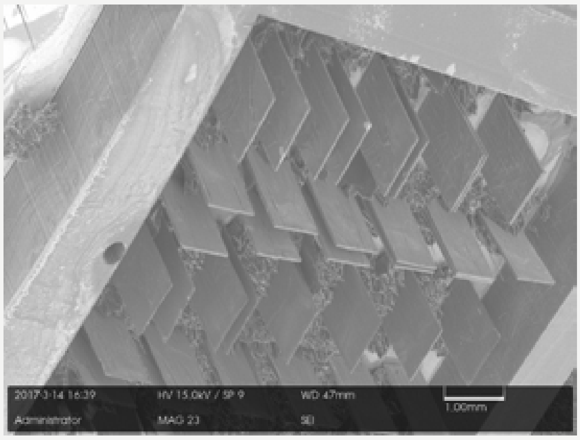
LIGA and its potential application to High Power Laser Science

G. Arthur *(Scitech Precision Limited, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The **LIGA** - **Li**thographie, **G**alvanoformung, **A**bformung (Lithography, Electroplating, Moulding) - process is the ultimate lithographic technique for making high aspect-ratio microstructures. Synchrotron x-rays are used for exposure, and resist walls with the ultimate in wall straightness and smoothness are obtained. Exposures in resist with thicknesses >1 millimetre and aspect ratios up to 100:1 are possible. The structure is used as a mould for subsequent electroplating to form a metallic structure which can either be used 'as is', or as the master for mass production by injection moulding.

This paper describes some early-stage research and development carried out by Scitech Precision in collaboration with Diamond Light Source with the objective of producing high aspect-ratio pinholes in gold. Structures in PMMA resist, from an early exposure, are shown in the figure.

Contact: G. Arthur (graham.arthur@scitechprecision.com)



1.3mm thick PMMA after exposure and development

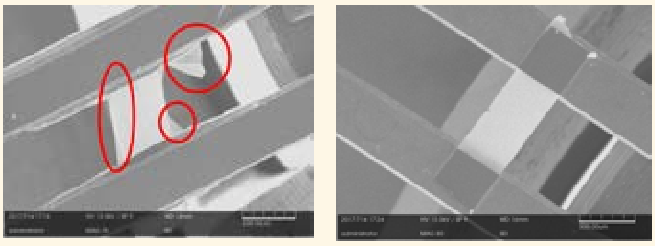
Characterisation of the oxide effects on aluminium opacity targets

D. Haddock, C. Spindloe, M. Tolley *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)* **S. White, D. Riley** *(School of Mathematics and Physics, Queens's University Belfast, UK)*

This paper presents the production and characterisation of an aluminium strip target made by Target Fabrication. Strips were required to be supported over an aperture held only at each end. To support the strip a plastic support layer was used which could be removed by oxygen plasma etching. This process was advantageous as it reliably batch-produced flat strips within specification. However there was contamination caused by the oxygen plasma which increased the relative abundance of oxygen rendering the targets unusable for the experiment. The contaminant was found to be made of carbon and some oxygen by Energy Dispersive X-ray Spectroscopy suggesting a chemical reaction between the oxygen plasma and the surface of the plastic.

In response a manual float-off method was used that was successful in producing the strips without contaminant.

Characterisation methods used included Scanning Electron Microscopy (SEM), Bright-field and Dark-field light microscopy and Interferometry.



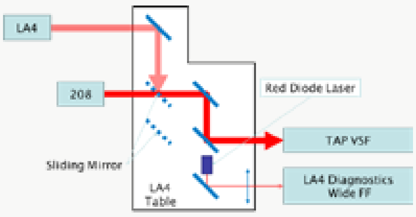
Left: SEM Image of aluminium strip produced by removal of a plastic support layer. Areas of contaminant can be seen circled in red.
Right: SEM image of an aluminium strip produced by method of "float-off". No contaminant seen.

Contact: D. Haddock (david.haddock@stfc.ac.uk)

LA4/Vulcan Pointing Mismatch Investigation

S. Ahmed, A. Boyle, A. Frackiewicz, P. Oliveira, M. Galimberti *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The pointing of the Vulcan beam on target in Target Area Petawatt was found to be not accurate enough for some experiments, leading to questions in the alignment procedure. The shift in the pointing was due to the weight of the sliding mirror in the laser area, which delivers the beam into the target area (Figure 1). To resolve the problem, the sliding mirror was fixed directly onto the frame of the table, improving the pointing stability (Figure 2).



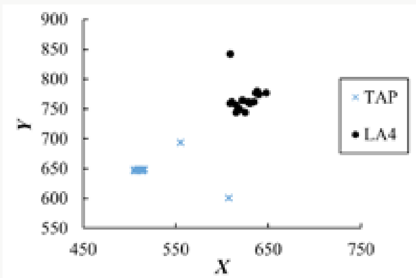


Figure 1 (top): LA4 table with the sliding mirror, showing the test setup using the red diode laser.

Figure 2 (bottom): Centroid data comparison between LA4 and TAP during the Lancaster experiment.

Contact: S. Ahmed (sajidah.ahmed@stfc.ac.uk)

Vulcan Laser Timing System Upgrade

D.A. Pepler, P.B.M. Oliveira, I.O. Musgrave *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The Vulcan Laser Timing and Synchronization System is a large conglomerate of analogue and digital electronics that provides a range of repetitive signals and single-shot triggers and which, over several decades, has evolved to match the ever-growing complexity of experimental requirements. As a result of having a cascade of varied time delay generators, electronic gating devices, fan-out units and long electrical cable runs, ±250ps optical jitter could be observed between short-pulse (ps) and the electrically driven long-pulse (ns) oscillators, which was becoming a limiting factor for running certain user experiments or high-speed diagnostics such as streak cameras.

A commercial Master / Slave timing system has now been sourced from Greenfield Technology, and has had an initial installation and commissioning within the Vulcan Front-End, as shown in the figure. Recent tests with this system have demonstrated a dramatic reduction of the temporal jitter to around 25ps RMS. Consequently, other fibre-optically coupled Slave units are expected to be deployed around the Facility over the coming months.

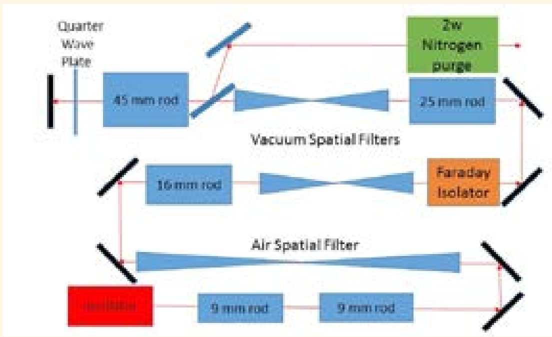
Contact: D.A. Pepler (dave.pepler@stfc.ac.uk)

Installation of the Greenfield Master Oscillator and Slave Unit in the Front-End Oscillator Room.

Observation of harmonic conversion efficiency clamping for nanosecond pulses due to wavefront distortion in Nd: Glass amplifier systems

W. Shaikh, M Galimberti, I.O. Musgrave *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

In this report we discuss our observation of second harmonic efficiency clamping from Nd:Glass amplifiers as we increase the crystal length. Initial measurements with 22 mm long KDP crystals demonstrate 50% conversion efficiency, and simulations for longer crystals predict this should increase to 90%. However, for longer crystals we do not observe this increase in efficiency and attribute this to on-shot aberrations that produce a curved wavefront and reduced conversion efficiency. We present simulations results based on our experimental observations to support this. These results have implications for the short-pulse OPCPA beamline being developed for Vulcan.



Schematic representation of the Component Test Lab with frequency doubling stage.

Contact: W. Shaikh (waseem.shaikh@stfc.ac.uk)

Design and Implementation of a Test Compressor for the Vulcan Front End

A.S. Wyatt *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Clarendon Laboratory, Department of Physics, University of Oxford, UK)*

H. Owen, P. Oliveira, B. Parry, M. Galimberti, I.O. Musgrave *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The Vulcan front end nanosecond OPCPA compressor was commissioned with the purpose of providing additional and improved diagnostic capabilities for the Vulcan Petawatt beamline. Practical constraints, such as available space and cost, dictated a quadruple passed folded design, aiming to provide an analogue of the single passed target area compressor.

Linear sonograms were used for the initial setup, enabling the linear and quadratic dispersion to be set approximately before fine tuning using a single-shot autocorrelator. The compressed pulses were measured to be less than 400 fs in duration using the autocorrelator. Despite showing indications of higher order dispersion, the compressed pulses are sufficently short to enable contrast measurements to be performed, allowing for pulse contrast from the front end to be routinely measured and optimised for user experiments.

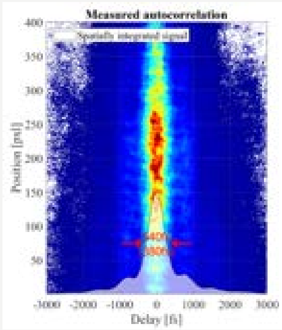


Figure 1: (left) Measured single-shot autocorrelation at the optimal grating separation indicating a 50% energy pulse width of 380 fs assuming a Gaussian intensity profile

Figure 2: (right) Photograph of initial compressor setup. Beam enters from top right, G1 is located in the bottom-right, G2 top-left and RM1 bottom-left

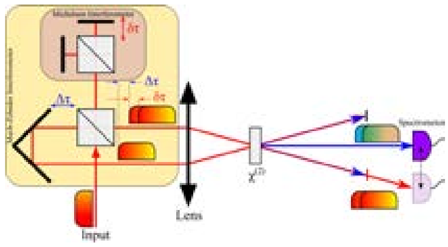
Contact: A.S. Wyatt (adam.wyatt@stfc.ac.uk)

Characterization of Highly Chirped Ultrabroadband Optical Pulses

A.S. Wyatt *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, UK)*

P. Oliveira, I.O. Musgrave *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Highly chirped ultrabroadband pulses play an almost ubiquitous role in ultrafast laser science. An accurate means to quantify not only the linear, but also the nonlinear, dispersion of these highly chirped pulses enables optimal performance of the laser systems and improves the experimental capabilities of any applications that use them. In principle, FROG can reconstruct highly chirped pulses provided that a suitably long delay range is available. However, it was found that existing pulse retrieval methods do not converge for highly chirped pulses, and thus we developed an alternative algorithm based on the stationary phase approximation (SPA). Due to the limited delay range that can easily be achieved in a single-shot geometry, we then applied the SPA to a 'SPIDER-like' measurement and developed a new method that we call chirped heterodyne interferometry for measuring pulses (CHIMP) that in principle can enable single-shot characterization. Since SHG-FROG is already commonly utilized in many ultrafast laser labs, we believe existing users of the method can utilize this simple algorithm to robustly measure highly chirped pulses. By extending the SPA further to an interferometric geometry, we show that it is possible to extract the frequency dependent group delay dispersion (GDD) of the pulses using a direct (i.e. non-iterative) algorithm using our CHIMP method. We believe that the ability to rapidly measure, with single-shot capability, and reconstruct the nonlinear dispersion of highly chirped pulses will prove beneficial in the development of large-scale [OP]CPA laser systems, as well as finding uses in other applications that make use of them, such as dispersive Fourier transform spectroscopy.



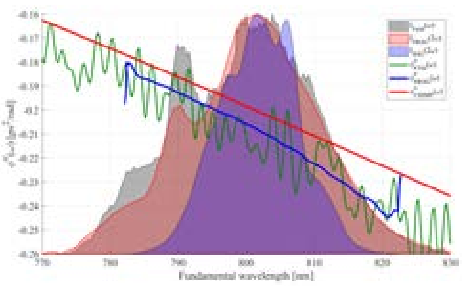


Figure 1: (above, top) Experimental FROG and CHIMP setups. An input chirped test pulse is split into two spatially separated beams using a Mach-Zehnder interferometer. In the upper arm, a Michelson interferometer is used to generate two time-delayed replicas. The two beams are focused and spatially overlapped in a $\chi^{(2)}$ nonlinear crystal whereby they frequency mix to generate the chirped signal pulses which are detected on a spectrometer.

Figure 2: (above, bottom) Measured and retrieved spectral intensity (shaded) and GDD (solid lines).

Contact: A.S. Wyatt (adam.wyatt@stfc.ac.uk)

Plasma Diagnostics

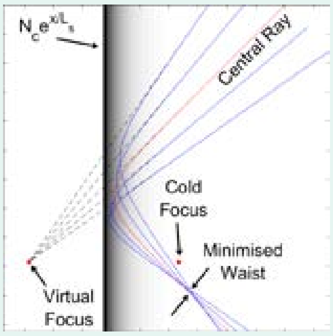
Plasma scale length effects on an imaging geometry

M.S. Huzan *(Department of Physics, Nottingham Trent University, Nottingham, UK)*
C.D. Armstrong *(Department of Plasma Physics, University of Strathclyde, Glasgow, UK)*
D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

This report characterises the severity of optical aberrations for planar and focusing plasma mirrors. Ray trace simulations enable characterisation of the geometric optics through measurements of the reflected beam's minimised waist. Planar investigations illustrated the radial displacement of optical aberrations to be directly proportional to the plasma scale length, and through normalisation enable a single profile to portray the resultant angular distortion.

The severity of aberration within an elliptical and hyperbolic plasma mirror was explored for a broad range of geometries, and demagnifications from an incident F/3 beam. Elliptical plasma mirrors harness the formation of a caustic within the reflected optical beam. Optimisation of this geometry deduced an optimal minor-to-major axis ratio of 0.654.

Simulations provide a theoretical minimum waist which is achievable within geometric optics for which results were consistently below the diffraction limit.



Schematic of a focusing beam incidence into an exponentially decaying plasma profile from a planar plasma mirror

Contact: M.S.Huzan (myron.huzan@stfc.ac.uk)

Shielding effectiveness of a copper box against laser driven electromagnetic pulses

P.J.R. Jones, B. Summers, D. Carroll, G.N. Wiggins, G.G. Scott, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
P.W. Bradford, N. Woolsey *(University of York, Department of Physics, University of York, York, UK)*
P. McKenna *(University of Strathclyde, John Anderson Building, Glasgow, UK)*

Laser interactions have been known to generate Electro-Magnetic Pulses (EMP) during high energy laser driven interactions with matter. EMP generated in this way can induced rapid changes in current in sensitive electronics, leading to often irreparable damage.

As a result, over the past year, research into the shielding effects of copper boxes (as shown in Figure 1) was conducted to try to improve the protection of critical diagnostics and computers near to the laser interaction chamber.

The diagnostics used were Mobius loops, which output a voltage relating to the changing electric field strength. One was placed inside the box and one outside, after having found their signals to be similar without any shielding in place. With the shielding in place, the integrated energy of the signals showed a reduction of ~25x, demonstrating that the boxes are a very effective for protecting electronics, as shown in Figure 2.

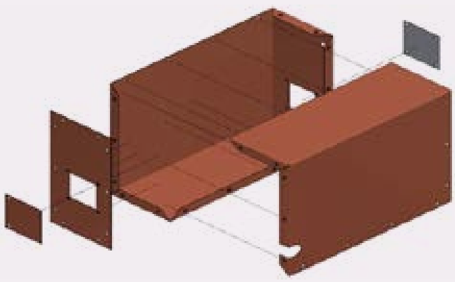


Figure 1: Schematic of box used, measuring ~50 x 40 x 20 cm, made of 1 mm thick copper.

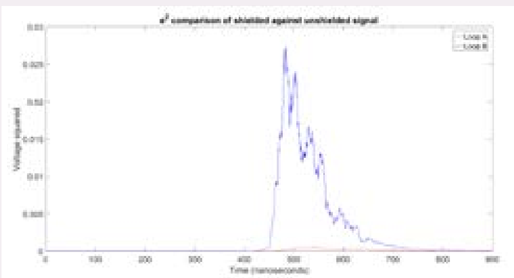


Figure 2: Graph comparing Mobius loop A's shielded signal to Mobius loop B's unshielded signal

Contact: P.J.R. Jones (N0579682@ntu.ac.uk)

Remote control of delay generators and high voltage output devices from Stanford Research Systems

P.J.R. Jones, D. Carroll, G.N. Wiggins *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Over the past year, two new pieces of software for the control of Stanford Research Systems devices have been developed, allowing the remote control of high voltage power supplies and delay generators.

The pieces of software were developed in C# for the Keithley USB to GPIB converter and most RS232 interfaces, allowing for a choice of connectors, while also providing the majority of functionality available manually.

The main interface of the high voltage control software can be seen in Figure 1. The software also includes a user management system for additional safety and data logging, to allow voltage stability testing of devices.

Figure 2 shows the main interface of the delay generator controller, which allows each channel to be set separately while also offering advanced output and triggering options in separate windows.

Contact: P.J.R. Jones (N0579682@ntu.ac.uk)

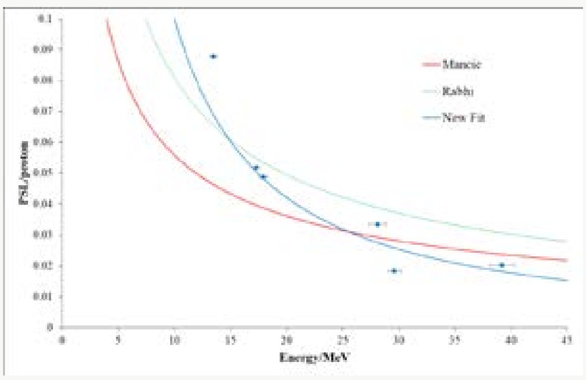
Figure 1: Graphical User Interface of the High Voltage Power Supply Controller

Figure 2: Graphical User Interface of the Delay Generator Controller

Absolute calibration of Fujifilm BAS-TR image plate response to high energy protons in the range 10-40 MeV

P. Martin, H. Ahmed, D. Doria, A. McIlvenny, S. Ferguson, S. Zhai, S. Kar, M. Borghesi *(Centre for Plasma Physics, Queen's University Belfast, University Road, Belfast, UK)*
J. Jarrett, P. McKenna *(Department of Physics, SUPA, University of Strathclyde, Glasgow, UK)*
J.S. Green *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The response of Fujifilm BAS-TR image plates to high energy laser accelerated protons up to 40 MeV has been determined. These were calibrated using a Thomson parabola spectrometer and Colombia Resin #39 (CR-39) solid state detector to determine absolute proton number in specific energy ranges determined through the use of specific iron or copper filters in front of the CR-39. This calibration fills the gap in the literature which has existed for calibrations between 20 and 80 MeV, and is in agreement with previous works. Proton spectra were taken from the Thomson parabola spectrometer to compare the new calibration with a previous one. The two spectra were found to be in good agreement, confirming the validity of the technique.



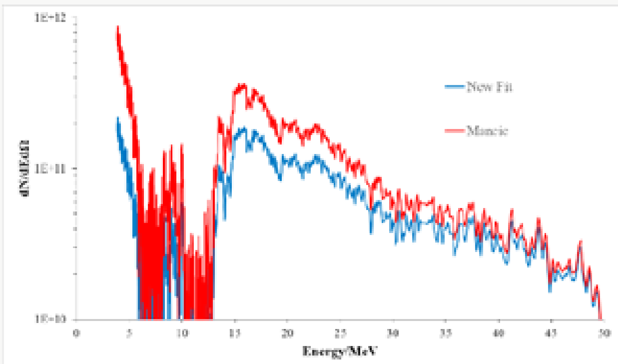


Figure 1 (left): PSL per proton calibration curve, compared to those extrapolated from previous works

Figure 2 (above): Comparison of proton spectra obtained with the two different calibration curves

Contact: P. Martin (pmartin21@qub.ac.uk)

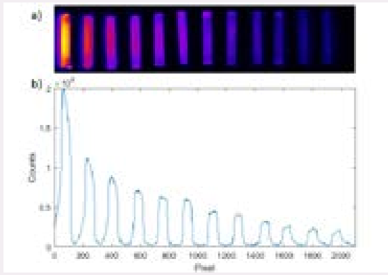
Monte Carlo simulations of x-ray generation to analyse scintillator spectrometer

D.R. Rusby, D. Neely, C. Brenner *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)* **C. Armstrong** *(Department of Plasma Physics, University of Strathclyde, Glasgow, UK)*

For a number of years, a scintillator based absorption x-ray spectrometer has been deployed in the CLF to measure the x-rays emitted from solid target experiments. The main advantage of this diagnostic compared to similar diagnostics is that it instantly digitises the data, and is able to operate at much higher repetition rates than current laser systems in the CLF. In order to take advantage of these capabilities, a number of simulations have been conducted and programmes have been developed to aid analysis of the experimental data taken using the diagnostic.

The operation and implementation of the scintillator based spectrometer is explained is detail in this paper. The method behind generating the response function is also discussed, along with the creation of the x-ray spectrum from different targets and input electron spectra using GEANT4. Using the response function and the spectra, we are able to show how both affect the outputs of the diagnostic in Figure 2.

Finally, we also show how to extract the temperature from the data using a least squares method that is fitted multiple times to take into account the uncertainty of the experimental data.



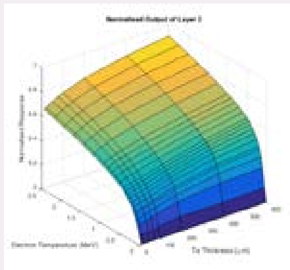


Figure 1 (top): a) Example data from the scintillator based x- ray spectrometer. The x-rays are entering from the left and being absorbed as they pass through the array. The photons that are emitted are recorded on a camera. b) shows a lineout of the image. The signal clearly falls as a function of layer.

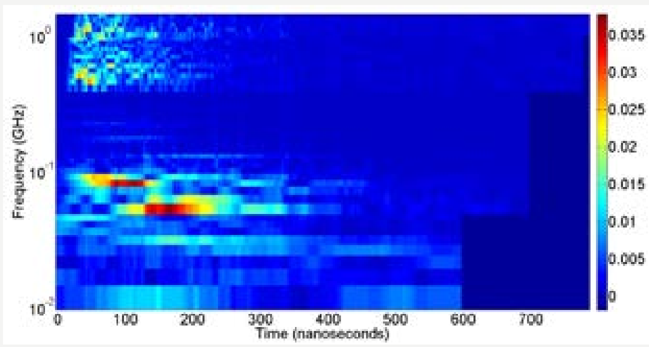
Figure 2 (bottom): A collection of normalised outputs for layer two as a function of electron temperature and Ta thickness

Contact: D.R. Rusby (dean.rusby@stfc.ac.uk)

Time-dependent Nyquist limited Fourier transform analysis of electromagnetic pulse data

M.P. Selwood, D.C. Carroll, M.E. Read, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

During a high power laser-target interaction, electromagnetic pulses (EMP) are generated with frequencies on the order of magnitude of 10^3 GHz. Current oscilloscope capabilities are on the order of 10 GHz; far below the pulses being measured. Therefore oscilloscope diagnostics on these experiments are working at their bandwidth limits, and sampling lengths begin to limit the valid frequency output from existing binned (time-dependent) Fourier transform techniques. We describe a technique created around Nyquist's theorem on digital sampling rates of analogue signals, varying bin sizes of different frequency blocks to allow for time-dependent valid and broad spectra analysis from EMP measurements.



Time-dependent Nyquist limited Fourier transform analysis of the experimental EMP data. This shows clearly how the different EMP frequencies vary over time after the laser interaction. On the right of the figure, and more prominently in the lower frequencies, there is a region that was not analysed due to bin length constraints and is highlighted in dark blue.

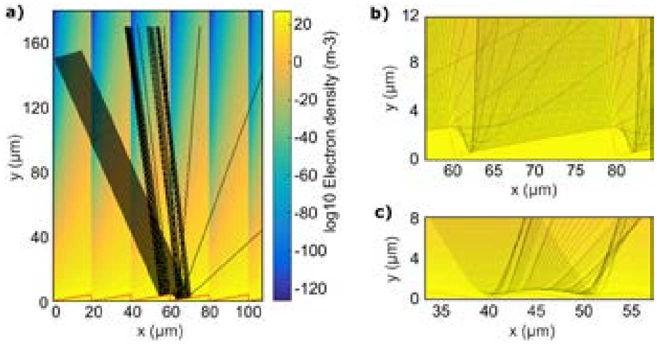
Contact: D.C. Carroll (david.carroll@stfc.ac.uk)

Ray tracing investigation of plasma gratings

E. Warne, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Based on the success of plasma mirrors as optics in high intensity laser systems, the possibility of forming a diffraction grating from a plasma in a similar manner was investigated. A ray tracing simulation was written in MATLAB for this purpose, and was used to find the path of light rays interacting with a plasma mirror and various models of plasma grating. The simulations show that if a sawtooth plasma structure could be produced, this could be effective as a >80% efficient plasma grating. However, the ray paths are very sensitive to inhomogeneities in the plasma, meaning that structures that could feasibly be produced by the interference of beams, such as a sinusoid and a Fourier series triangular waveform, will not act as effective, efficient plasma gratings.

Contact: D. Neely (david.neely@stfc.ac.uk)



[a] Ray trace of a sawtooth plasma grating structure, demonstrating that the majority of the incident rays are reflected from the grating at a consistent angle, which is different to the incident angle. The red line shows the critical surface of the plasma.

[b] A close-up of the sawtooth structure shown in [a].

[c] A similar close-up, this time of a Fourier sum triangular structure. It can be seen that, in contrast to [b], the rays are reflected over a wide range of angles, despite the apparently straight sides of the critical surface.

Ultrafast & XUV Science

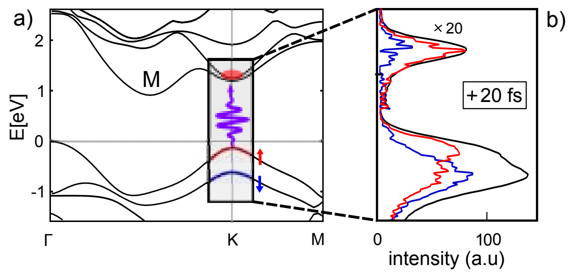
Spin-resolved electronic dynamics in bulk WSe_2

R. Bertoni *(Institut de physique de Rennes, Université de Rennes 1, Rennes, France)*
C. Nicholson, L. Rettig, R. Ernstorfer *(Fritz-Haber-Institute der Max-Planck-Gesellschaft Faradayweg, Berlin, Germany)*
C. Monney *(University of Fribourg, Department of Physics, Fribourgh, Switzerland)*
M. Hoesch *(DESY Photon Science, Notkestrasse, Hamburg, Germany)*
C. Cacho *(Diamond Light Source, Harwell Campus, Didcot, UK)*
E. Springate, R.T. Chapman *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

The ability to generate and control spin-polarized carriers is at the heart of spintronic science. One way of doing so is to use materials where several quantum degrees of freedom are strongly entangled. Natural candidates are transition metal dichalcogenides (TMDCs) where electrons, spins and valley indexes are coupled and can be simultaneously addressed via proper light excitation. However, the direct monitoring of the spin polarization of such short-lived states remains an experimental challenge.

Using time- and spin-resolved photoemission spectroscopy at the CLF Artemis facility, we were able to probe in the time domain, the spin-polarization of photo-excited carriers in bulk WSe_2. By using circular optical excitation, we observe the generation of an almost purely spin-polarized electron gas in the conduction band (K valley) of the material. It demonstrates that such excitation gives direct access to the spin and the valley degree of freedom in this class of material. Knowing the way to effectively generate such spin-polarized excited states, and their following evolution in the time domain, is mandatory in order to harvest these peculiar properties for spintronic devices.

Contact: R. Bertoni (roman.bertoni@univ-rennes1.fr)

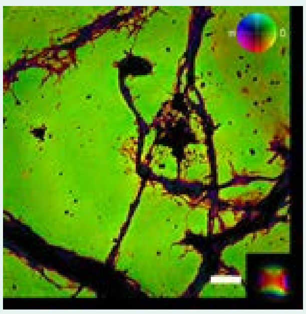


a) DFT calculations of the band structure of bulk WSe_2. At the K point, the two valence bands are purely spin polarized. The material is excited with 1.5 eV circular polarized light pulse populating the conduction band in the K valleys. The grey shaded area corresponds to the probed area with the spin-resolved detector.
b) Spin resolved photo-emitted signal 20 fs after photo-excitation. The red and blue curves correspond to the projected spin polarization of the photo-emitted electron. The generated photo-excited states in K valleys are almost purely spin-polarized.

XUV Ptychographic imaging of mouse hippocampal neurons with 50nm resolution using the Artemis HHG source

P.D. Baksh, W.S. Brocklesby *(Optoelectronics Research Centre, University of Southampton, UK)*
M. Odstrčil *(Optoelectronics Research Centre, University of Southampton, UK; RWTH Aachen, Germany)*
M. Miszczak *(Optoelectronics Research Centre, University of Southampton; University of Padova, Italy)*
R. Chapman, E. Springate *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
A. Wyatt *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK; Clarendon Laboratory, Department of Physics, University of Oxford, UK)*
J.G. Frey *(Department of Chemistry, University of Southampton, UK)*

The availability of coherent sources of XUV and soft x-ray radiation from sources based on high harmonic generation (HHG) means that imaging in these spectral regions can be performed using lens-less techniques such as ptychography. This allows for much increased resolution, as no imaging optics are required, and for measurement of the full complex transmission of the sample. In this paper, we describe coherent imaging of mouse hippocampal neurons grown on silicon nitride substrates at a wavelength of 29 nm with diffraction-limited resolution of ~100 nm. Transmission imaging was performed with an illumination-forming pinhole close to the sample, and also with an illumination-forming aperture at a large distance (~1 m) from the sample demagnified by EUV reflective optics. This allows much greater flexibility in designing measurement geometries without the need for a pinhole in close proximity to the sample.



Transmission image at 29 nm of 7DIV neurons grown on SiN substrate. Scale bar is 10 μm.

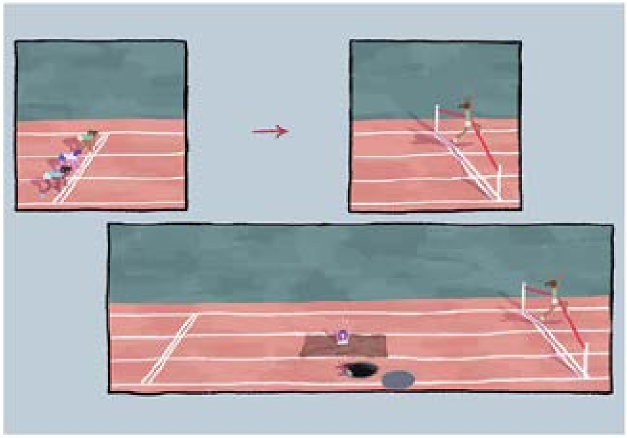
Contact: W.S. Brocklesby (W.S.Brocklesby@soton.ac.uk)

Observing the complete reaction pathway of CS_2 dissociation

A.D. Smith,, E.M. Warne, R.S. Minns *(Chemistry, University of Southampton, UK)*
D. Bellshaw, M. Tudorovskya, A. Kirrander *(EaStCHEM, School of Chemistry, University of Edinburgh, UK)*
A.J. Jones, P.E. Majchrzak, C. Cacho, E. Springate, R.T. Chapman *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
D.A. Horke *(Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany; The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Hamburg, Germany)*

Much of our current understanding of chemical dynamics relies on carefully applied assumptions, most famously the Born-Oppenheimer approximation, which allows us to disentangle the motion of electrons and nuclei from each other. Photochemistry, however, occurs on timescales too fast for those assumptions to stand. As a result, even relatively small and structurally simple molecules, when treated with light, undergo a complex cascade of competing processes and pass through a large number of electronic states of near-identical energy. We have shown that it is possible to use a high harmonic XUV probe to monitor the evolution of a photodissociation reaction initiated by an ultrafast UV pulse, following all of the intermediates involved. This work is backed up by kinetic modelling showing agreement with the observed spectra.

Contact: R.T. Chapman (richard.chapman@stfc.ac.uk)
R.S. Minns (r.s.minns@soton.ac.uk)



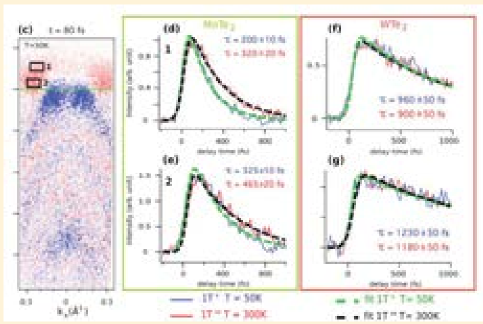
An artist's impression of the reported study's meaning and significance: if one only snapshots the beginning and the end of the reaction (here metaphorically depicted as a race), one is liable to miss the crucial events happening in-between, and misinterpret the entire situation. Courtesy of Helen Towrie, CLF

Out-of-equilibrium electronic dynamics of the transition metal dichalcogenides $MoTe_2$ and WTe_2

A. Crepaldi, G. Gatti, S. Roth, Ph. Bugnon, A. Magrez, H. Berger, M. Grioni *(Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland)*
G. Autès, O.V. Yazyev *(Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland ; National Centre for Computational Design and Discovery of Novel Materials MARVEL, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland)*
A. Sterzi, G. Manzoni, F. Parmigiani *(Universitá degli Studi di Trieste - Via A. Valerio 2, Trieste 34127, Italy)*
M. Zacchigna *(C.N.R. - I.O.M., Strada Statale 14, km 163.5, Trieste 34149, Italy)*
C. Cacho, R.T. Chapman, E. Springate *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
E.A. Seddon *(The Photon Science Institute, The University of Manchester, Manchester, UK; The Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK)*

Weyl semimetals are at the frontier of research activity on novel topological phases of matter. We have investigated the out-of-equilibrium electronic properties of two transition metal dichalcogenides, $MoTe_2$ and WTe_2. The former exhibits a topological phase transition as a function of temperature, while the topology of the latter is still under debate. Our data show that the electron dynamics are strongly sensitive to details of the material unoccupied band structure. In particular, the opening of bandgap in the topological trivial phase of $MoTe_2$ is found to act like a bottleneck. From the comparison with WTe_2, and the observation of a longer relaxation dynamics, we conclude that this material is a topological trivial semimetal.

Contact: A. Crepaldi (alberto.crepaldi@epfl.ch)



(c) Difference between the ARPES image 80 fs after and 200 fs before optical excitation. (d) - (e) Population dynamics of $MoTe_2$ integrated at 50 K (blue) and 300 K (red) in the area highlighted in panel (c) by the rectangles. (f) – (g) Comparison between the population dynamics measured at 50 K (blue) and 300 K (red) in WTe_2. The best fit and the corresponding characteristic time are shown, as well.

UV-pump-VUV-probe photoelectron spectroscopy experiments at ARTEMIS: unravelling the ultrafast relaxation dynamics of aniline

H.H. Fielding, M.A. Parkes, J.L. Woodhouse, Y. Zhang, G. Thornton *(Department of Chemistry, University College London, UK)*
K.L. Reid, L. Whalley *(Department of Chemistry, University of Nottingham, UK)*
R.S. Minns *(Chemistry, University of Southampton, UK)*

Using an XUV photon as a universal probe capable of detecting all of the possible product states, we tracked the dynamics of aniline following excitation into its $2^1\pi\pi^*$ excited state. The preliminary results highlighted here indicate that it is practical to perform this experiment at Artemis.

Contact: H.H. Fielding (h.h.fielding@ucl.ac.uk)

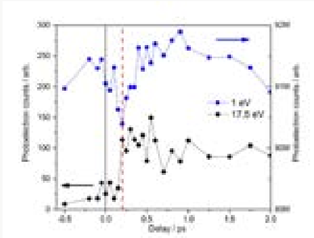


Figure 1 (left): Integrated photoelectron signal as a function of pump-probe delay. Top (blue) curve is in the region of the UV-pump + UV-pump signal, and the bottom (black) curve is in the region of the UV-pump + XUV-probe signal.

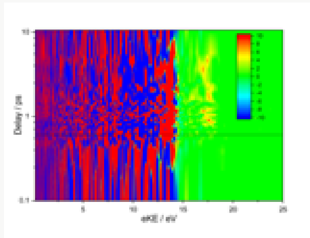


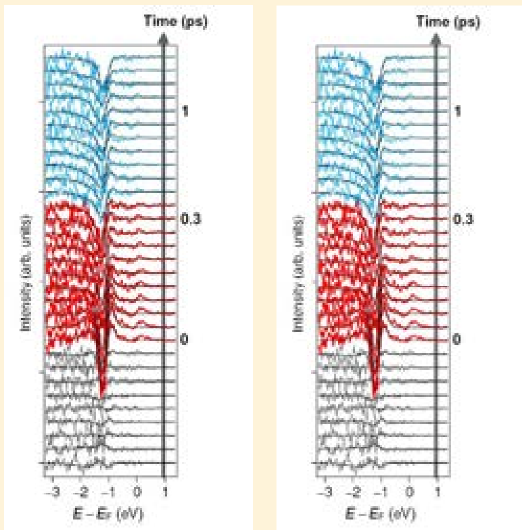
Figure 2 (right): Difference plot of the photoelectron spectra recorded using a 250 nm pump and 21.7 eV probe as a function of time. Note the increase in signal around 17.5 eV. This is the region where pump-probe photoionisation is observed.

Dynamics of correlation-frozen antinodal quasiparticles in superconducting cuprates

C. Giannetti, S. Peli *(Interdisciplinary Laboratories for Advanced Materials Physics, Università Cattolica del Sacro Cuore, I-25121 Brescia, Italy)*
F. Cilento *(Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy)*
G. Manzoni, A. Sterzi *(Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy; Dipartimento di Fisica, Università degli Studi di Trieste, Trieste, Italy)*
A. Ronchi *(Interdisciplinary Laboratories for Advanced Materials Physics, Università Cattolica del Sacro Cuore, Brescia, Italy; Department of Physics and Astronomy, Katholieke Universiteit Leuven, Celestijnenlaan, Leuven, Belgium)*
A. Crepaldi *(Institute of Physics, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland)*
F. Boschini, M. Berciu, A. Damascelli *(Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada; Quantum Matter Institute, University of British Columbia, Vancouver, British Columbia, Canada)*
C. Cacho, R. Chapman, E. Springate *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
H. Eisaki *(Nanoelectronics Research Institute, National Institute of Advanced Industrial Science Technology, Tsukuba, Ibaraki, Japan)*
M. Greven *(School of Physics and Astronomy, University of Minnesota, Minneapolis, USA)*
A.F. Kemper *(Department of Physics, North Carolina State University, Raleigh, USA)*
M. Capone *(Scuola Internazionale Superiore di Studi Avanzati (SISSA) and Consiglio Nazionale delle Ricerche–IstitutoOfficina deiMateriali (CNR-IOM)Democritos National Simulation Center, Via Bonomea, Trieste, Italy)*
F. Parmigiani *(Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy; Dipartimento di Fisica, Università degli Studi di Trieste, Trieste, Italy; International Faculty, University of Cologne, Albertus-Magnus-Platz, Germany)*

Many puzzling properties of high–critical temperature (T_c) superconducting (HTSC) copper oxides have deep roots in the nature of the antinodal quasiparticles, the elementary excitations with wave vector parallel to the Cu–O bonds. These electronic states are most affected by the onset of antiferromagnetic correlations and charge instabilities, and they host the maximum of the anisotropic superconducting gap and pseudogap. We use time-resolved extreme-ultraviolet photoemission with appropriate photon energy (18 eV) and time resolution (50 fs) to reveal the ultrafast dynamics of the antinodal states in a prototypical HTSC cuprate. After photoinducing a nonthermal charge redistribution within the Cu and O orbitals, we reveal a dramatic momentum-space differentiation of the transient electron dynamics. Whereas the nodal quasiparticle distribution is heated up as in a conventional metal, new quasiparticle states transiently emerge at the antinodes, similarly to what is expected for a photoexcited Mott insulator, where the frozen charges can be released by an impulsive excitation. This transient antinodal metallicity is mapped into the dynamics of the O-2p bands, thus directly demonstrating the intertwining between the low- and high-energy scales that is typical of correlated materials. Our results suggest that the correlation-driven freezing of the electrons moving along the Cu–O bonds, analogous to the Mott localization mechanism, constitutes the starting point for any model of high-T_c superconductivity and other exotic phases of HTSC cuprates.

Contact: C. Giannetti (claudio.giannetti@unicatt.it)



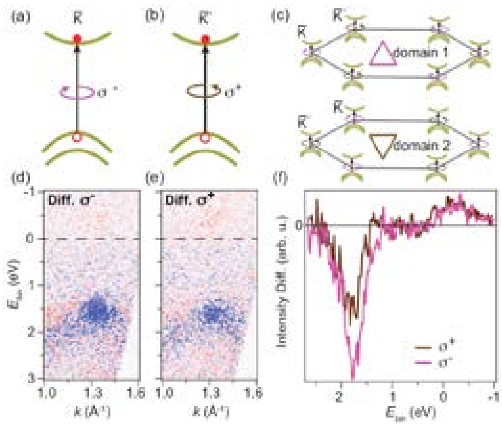
Differential EDC curves as a function of the time delay. The colours highlight three different characteristic temporal regions corresponding to negative delays (grey traces), short dynamics characterized by a transient broadening of the O-2p$_\pi$ peak (red traces), and long dynamics characterized by a long-lived decrease of the O-2p$_\pi$ peak spectral weight. The black lines are the differential fit to the data obtained by assuming both a Gaussian broadening and a spectral weight decrease of the O-2p$_\pi$.

Spin and valley control of free carriers in single-layer WS_2

S. Ulstrup *(Advanced Light Source, E.O. Lawrence Berkeley National Laboratory, Berkeley, California, USA)*
A. Grubišić Čabo, M. Dendzik, C.E. Sanders, M. Bianchi, J. A. Miwa, P. Hofmann *(Department of Physics & Astronomy, Interdisciplinary Nanoscience Center, Aarhus University, 8000 Aarhus C, Denmark)*
D. Biswas, J.M. Riley, P.D.C. King *(SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, UK)*
C. Cacho, D. Matselyukh, R.T. Chapman, E. Springate *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Time- and angle-resolved photoemission spectroscopy (TR-ARPES) is used to measure optically excited free carriers in the electronic band structure of single-layer (SL) tungsten disulphide (WS_2) grown on the (111) face of silver (Ag). This SL transition metal dichalcogenide (TMDC) is characterized by a strong spin splitting on the order of 420 meV at the valence band maximum. Such a strong spin-orbit coupling is desirable for a TR-ARPES experiment that aims to directly detect free carriers selectively excited in the spin-split states in a given valley. Our experiments reveal excited electron and hole populations that are at their maximum for a resonant excitation between the upper valence band spin state and the conduction band. In addition, a noticeable valley polarization of the free carriers results when the material is pumped with circularly polarized light.

Contact: J.A. Miwa (miwa@phys.au.dk)

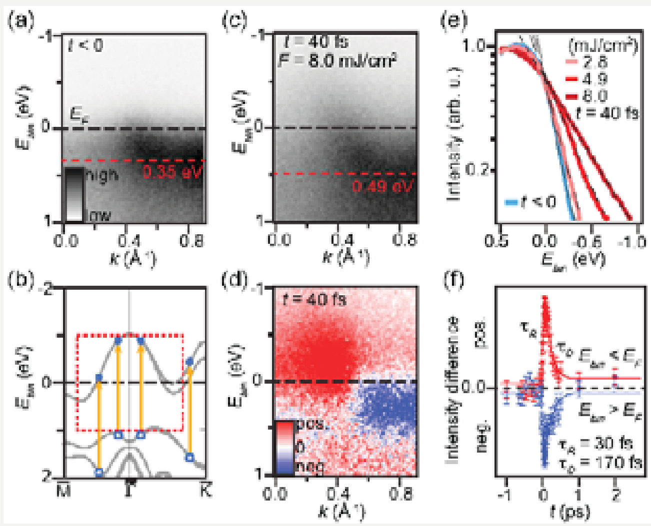


(a),(b) Schematics illustrating the selection rules for transitions from the upper VB to the CBM in the K and K' valleys. (c) BZ orientations and selection rules for the two mirror domains of the SL WS_2. (d),(e) Difference signal for optical pumping with (d) σ^+- and (e) σ^--polarization. (f) EDCs of the difference integrated over the VBM and CBM regions for the data in (d) and (e).

Carrier dynamics in a two-dimensional metal

A. Grubišić Čabo, F. Andreatta, C. E. Sanders, M. Bianchi, J.A. Miwa, P. Hofmann, S. Ulstrup *(Department of Physics & Astronomy, Interdisciplinary Nanoscience Center, Aarhus University, 8000 Aarhus C, Denmark)*
H. Rostami, A. Balatsky *(Condensed Matter, Statistical and Biological Physics, NORDITA, Roslagstullsbacken, Stockholm, Sweden)*
D. Biswas, I. Marković, P.D.C. King *(SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, UK)*
C. Cacho, P. Majchrzak, R.T. Chapman, E. Springate *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

We provide the first direct femtosecond study of single-layer (SL) tantalum disulphide (TaS_2) — a two-dimensional (2D) metal—using time- and angle-resolved photoemission spectroscopy (TR-ARPES) at the Artemis facility. We simulate the measured spectral function procedure in order to extract the electronic dispersion and temperature. We find that a decay time of 170 fs for the excited electrons. 40 fs after optical excitation of the SL-TaS_2, the electrons reach an exceptionally hot high temperature of 3080 K. The elevated electronic temperature is accompanied by a surprising renormalization of the electronic structure bandwidth, driven by interactions of the hot electron gas. Upon exploring the excitation and its temporal evolution for different fluences and sample temperatures, we find an ultrafast single-exponential decay of hot electrons.



TR-ARPES measurement of the 1H-TaS_2 dispersion around the Fermi level. (a) Measured spectrum before optical excitation, i.e. t<0.
(b) Calculated dispersion from Ref. [4] with possible excitation processes.
(c) TR-ARPES data acquired 40 fs after arrival of the pump pulse.
(d) Difference spectrum obtained by subtracting panel (a) from (b). Red (blue) corresponds to excited electrons (holes). (e) Plot of the momentum-integrated intensity over the measured region in panel (a) and (c) for the stated time delays and pump fluence. Time-dependent intensity difference (markers) summed above and below the Fermi level.

Contact: J. A. Miwa (miwa@phys.au.dk)

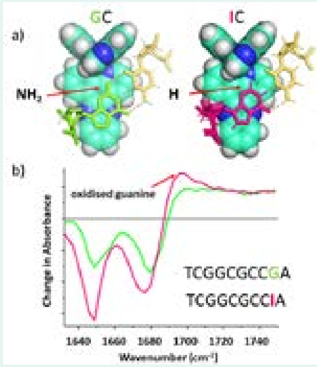
Imaging & Dynamics for Physical & Life Science

Time-resolved studies reveal that DNA photo-oxidation by a Ru(II) polypyridyl complex is highly sensitive to the presence of modified bases

P.M. Keane, J.P. Hall, S.P. Gurung, C.J. Cardin *(Department of Chemistry, University of Reading, Reading, UK)*
F.E. Poynton, T. Gunnlaugsson, J.M. Kelly *(School of Chemistry, Trinity College Dublin, Dublin 2, Ireland)*
I.V. Sazanovich, I.P. Clark, M. Towrie *(Central Laser Facility, Research Complex at Harwell, STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, UK)*
F.R. Baptista, S.J. Devereux, S.J. Quinn *(School of Chemistry, University College Dublin, Belfield, Dublin 4, Ireland)*

Small changes in DNA structure, such as occur in point mutations or base-pair mismatches, can have significant biological effects. There is therefore great interest in developing molecules that can target specific base sites in DNA. Here we have studied the photo-oxidation of DNA by an intercalating ruthenium complex in a series of short sequences where selected guanine bases have been substituted with inosine (I). Time-resolved visible and IR studies reveal that, depending on which guanine is replaced, the yield of photo-oxidation can either increase or drastically decrease. It is proposed that these effects are due to favoured binding at inosine-containing sites. Similar behaviour is observed when IC is replaced with AT, indicating that the complex recognises these steps similarly. These experiments reveal how the photodynamics of a bound complex can be sensitive to changes in one nucleobase, and aid identification of the sites in DNA these compounds target.

Contact: C.J. Cardin (c.j.cardin@rdg.ac.uk)
S.J. Quinn (susan.quinn@ucd.ie)
J.M. Kelly (jmkelly@tcd.ie)



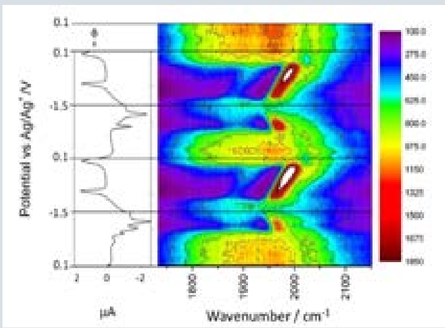
a) Portion of crystal structures of Λ-[Ru(TAP)$_2$(dppz)]$^{2+}$ intercalated at GC and IC steps (b) TRIR spectra of Λ-[Ru(TAP)$_2$(dppz)]$^{2+}$ bound to G9- and I9-substituted DNA sequences at 1150 ps after excitation (Keane et al., Chem. - Eur. J., 2017, 23, 10344)

Vibrational sum frequency generation (VSFG) spectroscopy of electrocatalytic mechanisms

G. Neri, A.J. Cowan *(Department of Chemistry and Stephenson Institute for Renewable Energy, University of Liverpool, UK)*
P.M. Donaldson *(Central Laser Facility, Research Complex at Harwell, STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, UK)*

Here we demonstrate the use of vibrational sum frequency generation (VSFG) spectroscopy to study the mechanisms that occur during electrocatalysis. The 10 kHz broad-band VSFG experiment allows for detection of intermediates present at the surface with only 1 s data averaging. The ability to study short-lived species at electrode surfaces is important as many key intermediates may persist only transiently and be present either at the electrode surface itself or within the electric double layer.

In the study of electrocatalytic H_2 evolution, we are able to identify the formation of a transition metal-hydride complex at the electrode surface even under conditions (low proton concentration) when such behaviour is unexpected. This is significant, as past studies using conventional techniques under similar conditions have struggled to detect this important intermediate, highlighting the advantage of being able to interrogate the electrode chemistry in situ.



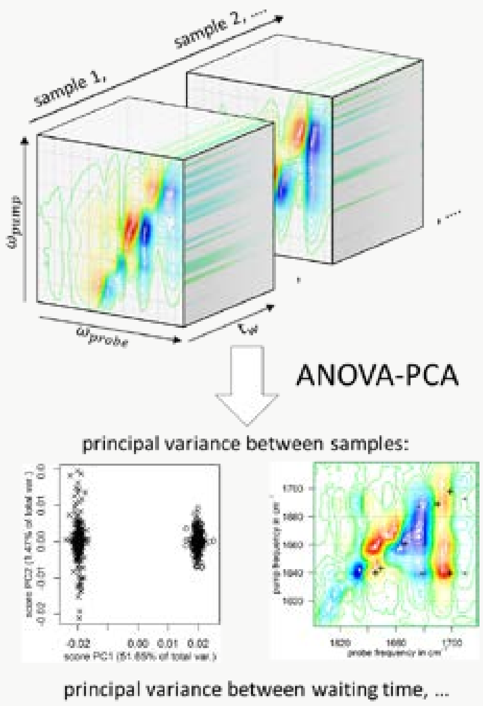
VSFG spectra showing how surface electrochemical events seen by the current-voltage response (left) can be monitored using VSFG spectroscopy (right) where we see new υ(CO) bands forming at the potentials of the electrochemical events.

Contact: A. J. Cowan (acowan@liverpool.ac.uk)

Using ANOVA-PCA to facilitate screening of large 2D-IR datasets

R. Fritzsch, N.T. Hunt *(Department of Physics, University of Strathclyde, SUPA, 107 Rottenrow East, Glasgow, UK)*
P.M. Donaldson, G.M. Greetham, M. Towrie, A.W. Parker *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
M.J. Baker *(Department of Pure and Applied Chemistry, University of Strathclyde, WestCHEM, Glasgow, UK)*

As a result of recent technical developments at the Central Laser Facility, two-dimensional infrared (2D-IR) spectroscopy has the potential to become a fast analysis tool for studying the molecular dynamics and interactions of biological molecules. Spectral acquisition times are now almost on a par with conventional infrared absorption spectroscopy measurements and so pave the way for larger 2D-IR studies across a broader range of analytes and samples. To address the ever-increasing size and complexity of the resulting 2D-IR datasets, we illustrate an approach to data handling using ANOVA-PCA, a combination of analysis of variance with principal component analysis. This method has been applied in a proof-of-concept 2D-IR screening study investigating the binding of small molecules to 12 different DNA sequences (Anal. Chem 2018, 90 2732–2740). The present report aims to generalise this approach to any 2D-IR dataset.

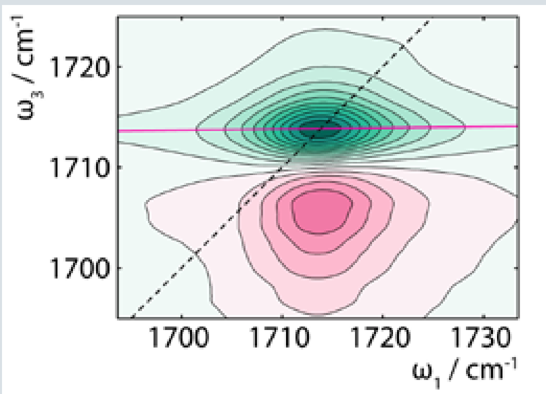


Contact: N.T. Hunt (Neil.hunt@strath.ac.uk)

Investigating electron-phonon coupling and re-orientation effects in hybrid lead-halide perovskites

V.C.A. Taylor, D. Tiwari, M. Duchi, D.J. Fermin, T.A.A. Oliver *(School of Chemistry, University of Bristol, Bristol, UK)*
P.M. Donaldson, I.P Clark *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Organic cation rotation in hybrid organic–inorganic lead halide perovskites has previously been associated with low charge recombination rates and (anti-) ferroelectric domain formation. Two-dimensional infrared spectroscopy (2DIR) was used to directly measure 470 ± 50 fs and 2.8 ± 0.5 ps time constants associated with the reorientation of formamidinium cations (FA^+, $NH_2CHNH_2^+$) in formamidinium lead iodide perovskite thin films. Time-resolved infrared measurements revealed a prominent vibrational transient feature arising from a vibrational Stark shift: photogenerated charge carriers increase the internal electric field of perovskite thin films, perturbing the FA^+ antisymmetric stretching vibrational potential, resulting in an observed 5 cm^{-1} shift. Our 2DIR results provide the first direct measurement of FA^+ rotation inside thin perovskite films, casting significant doubt on the presence of long-lived (anti-) ferroelectric domains, to which the observed low charge recombination rates have been attributed.



Isotropic 2DIR spectrum for the C–N anti-symmetric stretch vibration of the formamidinium cation in lead iodide perovskite films

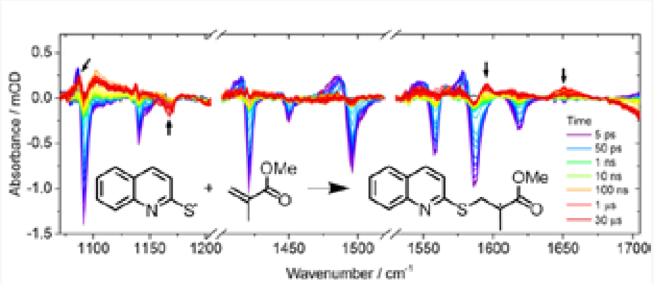
Contact: T.A.A. Oliver (tom.oliver@bristol.ac.uk)

Femtosecond to microsecond observation of photochemical reaction mechanisms

D. Koyama, A.J. Orr-Ewing *(School of Chemistry, University of Bristol, Bristol, UK)*

P.M. Donaldson *(Central Laser Facility, Research Complex at Harwell, STFC Rutherford Appleton Laboratory, Harwell Oxford, Didcot, UK)*

Transient absorption spectroscopy with the LIFEtime facility allows multiple steps in a sequential reaction mechanism to be observed in a single set of measurements. This capability has been demonstrated for photochemical production of thiyl radicals and their addition to alkenes, a class of reactions increasingly used for click-chemistry in the synthesis of molecules and materials. The same techniques can now be applied to study catalytic cycles initiated by absorption of visible or ultraviolet light.



Transient infra-red absorption spectra reveal the rates and products of an addition reaction of a thiyl radical to an alkene.

Contact: A.J. Orr-Ewing (a.orr-ewing@bristol.ac.uk)

Using surface plasmon resonance excitation to determine real-time distributions of gold nanoparticles in live cells

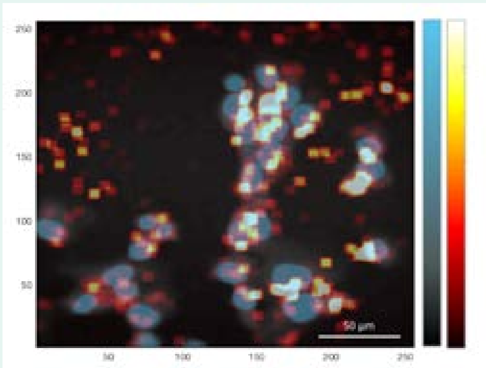
A. McCulloch *(School of Mathematics & Physics, Queen's University Belfast, UK)*
L. Bennie, J.A. Coulter *(School of Pharmacy, Queen's University Belfast, UK)*

S.W. Botchway *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
F.J. Currell *(Dalton Cumbrian Facility, University of Manchester, Cumbria, UK)*

Heavy atom nanoparticles are increasingly being studied for their potential use in cancer therapy. When localised at a tumour site nanoparticles have been shown to increase the success of traditional radiotherapy due to their dose-enhancing properties. As such, nanoparticles provide a pathway to better patient outcomes using equipment already in place at many medical facilities.

Of all the nanoparticles currently studied, gold nanoparticles, AuNPs, are of specific interest due to their low toxicity and their ability to be functionalised easily

Understanding the physically driven dose enhancement provided by AuNPs is crucial in order to progress toward patient trials. A new method for investing the uptake dynamics of a nanoparticle in live cell samples in real-time has been demonstrated. Cell membrane association has been shown for multiple formulations of functionalised gold nanoparticle as can be seen above. Additional refinements to this technique allowing imaging to further time points have also been suggested.



FLIM and plasmon resonance image of DU145 fixed cell sample 24 hours after treatment with RALA-modified AuNP solution

F.J. Currell (frederick.currell@manchester.ac.uk)

Gemini operational statistics 16/17

S. Hawkes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK)*

During the reporting year, April 16 – April 17, a total of seven complete experiments were delivered in the Astra-Gemini Target Area, and three experiments in TA2. In total, 31 high power laser experimental weeks were delivered the Gemini Target Area and 22 weeks to TA2. The delivered schedule is presented in Figure 2.

The availability of the Gemini laser system (delivery to the Gemini Target Area) was 84% during normal working hours, rising to 145% with time made up from running out of normal working hours. The reliability of the Gemini laser was 90%. An individual breakdown of the availability and reliability for the experiments conducted is presented in Figure 1.

The high levels of total availability were made possible by the continued unique operational model employed on Gemini, which involves running the laser late into the evening. In addition, frequent weekend operational days were made available.

During the year, two system access slots were made available. The first slot was used to separate the Astra and Artemis emergency power off systems, replace the Gemini compressor doors and perform testing of the beam stabilization system in TA3.

The second system access period was used to continue with development of the beam stabilization systems in Gemini and TA3 and to perform initial XPW pulse cleaning system tests in LA1/2. This included the commissioning of an additional Ti:S amplifier to recoup the losses introduced by the XPW system.

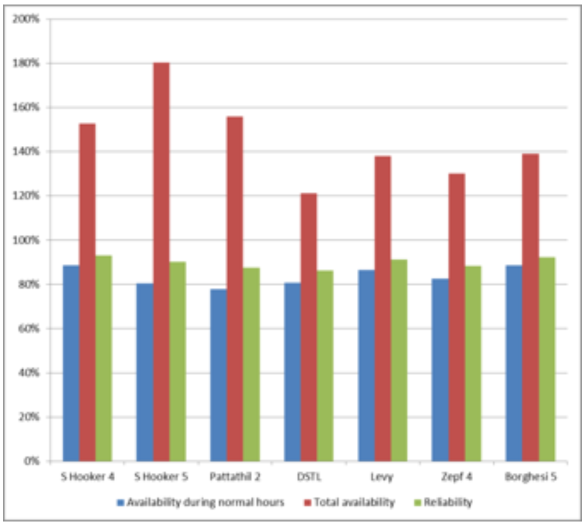


Figure 1. 2016/17 operational statistics

Week beginning	Gemini	TA2
04/04/2016	Extension	
11/04/2016		
18/04/2016	System	
25/04/2016	Access	
02/05/2016		
09/05/2016		
16/05/2016		Commercial Access
23/05/2016	Hooker	
30/05/2016	15210025	
06/06/2016		
13/06/2016		Norreys (pt. 1)
20/06/2016		15210000
27/06/2016	Hooker	
04/07/2016	16110004	
11/07/2016	Maintenance	
18/07/2016	Pattathil 15210023	
25/07/2016	Changeover	
01/08/2016		Norreys (pt. 2)
08/08/2016	Commercial Access	15210000
15/08/2016		
22/08/2016	Quantel	
29/08/2016	Service	
05/09/2016		
12/09/2016	Levy	
19/09/2016	16110013	
26/09/2016		
03/10/2016		
10/10/2016	Maintenance	
17/10/2016	System optimisation	
24/10/2016	Set up	Norreys (pt. 3)
31/10/2016		15210000
07/11/2016		
14/11/2016	Zepf	
21/11/2016	16110024	Symes (pt. 1)
28/11/2016		16110021
05/12/2016		
12/12/2016		
19/12/2016	Christmas	
26/12/2016		
02/01/2017		
09/01/2017		
16/01/2017	System Access	
23/01/2017		
30/01/2017		
06/02/2017		
13/02/2017		
20/02/2017		Symes (pt. 2)
27/02/2017	Borghesi	16110021
06/03/2017	16110016	
13/03/2017		
20/03/2017		
27/03/2017	Maintenance	

Figure 2. 2016/17 Gemini operational schedule

Contact: S. Hawkes (steve.hawkes@stfc.ac.uk)

Vulcan Operational Statistics

A.K. Kidd and T.B. Winstone *(Central Laser Facility, STFC, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, Oxon OX11 0QX, UK)*

Introduction

Vulcan has completed an active experimental year, with 53 full experimental weeks allocated to target areas TAW and TAP between April 2016 and March 2017.

Table 1 shows the operational schedule for the year, and reports the shot rate statistics for each experiment.

PERIOD	TAW	TAP
2016		
18 Apr – 22 May		**R Smith** A first investigation of ultra-high intensity laser interactions with levitated micro-targets (29, 0, 100.0%) (80.3%, 117.0%)
13 Jun – 17 Jul	**S White** Disentangling the contributions to plastic relaxation at a shock front: nucleation versus viscosity (116, 12, 89.7%) (81.7%, 111.3%)	
01 Aug – 04 Sep	**F Keenan** Novel Vulcan experiments to produce high photoionization parameter plasma: recreating a Seyfert galaxy in the laboratory (124, 13, 89.5%) (92.3%, 111.4%)	**N Woolsey** Resubmission of extreme x-ray radiation fields created during an ultra-intense laser-solid interaction (53, 3, 94.3%) (85.6%, 102.9%)
19 Sep – 24 Oct	**S Kar** Intense thermal and epithermal neutron source using high power lasers (87, 12, 86.2%) (83.5%, 108.3%)	**P McKenna** Ultra-intense laser-driven ion acceleration with near-diffraction limited focal spots (99, 6, 93.9%) (79.0%, 122.3%)
07 Nov - 11 Dec	**R Gray** Temporally resolved optical probing of picosecond laser propagation and filamentation in underdense and near-critical density plasmas (120, 10, 91.7%) (93.0%, 108.8%)	
2017		
16/23 Jan - 26 Feb	**D Riley** XUV probing of warm dense matter (150, 20, 86.7%) (84.7%, 122.4%)	**M Roth** Laser-driven acceleration by microstructured silicon targets (116, 15, 87.1%) (86.1%, 110.9%)
13 Mar - 30 Apr		**D Margarone** Proton acceleration from thin cryogenic ribbons (54, 2, 96.3%) (91.8%, 108.4%)

Table 1. Experimental schedule for the period April 2016 – March 2017

(Total shots fired, failed shots, reliability)
(Availability normal, additional hours)

Numbers in parentheses indicate the total number of full energy laser shots delivered to target, followed by the number of these that failed and the percentage of successful shots. The second set of numbers are the availability of the laser to target areas during normal operating hours and including outside hours operations.

The total number of full disc amplifier shots that have been fired to target this year is 948. Table 2 shows that this figure is less than in the three previous years. 93 shots failed to meet user requirements. The overall shot success rate to target for the year is 90%, compared to 89%, 88%, 88% and 91% in the previous four years. Figure 1 shows the reliability of the Vulcan laser to all target areas over the past five years.

	No of shots	Failed shots	Reliability
12 - 13	860	93	89%
13 - 14	1015	121	88%
14 - 15	1087	133	88%
15 - 16	1143	108	91%
16 - 17	948	93	90%

Table 2. Shot totals and proportion of failed shots for the past five years

The shot reliability to TAW is 89%, down a percent from the previous year. The shot reliability to TAP is 93% - up from 91% in 2015-16.

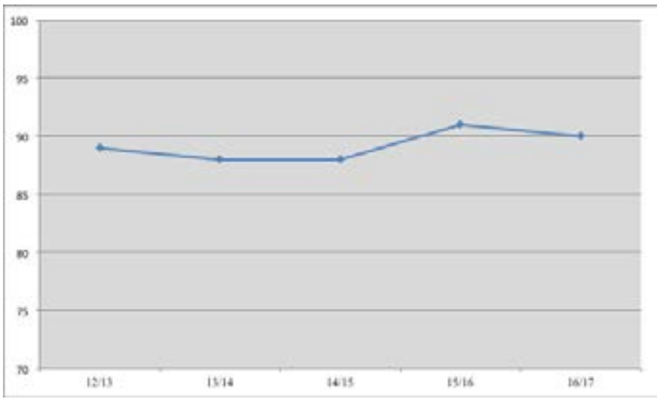


Figure 1. All areas shot reliability for each year 2012-13 to 2016-17

Analysis of the failure modes reveals that, as in recent years, the two overriding causes of failed shots are alignment and front end related issues. These two causes are manifested in low or high energy output of the roda amplifier chain. Approximately three-quarters of failed shots are due to this cause. Commissioning of further high repetition rate diagnostics in the front end and throughout the laser area should allow us to identify and resolve specific sources of instability.

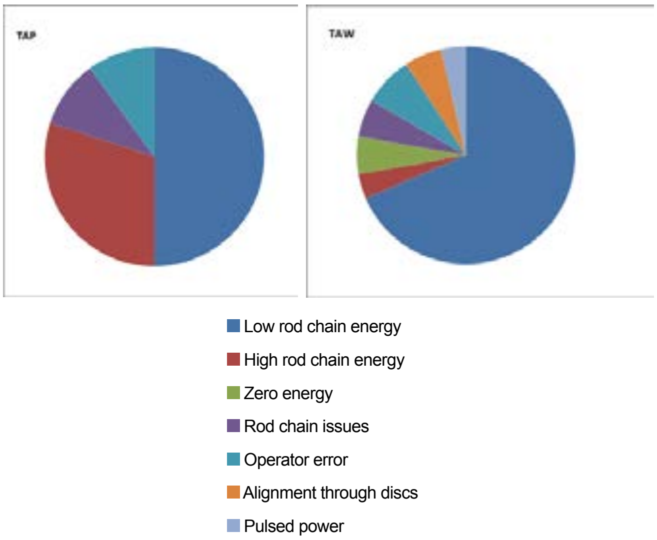


Figure 2. Individual contributions to failed shots for each target area TAP and TAW

There is a requirement which was originally instigated for the EPSRC FAA that the laser system be available, during the five week periods of experimental data collection, from 09:00 to 17:00 hours, Monday to Thursday, and from 09:00 to 16:00 hours on Fridays (a total of 195 hours over the five week experimental period). The laser has not always met the startup target of 9:00 am but it has been common practice to operate the laser well beyond the standard contracted finish time on several days during the week. In addition, the introduction of early start times on some experiments continues to lead to improvements in availability.

On average, Vulcan has been available for each experiment to target areas for 85.8% of the time during contracted hours, compared with 83.2% for the previous year. Although this figure is slightly up, the overall availability remains at the same level as 2015-16 which is 112.4% to all target areas. The time that the laser is unavailable to users is primarily the time taken for beam alignment at the start of the day.

Contact: A. Kidd (andy.kidd@stfc.ac.uk)

Artemis operational statistics

R. T. Chapman *(Artemis, Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, OX11 0QX, UK)*

The Artemis team delivered a total of eleven user experiments from April 2016 to March 2017, as well as two weeks of development projects in partnership with facility users. In total, we delivered 26 weeks of user access and twelve weeks of dedicated experiment setup. Table 1 shows the schedule for the year.

Week Beginning	Experiment
04/04/2016	Setup for Miwa
11/04/2016	
18/04/2016	Laser down due to excavations outside the lab
25/04/2016	Miwa 16120009
02/05/2016	
09/05/2016	Set-up for Chapman
16/05/2016	Chapman 16120011
23/05/2016	
30/05/2016	Imaging beamline engineering
06/06/2016	
13/06/2016	Set-up for Brocklesby
20/06/2016	Brocklesby 16120012
27/06/2016	
04/07/2016	Air conditioning installation
11/07/2016	Giannetti 16120004
18/07/2016	
25/07/2016	Crepaldi 16120002
01/08/2016	
08/08/2016	Spin TOF installation
15/08/2016	Few-cycle idler development
22/08/2016	Laser service - RedDragon
29/08/2016	Few-cycle idler development
05/09/2016	Topas service Mon 5 - Wed 7; Set-up for Cacho
12/09/2016	Set-up for Cacho
19/09/2016	Cacho 15120042
26/09/2016	
03/10/2016	Setup for Bertoni
10/10/2016	Bertoni 16120023
17/10/2016	
24/10/2016	
31/10/2016	AMO installation
07/11/2016	Setup for Chapman
14/11/2016	Chapman 16120011
21/11/2016	
28/11/2016	Setup for Fielding
05/12/2016	Fielding 16120021
12/12/2016	
19/12/2016	Maintenance
26/12/2016	
02/01/2017	Laser service - RedDragon
09/01/2017	Set-up for Miwa
16/01/2017	Miwa 16120009
23/01/2017	Miwa 16120018
30/01/2017	Setup for Scholl
06/02/2017	Scholl 16220013
13/02/2017	
20/02/2017	Spin TOF installation
27/02/2017	Set-up for Minns
06/03/2017	Minns 16120015
13/03/2017	
20/03/2017	Set-up for Carley
27/03/2017	Minns 16120015

Table 1. Artemis schedule for 2016-17

Experiments

Five of the eleven experiments conducted used the angle resolved photoemission chamber for studying condensed matter samples. Two further experiments were carried out using the spin time of flight chamber in conjunction with condensed matter samples. Two experiments used a new time of flight detector on the AMO chamber looking at small molecules in the gas phase. One experiment used the coherent imaging chamber and one experiment used the flat field spectrometer for high harmonic spectrometer. The Artemis team dedicates approximately one week of set-up to each experiment, before users arrive. Similar experiments are grouped together, to minimize set-up time.

Facility performance and reliability

Figure 1 shows the availability and reliability calculations for the 2016-17 year. We run the laser continuously from Mondays through to Fridays during experiments, and regularly carry on data-taking over weekends. In this calculation, the availability for unsupported data-taking overnight and at weekends is weighted equally with supported hours.

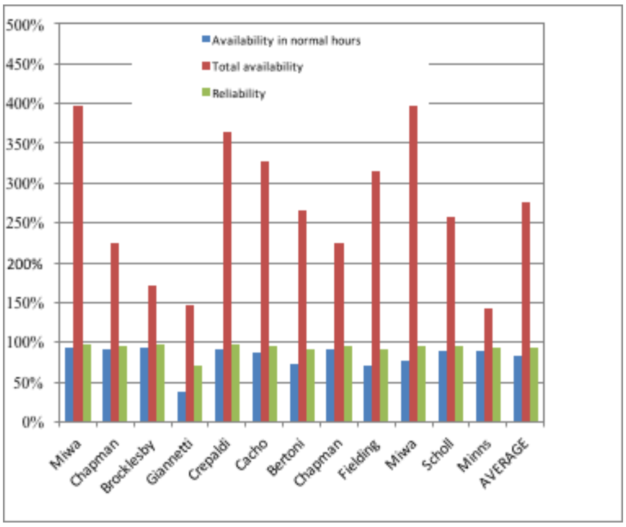


Figure 1. Availability and reliability for user experiments in 2016-17

Contact: R.T. Chapman (richard.chapman@stfc.ac.uk)

Octopus and Ultra Operational Statistics

B. C. Bateman, D.T. Clarke *(Central Laser Facility, STFC, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, Oxon OX11 0QX, UK)*

OCTOPUS facility

In the reporting period (April 2016 to March 2017), 56 unique User groups submitted a total of 71 proposals bidding for time at the Octopus facility. 33 experiments comprising of 87 weeks access time was awarded and delivered to the UK User community including 1 week to European Users throughout the year. A full breakdown of number of weeks applied for versus number of weeks scheduled is shown in Figure 1 indicating an oversubscription ratio of 2.36:1. Figure 3 shows that Biology and Bio-materials formed the majority of applications.

There were a total of 21 formal reviewed publications recorded throughout the year.

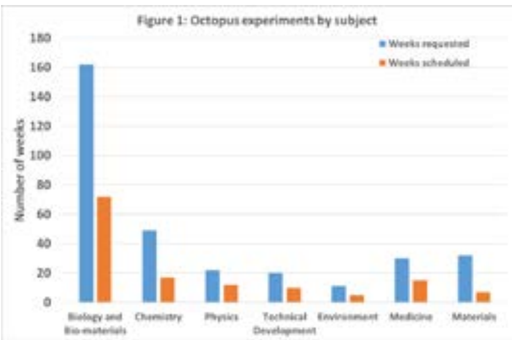
ULTRA facility

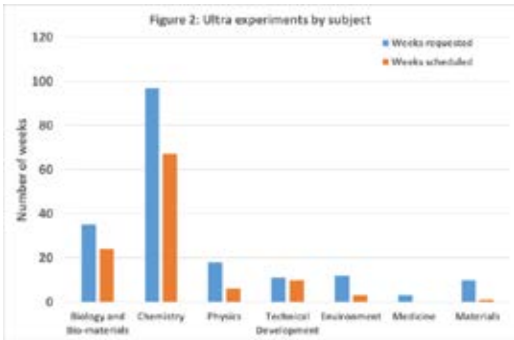
In the reporting period (April 2016 to March 2017), 30 unique User groups submitted a total of 41 proposals bidding for time at the Ultra facility. 28 experiments comprising of 73 weeks access time was awarded and delivered to the UK User community including 1 week to European Users throughout the year. A full breakdown of number of weeks applied for versus number of weeks scheduled is shown in Figure 2 indicating an oversubscription ratio of 1.50:1. Figure 4 shows that Chemistry formed the majority of applications.

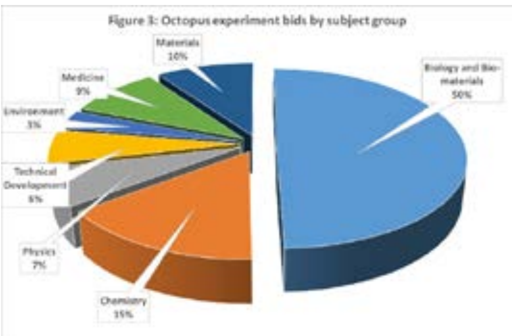
There were a total of 24 formal reviewed publications recorded throughout the year.

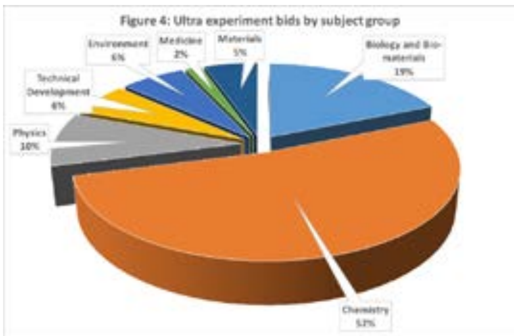
User satisfaction

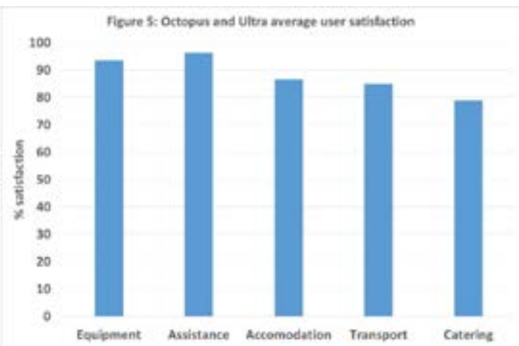
The average User satisfaction marks obtained from the scheduled Octopus and Ultra Users are shown in Figure 5, with an average satisfaction of 88.1% across the categories. There was a total of 337 hours downtime reported over the combined 160 weeks of access.











Contact: D.Clarke (dave.clarke@stfc.ac.uk)

Target Fabrication Operational Statistics

D. Haddock, C. Spindloe & M. K. Tolley *(Target Fabrication Group, Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, UK)*

RAL Experiments

This paper details Target Fabrication support given to experimental groups in the Vulcan target areas TAW and TAP, as well as the Gemini Target Area, between April 2016 and April 2017. Target Fabrication supported nine solid target Vulcan experiments and one solid target Gemini Experiment, totalling 50 weeks of Vulcan access (plus training weeks) and 6 weeks of Gemini access. Other Gemini experiments were also supported for filters and other diagnostic elements, which are non-trivial but not reported on in these statistics. The number of weeks supported is almost the same as last year (57), and lower than the 64 in 2014-15.

The Target Fabrication group also supported academic access experiments at AWE and internal experiments, such as the April 2017 HAMS campaign.

This report does not include support for other areas of the CLF, including Artemis and the LSF.

1) Target Numbers

For the reporting year, the total number of targets produced for each experiment is shown in Table 1. High specification targets are defined as targets that have taken significant staff research and development time, or have taken more than ten times as long to produce as a typical target.

The total number of targets supplied to target areas at RAL by the group this reporting year is 1546 compared to 2371 last reporting year, 1937 in 2014-2015, and 2507 in 2013-2014. Experiments in this period were not concentrated on foil type targets (which typically require high quantities) explaining the decrease. The number of high specification targets increased to 98 from 87 last reporting year, and 87 in 2014-2015. The number comprises 6% of the total targets delivered and is important because of its effect on staff workload.

Of particular note was the January 2017 period in which the TAW experiment required a significant number of targets to be delivered, with the total number of targets being the most ever delivered to a Vulcan experiment run. This experiment ran alongside an experiment in TAP that required significant characterisation support. The resource was able to be balanced due to the Target Fabrication Quality Management System (QMS), enabling streamlined and efficient processes.

The QMS enables the tracking of the targets delivered and also is used to record whether they were modified from the initial design during the run. The modification number is a useful metric, as it indicates the extra resources needed to support an experiment. For the reporting year, the number of modifications is shown in Table 1, recording targets that were delivered but not initially defined on the approved target list. The table includes modifications to designs or completely new requests during the campaign. It is important to note that the capability to change designs can often ensure experimental success and, consequently, understanding the required resource is important.

Experiment	Targets Produced	High Specification Targets	Modified Targets	
0616 TAW	198		152	77%
0816 TAW	158	38	80	51%
0816 TAP	68	30	47	69%
0916 TAW	63		1	2%
0916 TAP	150		116	77%
1116 TAW	97			
0117 TAP	153	20	83	54%
0117 TAW	403		82	20%
0217 GTA	150	10	26	
0317 TAP	106		26	24%
TOTAL	**1546**	**98 (6%)**	**587**	**38%**

Table 1: Target production summary for 2016-2017. High specification targets include 3D micro-structures, low density targets and mass limited targets. Modified targets are targets that were not in the pre-approved target list and are either modifications to approved designs or additional requests.

2) Experimental Response

It is seen as a significant strength of Target Fabrication to be rapidly responsive to experimental results and conditions by working collaboratively with user groups. The Target Fabrication group responds to experimental changes during a campaign, and often implements a number of modifications or redesigns to the original requests. The number of modifications and variations on each experiment is variable, dependent on the type of experiment and also on experimental conditions such as diagnostic and laser performance. For this reporting period, a total of 587 targets were modified or redesigned from the target list agreed in the planning stage which comprises 38% of the total targets delivered. In the last reporting year the percentage was 27.5% and the year prior to that the percentage modified was 25%. (It was 22% in 2013-2014.) This year there were five experiments that required significant modifications to their target requests (>50% modified targets), a rise from three in the previous year. This explains the increase in modified target numbers and can be attributed to increasing experimental complexity.

3) Target Categories

Targets can be separated into seven main categories, as shown in Figure 1 and Table 2.

Ultra-thin foil targets are specified as having a thickness <500nm and require a coating capability and a skilled fabricator to process; thick foils make up the rest of single component foils. Multilayer foils are stacks or layers of foils that require thin film coating capability to deposit multiple layers onto an existing foil; there are often different composition layers with different thicknesses. Alignment targets are specified as wires or pinholes that are used for set-up purposes. 3D micro-structures are complex 3D geometries that require skilled assembly or micro-machining to produce them. Foam targets are low density polymer structure manufactured through chemistry based techniques.

Target Category	2016-2017	2015-2016	2014-2015
Ultra-thin Foil	449	197	530
Thick Foils	743	1349	708
Multi-layered Foils	237	605	500
Alignment	78	110	85
3D Micro-structures	38	99	82
Foams	0	0	5
Mass-limited	0	11	0
TOTAL	**1546**	**2371**	**1937**

Table 2: Target category summary for the last 3 reporting years. 3D micro-structures are targets that require micromachining or skilled micro-assembly. Mass-limited targets are targets designed to have minimal support structures

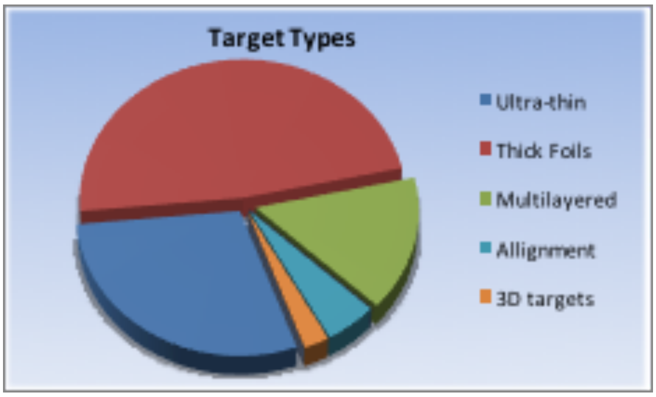


Figure 1: Targets delivered by type

It should be noted that Figure 1 is not a reflection of staff effort, because assembly time for a single thick foil target is relatively short, whereas for a batch of 3D targets, trials, manufacture and characterisation activities can amount to weeks of effort.

Single experiments generally require similar targets types usually with varying thickness, composition or geometry; for example, a thin foil experiment typically requests a thickness scan of a particular material. In such experiments, each thickness or composition change requires a separate coating run.

For experiments using 3D targets, each geometry change usually requires a new assembly set up. Within the total of 1546 targets there were 277 unique target variations, which averages 6 targets per variation. Last reporting year the average number of targets per variation was 7 (324 total) and the two years previous to this the average was 6. The flexibility provided by the group is a key capability of the CLF and enables the user community to fully utilize the limited time that is available during each experiment on both the Vulcan and Gemini laser systems.

4) Adapting to Demand

The Target Fabrication group endeavours to be adaptable to the changing demands of the experimentalists as experiments develop. Each experiment that is carried out often has widely varying target demands and as a result the group is constantly developing its capabilities.

For this and the previous two reporting years, foils have dominated the target types, comprising just over 75% of the targets delivered.

Ultra-thin and multilayer targets are reliant on coating plant capability and numbers are largely in line with the two previous years.

5) Waste Reduction

Unexpected delays or changes during an experiment often result in a number of targets that have been fabricated but that are not used by the end of experimental campaign. Un-shot targets in this reporting period totalled 154, accounting for 10% of the total targets made. Statistics for the return of un-shot targets in previous years are as follows: 2014-2015 12%; 2013-2014 16%; 2012-2013 19%; 2011-2012 43%; and 2010-2011 10%.

Any un-issued or returned targets are carefully sorted and high specification targets are stored under closely controlled conditions for potential use on future experiments. Where possible all spare target components and mounts are also stored for future use. The variety of mounts and components held in stock by the Target Fabrication group contributes to their ability to adapt target designs quickly in response to experimental changes.

There has been a noticeable reduction in waste since the complete implementation of the ISO9001 Quality Management System (QMS), which has allowed the Target Fabrication group to plan experimental delivery of targets in a more structured way. The improved planning processes enable long-term delivery projects to be managed effectively. It should be noted that this has not led to less flexibility, as the percentage of modified and re-designed targets is in line with the figures for before the implementation (2009-2010, 2010-2011).

Approximately 3% of targets were returned as non-conforming under the QMS in this reporting period. It should be noted that reporting will be improved because such targets are often recorded as "returned un-shot".

Orion Academic Access

The Target Fabrication Group has supplied targets to the AWE Orion academic access campaign for Strathclyde led consortium experiment on proton focusing. The collaboration included target supply from TUD and GA with design, assembly and target manufacture conducted by the CLF. A total of 41 complex targets were provided over two weeks of experiments. The targets were complex and required the implementation of a range of existing and new technologies including complex assembly integrated with real-time, high specification characterisation.

External Contracts

Scitech Precision Ltd (a spinout company from CLF Target Fabrication) has supplied micro-targets, specialist coatings and consultancy to a number of external contracts. In the year 2016-2017, a total of 150 contracts were completed including coatings, characterisation, full target design and assembly, and laser machining. Of the contracts, 32% were for laser machining which is an increase from the previous year, partly attributable to an increase in onsite support contracts. Scitech contracts were delivered to external facilities internationally including France, Germany, Italy, India and the US. In this reporting year Scitech Precision has supplied phase plates to LULI, LCLS and other large facilities.

Summary

Target Fabrication has supported ten experiments in the CLF and eleven other international facilities in the last year, as well as providing an increasing amount of characterisation services and acting as a knowledge base for Target Fabrication activities throughout Europe. This year has seen a total number of 56 weeks supported and a decrease in the total number of targets delivered to 1546. The decrease is mainly accounted for by a lower number of high repetition rate target experiments supported on Gemini. Generally, the type of targets has largely followed the same pattern over the past three years, with a large proportion being ultra-thin foils. The complexity of experiments was substantial with more high-specification targets than the previous two years. Also five experiments required more than half of the initial target requests to be modified.

Contact: D. Haddock (david.haddock@stfc.ac.uk)

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Panel Membership and CLF Structure

LASERS FOR SCIENCE FACILITY ACCESS PANEL 2016/17

REVIEWERS

Professor J. Molloy (Chair)
Francis Crick Institute, London

Dr S. Cox
Randall Division of Cell and Molecular Biophysics
King's College London

Professor C. Eggeling
The Weatherall Institute of Molecular Medicine
University of Oxford

Dr M. Frogley
Diamond Light Source

Professor M. Garcia Parajo
The Institute of Photonic Sciences
Barcelona

Dr N. Hunt
Department of Physics
University of Strathclyde

Dr M. Kuimova
Department of Chemistry
Imperial College London

Dr D. Mulvihill
School of Biosciences
University of Kent

Dr E. Nibbering
Max Born Institute
Germany

Dr S. Parrinello
MRC Clinical Sciences Centre
Imperial College London

Dr S. Pascu
Department of Chemistry
University of Bath

Professor M. Peckham
Faculty of Biological Sciences
University of Leeds

Dr S. Quinn
School of Chemistry and Chemical Biology
University College Dublin

Professor K. Vincent
Department of Chemistry
University of Oxford

Dr M. Volk
Department of Chemistry
University of Liverpool

Professor K. Wynne
School of Chemistry, WestCHEM
University of Glasgow

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Central Laser Facility
Science & Technology Facilities Council

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Central Laser Facility
Science & Technology Facilities Council

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Central Laser Facility
Science & Technology Facilities Council

Dr M. Martin-Fernandez (OCTOPUS Group Leader)
Central Laser Facility
Science & Technology Facilities Council

Dr P. Donaldson (Panel Secretary)
Central Laser Facility
Science & Technology Facilities Council

Dr Andrew Kaye
CLF User Office
Science & Technology Facilities Council

Dr E. Springate (Artemis Group Leader)
Central Laser Facility
Science & Technology Facilities Council

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Research Complex at Harwell

Professor L. Chapon (Physical Sciences Director)
Diamond Light Source

Dr E. Gozzard
Central Laser Facility
Science & Technology Facilities Council

ARTEMIS FACILITY ACCESS PANEL 2016/17

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Max Born Institute, Berlin

Professor M. Aeschlimann
University of Kaiserslautern, Germany

Professor S. Dhesi
Diamond Light Source

Professor H. Fielding
Department of Chemistry, Christopher Ingold Laboratories
University College London

Professor J. Marangos
Department of Physics, Blackett Laboratory
Imperial College London

Professor l. Perfetti
Laboratoire des Solides Irradies, Ecole Polytechnique Palaiseau Cedex

Professor A. Taleb-Ibrahimi
Synchrotron SOLEIL, L'Orme des Merisiers, France

Dr P. King
School of Physics and Astronomy
University of St. Andrews

RESEARCH COUNCIL REPRESENTATIVES

Mr R. Matthewman
EPSRC

Dr J. Scratcher
Science Programme Office

SCIENCE & TECHNOLOGY FACILITIES COUNCIL REPRESENTATIVES

Professor J. L. Collier (Director)
Central Laser Facility
Science & Technology Facilities Council

Ms C. Hernandez-Gomez (Head, High Power Laser Programme)
Central Laser Facility
Science & Technology Facilities Council

Dr E. Springate (Artemis Group Leader)
Central Laser Facility
Science & Technology Facilities Council

Dr C. Cacho (Artemis, Condensed Matter Physics)
Central Laser Facility
Science & Technology Facilities Council

Dr R. T. Chapman (Artemis, AMO and Imaging)
Central Laser Facility
Science & Technology Facilities Council

Dr D.T Clarke (Head of Laser for Science Facility)
Central Laser Facility
Science & Technology Facilities Council

Professor M Towrie (Molecular and Structural Dynamics)
Central Laser Facility
Science & Technology Facilities Council

VULCAN, ASTRA TA2 & GEMINI FACILITY ACCESS PANEL 2016/17

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Professor S. Rose (Panel Chair)
Blackett Laboratory,
Imperial College London

Professor T. Bell
Clarendon Laboratory
University of Oxford

Dr R. Kingham
Blackett Laboratory
Imperial College London

Professor S. Hooker
Clarendon Laboratory
University of Oxford

Professor P. McKenna
Department of Physics
University of Strathclyde

Professor D. Riley
Department of Pure and Applied Physics
Queen's University of Belfast

Professor M. Roth
Technische Universität Darmstadt
Darmstadt, Germany

Professor G. Tallents
York Plasma Institute
University of York

Professor M. Tatarakis
Department of Electronics
Technological Educational Institute of Crete

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Queen's University Belfast

RESEARCH COUNCIL REPRESENTATIVES

J. Kular
EPSRC

Dr L. Martin
EPSRC

Dr J. Scratcher
Science Programme Office

Mr C. Danson
AWE

SCIENCE & TECHNOLOGY FACILITIES COUNCIL REPRESENTATIVES

Professor J. L. Collier (Director)
Central Laser Facility
Science & Technology Facilities Council

Ms C. Hernandez-Gomez (Head, High Power Laser Programme)
Central Laser Facility
Science & Technology Facilities Council

Dr I. O. Musgrave (Vulcan Group Leader)
Central Laser Facility
Science & Technology Facilities Council

Mr R. J. Clarke (Experimental Science Group Leader)
Central Laser Facility
Science & Technology Facilities Council

Dr R. Pattathil (Gemini Group Leader)
Central Laser Facility
Science & Technology Facilities Council

Dr D. Symes (Gemini Target Area Section Leader)
Central Laser Facility
Science & Technology Facilities Council

Dr N. Booth (Panel Secretary)
Central Laser Facility
Science & Technology Facilities Council

Mr C. Spindloe
Scitech Precision

Dr A. Kaye
ISIS Neutron & Muon Source
Science & Technology Facilities Council

CENTRAL LASER FACILITY STRUCTURE