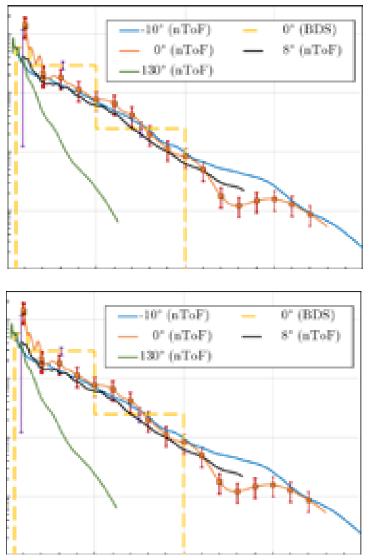
High Density Energy Science

High flux, beamed neutron sources employing deuteron-rich ion beams from D_2O-ice layered targets

S. Kar *(Centre for Plasma Physics, Queen's University Belfast, UK, Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
R.J. Clarke, J. Green, P. Norreys, M. Notley, M. Oliver *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
A. Alejo, H. Ahmed, A. Green, D. Jung, M. Zepf, M. Borghesi *(Centre for Plasma Physics, Queen's University Belfast, UK)*
Z. Najmudin, H. Nakamura *(Blackett Laboratory, Imperial College London, UK)*
A. Krygier, R.R. Freeman *(Department of Physics, Ohio State University, USA)*
J.T. Morrison *(Propulsion Systems Directorate, Ohio, USA)*
J. Fuchs, L. Vassura *(LULI-CNRS, France)*
A. Kleinschmidt, M. Roth *(Institut fur Kernphysik, TU Darmstadt, Germany)*

A bright, directional neutron source was produced by employing a laser-driven, deuteron-rich ion beam in a pitcher-catcher scenario. Au foils having a thin layer of D_2O ice at the rear side were irradiated by the petawatt arm of the Vulcan laser ($I\sim2\times10^{20}$ Wcm^{-2}), producing a deuteron-rich, proton-free ion source. Neutrons of maximum energy up to 40 MeV and peak flux ~2×10^9 n/sr were produced, preferentially emitted along the ion beam forward direction in a beam of ~70° (FWHM) cone. Simulations of the neutron generation via the d(d,n)^{3}He reaction considering the deuteron beam produced by the ice-layered targets is in a good-agreement with the experimental results.



Top: Neutron spectra, measured along different angles with respect to the laser axis, for the neutrons generated by a deuteron-rich ion source from an ice-layered target in a pitcher-catcher scenario. Bottom: Neutron beam profile experimentally measured by using a suite of neutron diagnostics (CR-39 nuclear track detector, neutron scintillators, and bubble detector spectrometers), compared to the numerical simulation of the neutron generation.

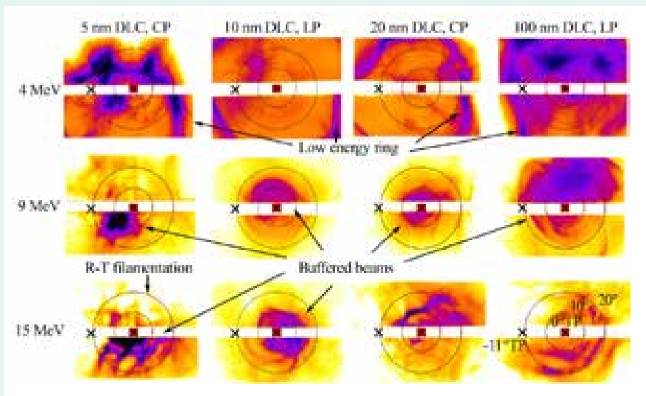
Contact: A.Alejo (aalejo01@qub.ac.uk)

Buffering and spectral control of protons accelerated from relativistically transparent thin foils

N. P. Dover, C. A. J. Palmer, M. J. V. Streeter, S. R. Nagel, Z. Najmudin *(The John Adams Institute for Accelerator Science, Imperial College London)*
H. Ahmed, K. F. Kakolee, S. Kar, R. Prasad, M. Zepf, M. Borghesi *(Centre for Plasma Physics, Queen's University Belfast)*
B. Albertazzi, M. Nakatsutsumi, J. Fuchs *(LULI, Ecole Polytechnique)*
D. C. Carroll, G. Scott, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK and SUPA Department of Physics, University of Strathclyde)*
D. A. MacLellan, P. McKenna *(SUPA Department of Physics, University of Strathclyde)*
R. Heathcote, M. M. Notley *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
P. Hilz, J. Schreiber *(Fakultat fur Physik, Ludwig-Maximilians-Universitat Munchen, and Max-Plack-Institut fur Quantenoptik)*
A. Kon, M. Tampo, R. Kodama *(Graduate School of Engineering, Osaka University)*

The generation of spectrally peaked ($\Delta E\sim4$ MeV, $E\sim8$ MeV), high charge (~50 nC) proton beams was measured from irradiation of ultra-thin carbon foils with the Vulcan Petawatt system [1]. A clear correlation was observed between the maximum carbon velocity and the proton spectral peak, indicating the protons are buffered ahead of the carbon species, preventing break up of the beam due to Rayleigh-Taylor-like instabilities. The beam divergence narrows down to ~8° with decreasing target thickness due to a space charge lens generated by pinched electrons in the relativistically transparent target.

[1] N. P. Dover et al., "Buffered high charge spectrally-peaked proton beams in the relativistic-transparency regime", New Journal of Physics 18, 013038 (2016).



Selected radiochromic film layers from stack diagnostic showing proton beam pattern at different energy bands for different target thicknesses. The low energy beam (top row) is dominated by an annular ring, whereas at high energy (middle/bottom row) a collimated beam appears along the laser axis.

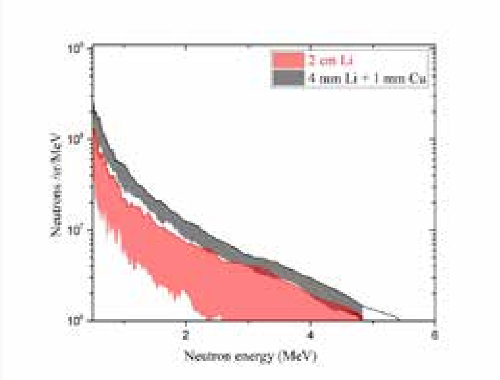
Contact: N. P. Dover (dover.nicholas@qst.go.jp)

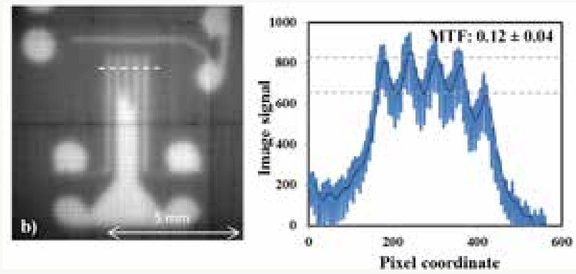
Laser-driven x-ray and neutron source development for industrial applications of plasma accelerators

C M Brenner, D R Rusby, C Armstrong, L A Wilson, R Clarke, D Haddock, A McClymont, M Notley, P Oliver, R Allott, C Hernandez-Gomez, D Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
S R Mirfayzi, H Ahmed, A Alejo, S Kar *(Centre for Plasma Physics, Queen's University Belfast)*
N M H Butler, A Higginson, P McKenna *(Department of Physics, SUPA, University of Strathclyde)*
C Murphy *(York Plasma Institute, University of York)*

Pulsed beams of energetic x-rays and neutrons from intense laser interactions with solid foils are promising for applications where bright, small emission area sources, capable of multi-modal delivery are ideal. Possible end users of laser-driven multi-modal sources are those requiring advanced non-destructive inspection techniques in industry sectors of high value commerce such as aerospace, nuclear and advanced manufacturing.

We report on experimental work that demonstrates multi-modal operation of high power laser-solid interactions for neutron and x-ray beam generation. Measurements and Monte Carlo radiation transport simulations show that neutron yield is increased by a factor ~2 when a 1 mm copper foil is placed behind a 2 mm lithium foil, compared to using a 2 cm block of lithium only. We also explore x-ray generation and demonstrate imaging using a novel active detector with a 10 picosecond drive pulse in order to tailor the spectral content for radiography with medium density alloy metals.





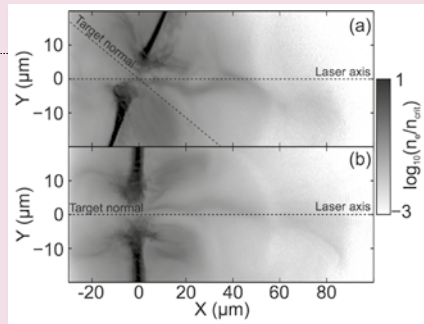
Top: Measured neutron spectra for the two convertor designs, showing an enhancement in the neutron flux when a 4mm Li + 1mm Cu convertor is used compared to a bulk (2 cm) Li convertor. Bottom: Radiograph of a 5 mm thick tungsten plate wire cut with 200 micron width slits imaged using the CsI active detector under high magnification alongside a line profile of the area indicated by the dashed line used to calculate the modulation transfer function (MTF) of the image.

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

Ion acceleration and plasma jet formation in ultra-thin foils undergoing expansion and relativistic transparency

M. King, R. J. Gray, H. W. Powell, D. A. MacLellan, B. Gonzalez-Izquierdo, D. R. Rusby, H. Padda, P. McKenna, D. Neely *(SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)*
L. C. Stockhausen, R. Torres *(Centro de Laseres Pulsados (CLPU), Parque Cientifico, Salamanca, Spain)*
G. S. Hicks, N. P. Dover, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
D. R. Rusby, D. C. Carroll, R. J. Clarke, I. O. Musgrave, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, UK)*
S. Kar, M. Borghesi *(Centre for Plasma Physics, Queens University Belfast, UK)*

During the interaction of an ultra-intense laser pulse with an ultra-thin solid density target, the rapid heating to relativistic velocities and resulting decompression of plasma electrons can result in the target becoming relativistically transparent to the laser light. Within this regime, ion acceleration can be strongly affected by the transition from an opaque to a relativistically transparent plasma. Through the experimental measurement of the laser-accelerated proton beam at both near-normal laser incidence and at an incidence angle of 30, and through detailed particle-in-cell simulations, we identify characteristics which are consistent with the onset of three distinct ion acceleration mechanisms: sheath acceleration; radiation pressure acceleration; and transparency-enhanced acceleration. This latter acceleration mechanism, which occurs late in the interaction, is induced by the formation of a plasma jet propagating through the expanding ion population. The impact of laser incident angle on the formation of this plasma jet is investigated.



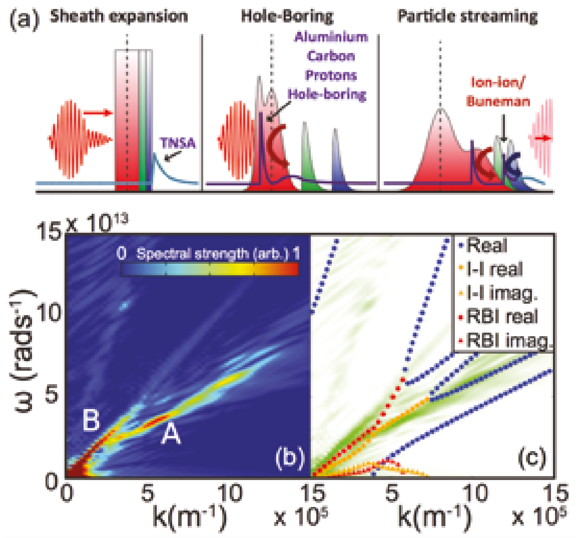
2D Simulation results showing electron density for a target initialised at (a) 0° and (b) 30° incident angle to the laser at an example time of 0.3 ps after the peak of the laser pulse has reached the target surface.

Contact: M. King (m.king@strath.ac.uk)

Energy exchange via multi-species streaming in laser-driven ion acceleration

M. King, R. J. Gray, H. W. Powell, R. Capdessus, P. McKenna
(SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)

Throughout the interaction of an ultra-intense laser pulse with a thin foil, a variety of complex collective electron dynamics and multiple ion acceleration mechanisms can occur. This can lead to a multitude of charged particle populations overlapping spatially with differing momentum distributions. For certain scenarios, it is possible for this behaviour to induce streaming instabilities such as the relativistic Buneman instability and the ion-ion acoustic instability. Through the use of particle-in-cell simulations, the potential for these instabilities to grow and evolve is demonstrated. Energy-exchange via the ion-ion acoustic instability can occur between ion species if a population of ions can be accelerated to achieve sufficient momentum such that it can propagate through other more slowly expanding ion populations.



(a) Schematic illustrating the three-stages of the forward-directed ions of a 1D laser-acceleration simulation. (b) Spectral power from the 1D simulation as a function of frequency and wavenumber during the particle streaming stage (c) Analytic solutions to the combined dispersion relation for the ion-ion acoustic instability (I-I) and relativistic Buneman instability (RBI) for the averaged electron and ion densities and momentum over the same period as (b).

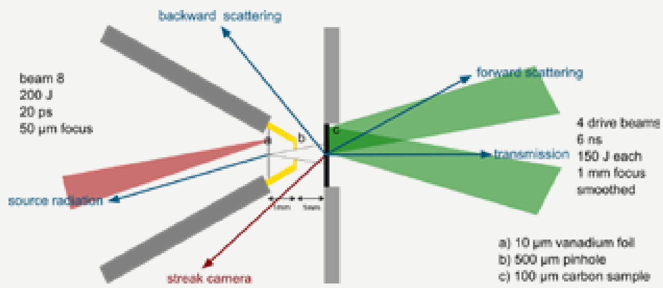
Contact: M.King (m.king@strath.ac.uk)

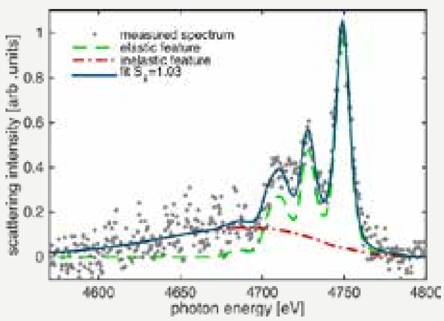
The complex ion structure of warm dense carbon measured by spectrally resolved x-ray scattering

D. Kraus *(Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstr. 400, 01328 Dresden, Germany)*
J. Helfrich, A. Ortner, M. Roth *(Technische Universität Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt, Germany)*
N. Hartley, G. Gregori (University of Oxford, Parks Road, Oxford, OX1 3PU, UK)
B. Kettle, D. Riley *(Queen's University of Belfast, University Road, Belfast, BT7 1NN, UK)*
D. C. Carroll, M. M. Notley, C. Spindloe *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*

An improved understanding of carbon in the warm dense matter (WDM) regime has motivated an increasing number of experimental and theoretical studies, mainly driven by particular problems in planetary physics and inertial confinement fusion.

At CLF, we have performed measurements of the complex ion structure of warm dense carbon close to the melting line at pressures around 100 GPa. High-pressure samples were created by laser-driven shock-compression of graphite and probed by intense laser-generated x-ray sources with photon energies of 4.75 keV and 4.95 keV. High-efficiency crystal spectrometers allow for spectrally resolving the scattered radiation. Comparing the ratio of elastically and inelastically scattered radiation, we find evidence for a complex bonded liquid that is predicted by ab initio quantum simulations showing the influence of chemical bonds under these conditions. Using graphite samples of different initial densities, we demonstrate the capability of spectrally resolved x-ray scattering to monitor the carbon solid-liquid transition at relatively constant pressure of 150 GPa.





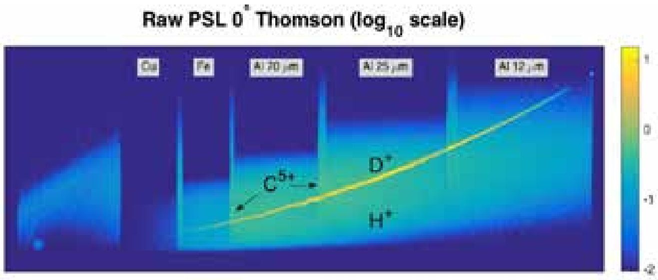
Top: Schematic of the experimental setup at Target Area West. Bottom: Spectrally resolved x-ray scattering from a carbon sample that was driven to a liquid state.

Contact: D. Kraus (d.kraus@hzdr.de)

Selective deuterium ion acceleration using the Vulcan Petawatt laser

AG Krygier *(Laboratoire pour l'Utilisation des Lasers Intenses, École Polytechnique; Physics Department, The Ohio State University)* ,
JT Morrison *(Physics Department, The Ohio State University; Propulsion Systems Directorate, Air Force Research Lab)*
S Kar, H Ahmed, A Alejo, A Green, D Jung *(Centre for Plasma Physics, School of Mathematics and Physics, Queens University Belfast)*
R Clarke, M Notley *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
J Fuchs *(Laboratoire pour l'Utilisation des Lasers Intenses, École Polytechnique)*
A Kleinschmidt, M Roth *(Institut für Kernphysik, Technische Universität Darmstadt)*
Z Najmudin, H Nakamura *(Blackett Laboratory, Department of Physics, Imperial College)*
P Norreys *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK; Department of Physics, University of Oxford)*
M Olivier *(Department of Physics, University of Oxford)*
L Vassura *(Laboratoire pour l'Utilisation des Lasers Intenses, École Polytechnique)*
M Zepf *(Centre for Plasma Physics, School of Mathematics and Physics, Queens University Belfast; Helmholtz Institute Jena)*
M Borghesi *(Centre for Plasma Physics, School of Mathematics and Physics, Queens University Belfast; Institute of Physics of the ASCR, ELI-Beamlines Project)*
RR Freeman *(Physics Department, The Ohio State University)*

We report on the successful demonstration of selective acceleration of deuterium ions by target-normal sheath acceleration (TNSA) with a high-energy petawatt laser. TNSA typically produces a multi-species ion beam that originates from the intrinsic hydrocarbon and water vapor contaminants on the target surface. An ion beam with >99% deuterium ions and peak energy 14 MeV/nucleon is produced with a 200 J, 700 fs, $>10^{20}$ W/cm^2 laser pulse by cryogenically freezing heavy water (D_2O) vapour onto the rear surface of the target prior to the shot. Within the range of our detectors (0°–8.5°), we find laser-to-deuterium-ion energy conversion efficiency of 4.3% above 0.7 MeV/nucleon while a conservative estimate of the total beam gives a conversion efficiency of 9.4%.



Raw Thomson parabola spectrometer data. The bright yellow line is the deuterium ion trace; a faint proton trace is also seen below; C ions are also present in the gaps of the heavy ion filters. The ratio of deuterium ions to protons is in excess of 99.9% demonstrating practically complete annihilation of the proton beam while achieving a bright deuterium ion beam.

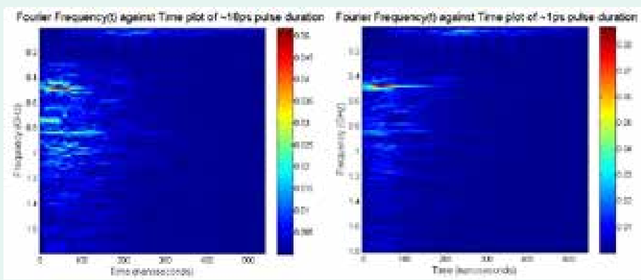
Contact: A.G Krygier (krygier1@llnl.gov)

Effects of Pulse Duration, Energy and Target Type on the frequencies of Electromagnetic Pulses in a Petawatt laser system

M.E. Read, D.C. Carroll, M.P. Bone
(Central Laser Facility, STFC Rutherford AppletonLaboratory, UK)
D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK; SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)*

High powered laser-target interactions emitting Electromagnetic Pulses (EMP) has been an ongoing problem for laser systems such as Vulcan. Previous work has demonstrated that charged particles accelerated during the laser pulse draw a large return current from ground and into the target. These currents can generate bursts of EMP, with some measurements showing 2 main modes around 59 and 63MHz in Vulcan Petawatt. In this work the effect of laser pulse duration, energy and target type on the frequency of EMP was measured. A combination of B-dot, D-dot and Moebius loop detectors were used to obtain the data.

A wide range of responses and effects in the frequency modes of the EMP was found when changing the pulse duration, energy and target type. When lengthening the pulse duration there was a significant rise in the range of frequency modes seen. By increasing the energy of the pulse by an order of magnitude, we observed a large rise in the intensity and spectrum of frequencies. Changing to a trimmed target type decreased the EMP frequency intensity, although there are still traces of common frequency modes between the standard and trimmed target types.



Comparison of the 1 ps pulse (Right) and the 18ps pulse (Left) using a Nyquist Fourier Transform Program

Contact: M. Read (margaret.read@stfc.ac.uk)

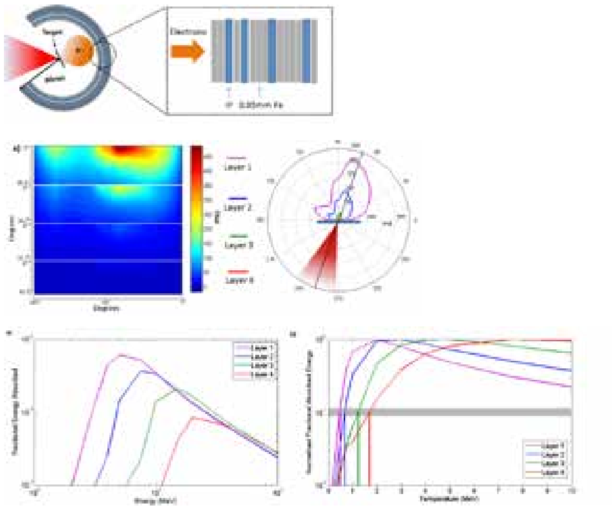
Measurement of the Angle, Temperature and Flux of Fast Electrons Emitted from Intense Laser-Solid Interactions

D. R. Rusby, L. A. Wilson, G. G. Scott, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
R. J. Gray, R. J. Dance, N. M. H. Butler, D. A. MacLellan, P. McKenna *(SUPA Department of Physics, University of Strathclyde, Glasgow)*
V. Bagnoud, B. Zielbauer *(PHELIX Group, Gesellschaft fur Schwerionenforschung, Darmstadt)*

High-intensity laser-solid interactions generate relativistic electrons, as well as high-energy (multi-MeV) ions and x-rays. The directionality, spectra and total number of electrons that escape a target-foil is dependent on the absorption, transport and rear side sheath conditions. Measuring the electrons escaping the target will aid in improving our understanding of these absorption processes and the rear-surface sheath fields that retard the escaping electrons and accelerate ions via the Target Normal Sheath Acceleration (TNSA) mechanism.

A comprehensive Geant4 study was performed to help analyse measurements made with a wrap-around diagnostic that surrounds the target and uses differential filtering with a FUJI-film image plate detector. The contribution of secondary sources such as x-rays and protons to the measured signal have been taken into account to aid in the retrieval of the electron signal. Angular and spectral data from a high-intensity laser-solid interaction are presented and accompanied by simulations. The total number of emitted electrons has been measured as 2.6×10^{13} with an estimated total energy of 12±1J from a 100µm Cu target with 140J of incident laser energy during a 4×10^{20} W/cm^2 interaction.

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



Top: Schematic of the diagnostic arrangement of Fuji BAS-TR Image Plate (IP) between 0.85mm Fe filter. Middle: The fractional absorption in the IP layers from mono-energetic electrons incident onto the array of Fe filters as a function of energy. Bottom: PSL signal from the remapped layers of IP between the Fe filtering from a 140J shot onto a 100µm Cu target and its corresponding polar plot.

Optimization of plasma mirror reflectivity and optical quality using double laser pulses

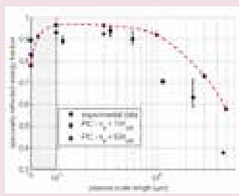
G.G. Scott *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK; SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)*
V. Bagnoud, C. Brabetz, B. Zielbauer *(PHELIX group, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany)*
R.J. Clarke, J.S. Green, R.I. Heathcote *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
H.W. Powell, P. McKenna *(SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)*
T.D. Arber *(Department of Physics, University of Warwick, Coventry, UK)*
D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK; SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)*

Experimentally we have measured a specularly reflected energy fraction of 96% from a plasma mirror interaction, which was achieved by introducing a density scale length on the plasma mirror surface prior to the main pulse interaction. Experimentally, for a 1.054 µm wavelength laser, this scale length was estimated to be 0.1-0.3 µm, and this yields excellent agreement with particle-in-cell modelling that shows that absorption is minimised in scale lengths of preplasma of this order.

Further than this, an analytical model of the plasma mirror optical quality from interaction with a non-homogeneous preplasma is developed. This provides the understanding for control of the plasma mirror optical quality when fielded in the reflectivity enhancing regime. This again gives excellent agreement with experimental measurements, which show very good optical quality to be achieved in the regime where optimal reflectivity is achieved.

Contact: G.G. Scott (graeme.scott@stfc.ac.uk)
D. Neely (david.neely@stfc.ac.uk)

In this proof of principle experiment the preplasma was introduced by a collinear prepulse prior to the main pulse arrival. By triggering a plasma expansion on the plasma mirror surface using a non-collinear prepulse, a high reflectivity, high optical quality, contrast enhancing plasma mirror is a realisable and attractive optical component compared with the highly inefficient plasma mirror arrangements fielded until present.

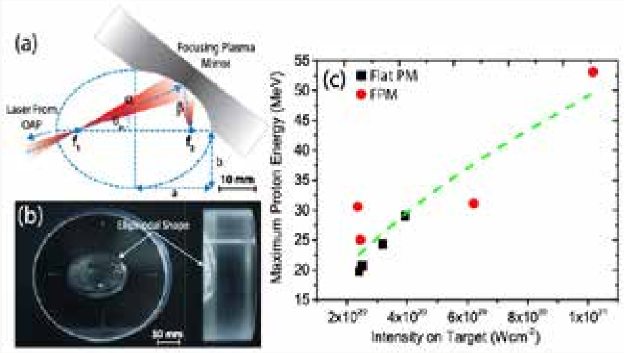


The figure shows the experimentally measured plasma mirror reflectivity for the main pulse interaction, neglecting any contributions from the controlled prepulse, as a function of preplasma scale length. This is compared to the reflectivity measured in 1D collisional PIC modelling, which is shown for two maximum electron densities. Both clearly show an optimisation of the reflectivity for a finite scale length, and the full article provides the physical interpretation for these results.

Ellipsoidal plasma mirror focusing of high power laser pulses to ultra-high intensities

R. Wilson, M. King, R. J. Gray, R. J. Dance, P. McKenna
(SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK)
C. Armstrong, D. Neely *(SUPA/Dept of Physics, University of Strathclyde, Glasgow, UK; Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
D. C. Carroll, S. J. Hawkes, R. J. Clarke,
(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)
D . J. Robertson *(Dept of Physics, Durham University, Durham, UK)*

This paper reports on the development of a small F-number focusing plasma mirror (FPM) capable of increasing the peak intensity achievable on the Vulcan-PW laser system. A factor of 2.5 reduction in focal spot size is achieved, compared to F/3 focusing using a conventional (solid state) optic, indicating a ×3.6 enhancement in peak intensity, accounting for changes in optic reflectivity and focal spot quality. An example use of the FPM in an investigation of laser-driven proton acceleration is demonstrated. An increase in the peak laser intensity from 3×10^{20} Wcm^{-2} to 10^{21} Wcm^{-2} is found to produce a factor of 2 increase in the maximum energy of sheath-accelerated protons from a thin foil positioned at the optic focus. This finding is consistent with sheath-acceleration intensity scalings. This study helps to bring plasma-based optical technology closer to maturity, with the aim of enabling the exploration of ultra-intense laser-plasma phenomena.



(a) Illustration of ellipsoidal focusing plasma mirror (FPM) concept. (b) Image of the manufactured FPM. (c) Plot of the max. proton energy achieved using either a FPM or flat PM.

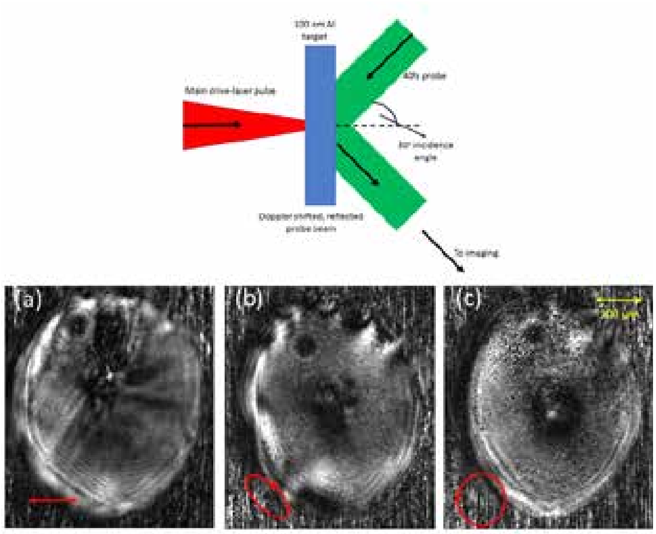
Contact: R. Wilson (robbie.wilson@strath.ac.uk)

Dependence of target-rear-surface transverse plasma expansion on laser polarisation

N. M. H. Butler, R. J. Gray, R. Wilson, M. King, B. Gonzalez-Izquierdo, R. J. Dance, J. McCreadie, P. McKenna *(Department of Physics, SUPA, University of Strathclyde, Glasgow, UK)*
J. S. Green, S. Hawkes, D. C. Carroll, N. Booth, D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
M. Borghesi *(Centre for Plasma Physics, Queen's University Belfast, Belfast, UK)*

The dynamics of plasma electrons in ultrathin foil targets irradiated by intense (~6 x 10^{20} W/cm^2) laser fields is investigated experimentally. Through the use of optical probing techniques, the reflectivity of the rear surface of a target during a laser-foil interaction was characterised, enabling the target heating and plasma formation to be diagnosed, including observations of the lateral expansion of plasma.

Through variation of the laser optical polarisation incident on target, it is shown that plasma expansion is sensitive to the initial laser polarisation. Furthermore, we have observed that the lateral plasma velocity on the rear-surface of the target greatly increased when linearly polarised light was incident on the target front side.



(Top) Schematic of the experimental set-up.
(Bottom) Raw probe images of the target rear-surface for targets irradiated by (a) linear, (b) elliptical, and (c) circular polarised laser pulses. Images taken 3ps after main pulse arrived at the target.

Contact: N. M. H. Butler (Nicholas.butler.2014@uni.strath.ac.uk)

High resolution imaging of embryonic mouse samples with a laser-driven betatron x-ray source

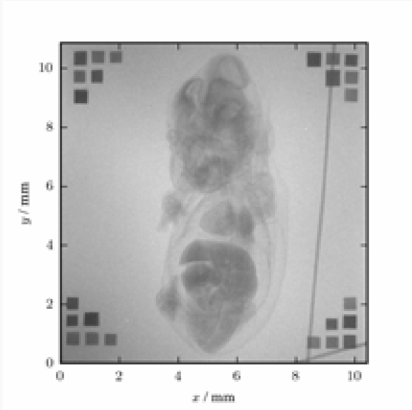
J. M. Cole, K. Poder, N. C. Lopes, J. C. Wood, S. Alatabi, C. Kamperidis, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
D. P. Norris, J. Sanderson, L. Teboul, H. Westerberg, M. Sandholzer, S. Johnson, Z. Szoke-Kovacs *(Mammalian Genetics Unit, MRC Harwell, Harwell Campus, UK)*
M. A. Hill, M. De Lazzari, J. Thomson *(CRUK/MRC Oxford Institute for Radiation Oncology, University of Oxford, Oxford, UK)*
D. R. Symes, D. Rusby, P. S. Foster, S. Botchway, S. Gratton *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
C. A. J. Palmer, O. Kononenko *(Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany)*
J. R. Warwick, G. Sarri *(Centre for Plasma Physics, Queen's University Belfast, Belfast, UK)*

A radiographic imaging beamline was constructed around a laser wakefield-driven betatron x-ray source at the Gemini laser facility. Laser-wakefield acceleration is a compact plasma-based electron acceleration technique, capable of the production of GeV energy electron beams in an acceleration length of a few centimetres. The x-rays radiated by this electron beam are highly suitable for imaging purposes, investigated in this experiment through the radiography of embryonic mouse samples.

The x-ray source was found to be energetically stable to within 6% over hundreds of laser shots, with a characteristic energy of 18 keV. The average x-ray photon flux was above 10^6 photons/second/mrad^2, significantly brighter than laboratory-scale x-ray sources of similar resolution. This high flux facilitated the acquisition of hundreds of 2D radiographs in a short period.

The images were of high spatial resolution and signal-to-noise ratio, and represent an important step towards the routine application of laser-driven x-ray sources for preclinical imaging purposes.

Contact: J. M. Cole (j.cole11@imperial.ac.uk)



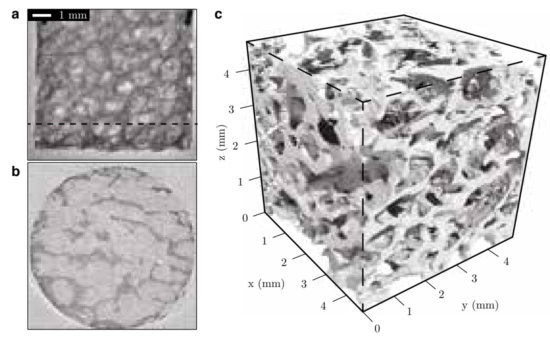
An exemplary radiograph of the mouse sample. Detector non-uniformities have been subtracted and hot pixels removed with a 3 x 3 median filter. The image has not been corrected for x-ray beam inhomogeneity, and so is indicative of the spatial profile of the x-ray beam during the experiment. The squares in each corner are elemental filters for the on-shot transmission spectroscopy, and the thin wires act as fiducials to account for the source motion.

Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone

J. M. Cole, J. C. Wood, N. C. Lopes, K. Poder, S. Alatabi, J. S. J. Bryant, S. Kneip, K. Mecseki, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Imperial College London, UK)*
R. L. Abel *(Department of Surgery and Cancer, MSk Laboratory, Imperial College London, UK)*
A. Jin *(Department of Mechanical Engineering, City and Guilds Building, Imperial College London, UK)*
D. R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*

A bright µm-sized source of hard synchrotron x-rays (critical energy E_{crit} > 30 keV) based on the betatron oscillations of laser wakefield accelerated electrons has been developed. The potential of this source for medical imaging was demonstrated by performing micro-computed tomography of a human femoral trabecular bone sample, allowing full 3D reconstruction to a resolution below 50 µm. The use of a 1 cm long wakefield accelerator means that the length of the beamline (excluding the laser) is dominated by the x-ray imaging distances rather than the electron acceleration distances. The source possesses high peak brightness, which allows each image to be recorded with a single exposure and reduces the time required for a full tomographic scan. These properties make this an interesting laboratory source for many tomographic imaging applications.

Contact: J. M. Cole (j.cole11@imperial.ac.uk)



Tomographic reconstruction of trabecular bone sample: a, A raw image of the bone sample recorded on the x-ray camera. b, 2D reconstruction of a one-pixel high horizontal slice of the sample at the position indicated in a). c, Stacking together 1300 such slices generates a 3D voxel map of the bone sample. An isosurface marking the detailed structure of the bone surface is constructed, rendered using a ray-tracing method.

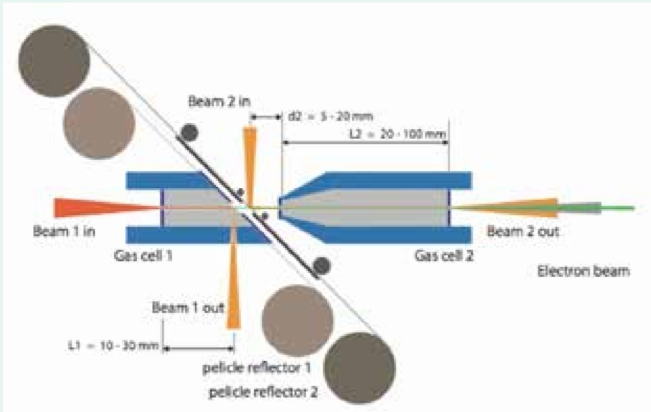
Modelling of a Plasma Mirror for a Laser Plasma Wakefield Staging Experiment

J.-N. Gruse, R. A. Watt, K. Poder, N. C. Lopes, S. Rozario, A. Sahai, J. C. Wood, J. M. Cole, S. P. D. Mangles and Z. Najmudin
(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London)

The particle-in-cell EPOCH code was used to simulate the reflection of a high intensity laser pulse, ~2×10^{18} Wcm^{-2}, corresponding to the Gemini laser pulse with a f/40 focusing parabola, from a 25 μm thick Kapton® tape featuring a preplasma formed by the laser pedestal. This is of interest for staging two gas cells in laser plasma wakefield acceleration to overcome the energy limitations due to depletion of the laser.

The tape was set 10 – 20 mm in front of the focal plane and the pre-plasma interaction was simulated with the hydrodynamics code FLAS. The resulting density distributions were used as inputs for EPOCH simulations to investigate the reflectivity of the s-polarised laser pulse off the tape for different tape positions. Additionally, an exemplary p-polarisation reflection was simulated to show the expected increased energy loss. It is found that reduced pre-ionisation results in higher reflectivity.

Contact: J.-N. Gruse (j.gruse16@imperial.ac.uk)



Staging two gas cells in laser plasma wakefield acceleration to overcome energy limitations.

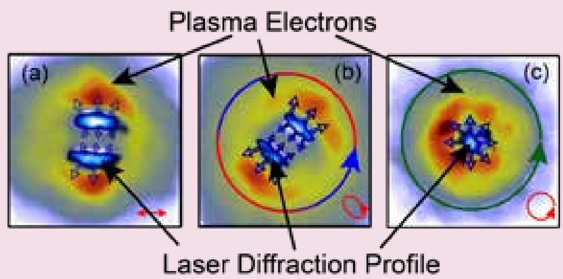
Optically controlled dense current structures driven by relativistic plasma aperture-induced diffraction

B. Gonzalez-Izquierdo, R. J. Gray, M. King, R. J. Dance, R. Wilson, J. McCreadie, N. M. H. Butler, R. Capdessus (*SUPA Department of Physics, University of Strathclyde, Glasgow, UK*), **S. J. Hawkes, J. S. Green** *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*, **M. Borghesi** *(Centre for Plasma Physics, Queens University Belfast, Belfast, UK)*
D. Neely *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK; SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*
and Paul McKenna *(SUPA Department of Physics, University of Strathclyde, Glasgow, UK)*

In this work we show that an ultraintense laser pulse induces a 'relativistic plasma aperture' in a thin foil, and as a result undergoes the fundamental optic process of diffraction. Numerical investigations demonstrate that the plasma electrons collectively respond to the resulting laser near-field diffraction pattern (including angular frequency of rotation), producing a beam of energetic electrons with a spatial structure that can be controlled by variation of the laser pulse polarisation (see figure). The predicted electron-beam distributions are verified experimentally using the Gemini laser.

It is also shown that static electron-beam and induced-magnetic-field structures can be made to rotate at fixed or variable angular frequencies depending on the degree of ellipticity in the laser polarization. This new insight into relativistic transparency and charged particle dynamics is important for a wide variety of applications, including ion and radiation source development.

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



(a) 2D (Y-Z) plane showing laser light intensity and electron density for linear laser polarisation.

The hollow arrows illustrate the direction of the ponder-omotive force arising from the gradients in laser intensity. (b), same for elliptical polarisation. (c), same for circular polarisation.

Plasma wakefield diagnostics with oblique crossing angle probe

M. F. Kasim*, L. Ceurvorst*, J. Sadler, N. Ratan, A. Ross, A. Savin, J. Holloway, P. N. Burrows, P. A. Norreys *(Clarendon Laboratory, University of Oxford, Parks Road, UK)*
K. Glize, D. Symes, N. Bourgeois, R. Trines, R. Bingham, R. Pattathil
(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)
F. Keeble, M. Wing *(University College London, Gower Street, London,UK)*
**authors contributed equally*

In this work, we present an experimental result from TA2 on capturing wakefields. The diagnostic was performed by sending a laser pulse as a probe crossing the wakefield at an oblique angle. This makes it possible to capture the wakefield at a certain position in plasma. Picture of modulations with similar wavelength with plasma wakefields are shown in the report. This experiment serves as a proof-of-concept of plasma wakefield diagnostics in a long plasma column and evolving wakefield, as in AWAKE experiment.

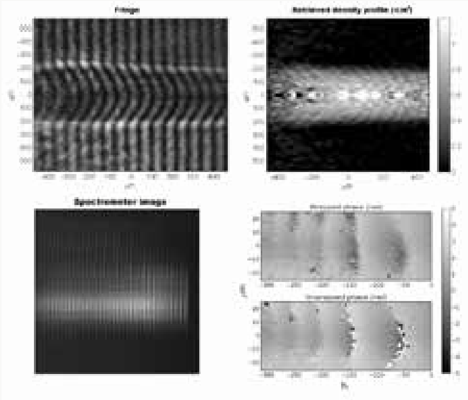


Figure 1. (Top, left) Mach-Zehnder interferometer result on the plasma density profile diagnostic. The modulation at the axis position in Figure (top, right) is due to the singularity near the axis in Abel inversion.
(Bottom, left) The spectrometer image of the spectral interferometry by the oblique angle probe pulses. (Bottom, right) The retrieved wrapped and unwrapped phase modulation when the plasma was present.

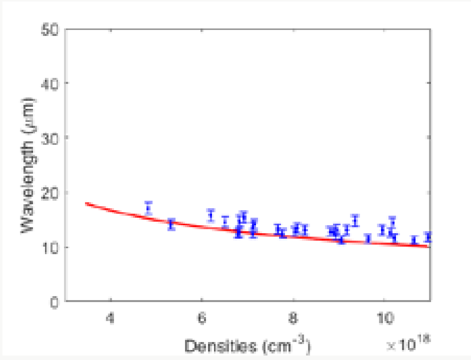


Figure 2. Plot of wakefield wavelengths against the plasma densities. The red line shows the theoretical wavelength.

Contact: M. F. Kasim (m.kasim1@physics.ox.ac.uk)

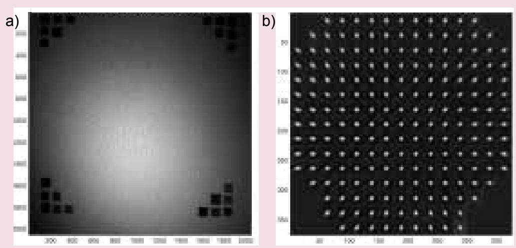
Measurement of the LWFA Betatron source length by cross-correlations over images of granular random targets

N. C. Lopes *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, SW7 2AZ, UK and GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, U.L., Lisboa 1049-001, Portugal)*
J.M. Cole, K. Poder, J. C. Wood, S. Alatabi, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
D. J. Chapman, M. E. Rutherford, D. Eakins
(Institute of Shock Physics, Imperial College London,UK)
D. R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*

Electron beams being accelerated in laser driven plasma waves have micron size radial oscillations resulting in a forward flash of betatron radiation. In large laser systems like Gemini, it becomes very bright (>10^{12} photons per pulse), energetic (hard x-rays) and can be used for time resolved high-quality x-ray microscopy in absorption or phase-contrast.

A new method to characterize these x-rays beams was tested using Gemini. The blurring of an image of a random granular target (we used sand paper) is analysed and used to measure x-ray emission length and beam direction. The random but regular pattern of the target allows the image blurring to be mapped by autocorrelation of small samples of the image, and the emission length to be inferred. This diagnostic can be used to measure the blurring due to source length of a beamline in a single shot and to optimize the beamline for imaging with a reduced number of shots.

Contact: N. C. Lopes (n.carreira-lopes@imperial.ac.uk)

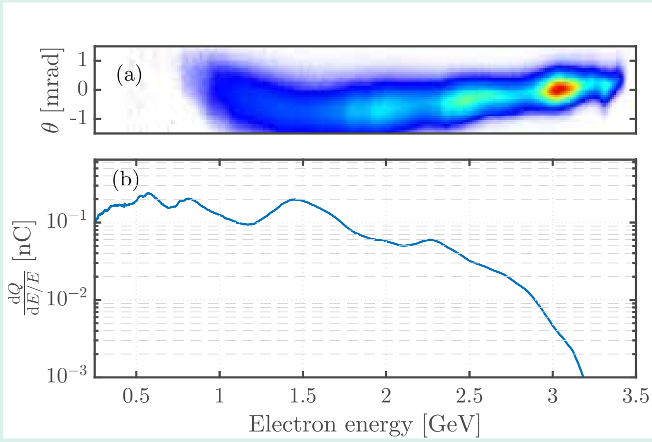


a) imaging of random granular target used to measure the blurring introduced by the x-ray emission length. b) montage of the image sample autocorrelations. We can see the autocorrelation in the centre of the beam presents a round shape corresponding to approximately the point spread function of the detector, but it becomes elongated with increasing radius due to the effect of the emission source length. This image is the extreme case for easy visualization of the effect. Using this diagnostic it is possible to optimize the beamline so this effect becomes negligible.

Enhancement of laser wakefield acceleration generated electron beam energies on Gemini by employing f/40 focusing

K. Poder, J. C. Wood, N. Lopes, S. Alatabi, J. M. Cole, C. Kamperidis, A. Sahai, S. P. D. Mangles, Z. Najmudin
(The John Adams Institute for Accelerator Science, Imperial College, London, UK)
P. S. Foster, D. Rusby, D. R. Symes
(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)
O. Kononenko, C. A. J. Palmer
(Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany)
J. R. Warwick, G. Sarri *(Queen's University Belfast, Belfast,UK)*

Experimental electron acceleration results from the 250TW Gemini laser system are presented. Driven by scalings for maximum energy gain in a single stage laser wakefield accelerator, an extended focusing geometry comprising of an f/40 spherical mirror was implemented. The new focal geometry allowed for maximum electron beam energies to be increased beyond 2 GeV; the peak beam energies were measured to be more than doubled compared to the previously used f/20 focusing geometry. Three-dimensional particle-in-cell simulations were performed to understand the increased energy gain. The simulations reveal that the increased energy gain is caused by very smooth self-focusing dynamics resulting from a large initial laser spot size. This leads to much less wake evolution, allowing the self-injected electrons to remain near the regions with the highest accelerating field for much longer.



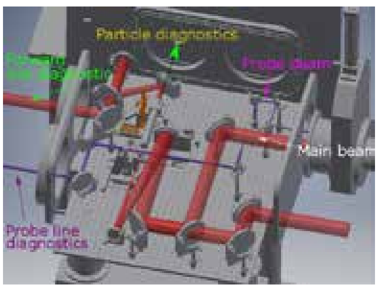
High-energy electron beam measured with the f/40 focusing geometry. Panel (a) shows the raw data, highlighting the beam's very narrow (~1 mrad) divergence. The electron beam spectrum is plotted in Panel (b), emphasizing the multi-GeV energy scale acceleration.

Contact: K. Poder (k.poder12@imperial.ac.uk)

Investigating the effects of clustering in a laser wakefield accelerator

S. V. Rozario, E. Gerstmayr, J. M. Cole, N. Lopes, K. Poder, J. C. Wood, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
L.Wilson, D, Rusby, E. Zemaityte, D. Neely, D. R. Symes, N. Booth, N. Bourgeois, O. Chekhlov, S. Hawkes, C. Hooker, R. Pattathil *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
S. Dorking, D. Lockley, G. Cook, R. Deas
(DSTL Innovations, Porton Down, Salisbury, Wiltshire, UK)

This report examines a new injection mechanism involving the ionization of clusters to generate electron beams in a self-guided laser wakefield accelerator. The experiment was performed using the Gemini (TA2) laser, which delivers 500 +/- 50 mJ, 45 +/- 5 fs into a 15 micrometre spot using an f/17 focusing geometry as can be seen in Figure 1. A cluster is a collection of small atoms or molecules which are locally at solid density. Methane readily clusters at room temperature in a gas jet and was chosen as the target gas for this experiment. The charge of the generated electron beam is observed to be greater by a factor of up to 2 on the beam profile monitor (Figure 2a) and up to 35 times on the electron spectrometer (Figure 2c). This novel injection mechanism provides a new way to control the charge of the electron beam in a wakefield accelerator.



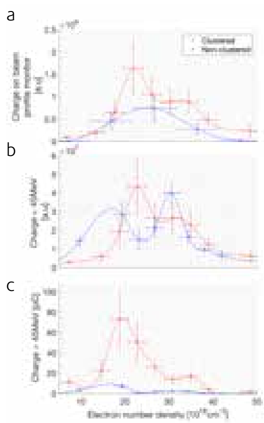


Figure 1 (left): Main chamber layout Figure 2 (Right): Comparison of beam charge between the clustered (red) & non-clustered (blue) on a) Beam profile monitor, b) Low energy electron spectrometer and c) High energy electron spectrometer.

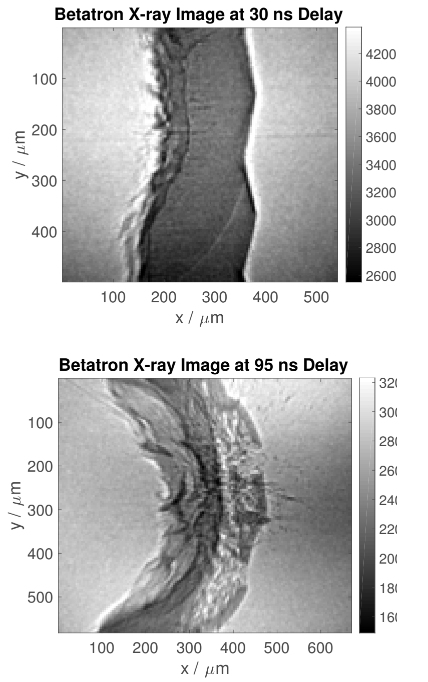
Contact: S. V. Rozario (savio.rozario11@imperial.ac.uk)

Density measurements in shock-compressed aluminium via betatron x-ray radiography

M. E. Rutherford, D. J. Chapman, D. E. Eakins *(Institute of Shock Physics, Blackett Laboratory, Imperial College London, UK)*

J. C. Wood, N. C. Lopes, K. Poder, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*

A GeV level laser wakefield accelerator driven by the Gemini laser was used to produce a bright (> 10^7 photons/shot/mm^2 at the detector), hard (18.0 ± 0.6 keV critical energy) source of betatron x-ray radiation. The betatron pulse was used as an ultrafast, high signal to noise ratio probe of the subsurface physics of a laser driven shock wave in a solid density aluminium target. The target dynamics were imaged as a function of delay in the range 0-130 ns with a spatial resolution of approximately 4 µm. It is shown that quantitative density measurements of the shock-compressed material can be made with this source, and that this source is capable of directly measuring spall fracture at the mesoscale. Spatially-resolved measurements of density in materials under extreme conditions are important for validating equation of state models and understanding the phases of matter inside planets.



Top: High resolution betatron x-ray image of a double shock structure driven by a shaped laser pulse in to an aluminium target. Bottom: Betatron x-ray image taken at a later time showing that the material has spalled close to the rear surface.

Contact: M. E. Rutherford (m.rutherford13@imperial.ac.uk)

Calibration of the CLF Andor iKon Indirect Detection x-ray Camera

J. C. Wood, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*

R. J. Clarke, D. R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*

To detect hard x-rays (>10 keV), systems based on indirect detection are common. In this scheme x-ray photons are absorbed by a scintillator, and the visible light produced is imaged onto a camera. For hard x-ray detection the CLF owns an Andor iKon L 936, which is a scientific CCD camera fibre-coupled to a structured 150 µm thick caesium iodide scintillator.

An important property to measure about an x-ray source is the amount of energy it emits. To enable the use of this camera for this measurement, a calibration was performed so that camera counts can be converted to x-ray energy deposited in the scintillator. The camera was exposed to a disk source of radioactive iron-55 with a known activity and x-ray spectrum. The camera produced 0.245 ± 0.002 counts per keV of energy deposited into the scintillator with a gain setting of 1x.

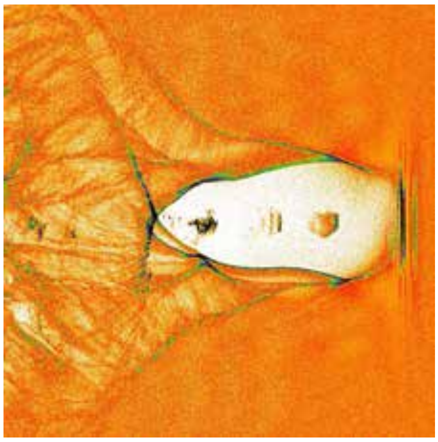
An Andor iKon L 936 indirect detection camera

Contact: J. C. Wood (jonathan.wood08@imperial.ac.uk)

Laser-driven plasma acceleration in a regime of strong mismatch between the incident laser envelope and the nonlinear plasma response

A. A. Sahai, K. Poder, J. C. Wood, J. M. Cole, N. C. Lopes, S. P. D. Mangles, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*

Laser-driven plasma wakefield acceleration of electrons in a strongly mismatched regime is explored and shown to have several advantages over the matched regime. Experimentally, larger laser focal spots of a high quality are much easier to produce and thus allow the plasma waves in this regime to have a high-quality transverse profile. An adjusted a0 model is presented to unravel the underlying laser-plasma dynamics while predicting the experiments more accurately. The injection events in this regime correspond to the formation of an optical shock. Its unbalanced radial and longitudinal ponderomotive force results in an elongated bubble that injects electrons with ultra-low emittance and high charge. Since laser slicing and bubble elongation are only activated over a small density range, the mismatched regime is useful only over a small density range. The triggering of optical shock also results in plasma fields as high as a TV/m, enabling multi-GeV electron beams in less than a centimetre.



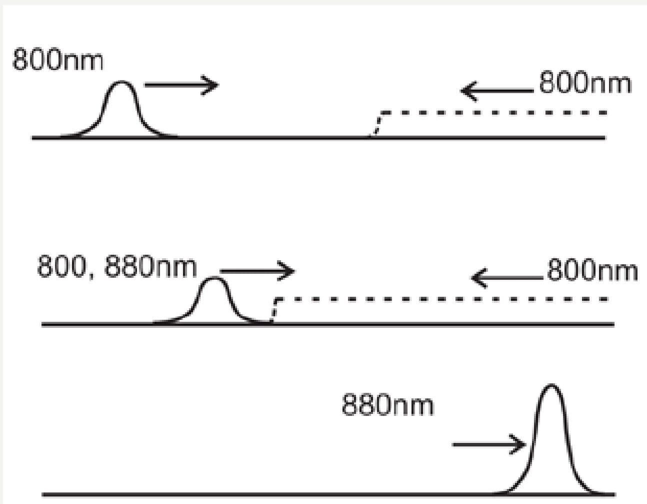
A laser-driven plasma wakefield with an elongating bubble structure in the strongly mismatched regime driven in response to the unbalanced ponderomotive forces of the laser pulse driving it. The laser pulse enters an optical shock state triggered by its slicing due to the radial envelope oscillations changing the wake structure interacting with the head of the pulse. As the longitudinal ponderomotive force in the optical shock state is much higher than the radial force an asymmetry is induced in the electron trajectories, this results in the injection of an electron bunch with ultra-low emittance and high charge in the back of the bubble. This bunch gets accelerated to nearly 2.25GeV.

Contact: A. Sahai (a.sahai@imperial.ac.uk)

Use of Raman Forward Scatter for seeding a Plasma Amplifier

J. D. Sadler*, L. Ceurvorst, M. F. Kasim N. Ratan, A. Savin, A. Ross, P. Norreys (PI)
(Clarendon Laboratory, University of Oxford, Parks Road, Oxford, UK)
K. Glize*, R. M. G. M. Trines, R. Bingham, N. Bourgeois, D. Symes, R. Pattathil
(Central Laser Facility, STFC Rutherford Appleton Laboratory, Chilton, Didcot, UK)
F. Keeble *(University College London, Gower Street, London, UK)*
**These authors contributed equally*

Raman plasma amplifiers offer a promising new route to compress laser pulses to frontier powers, possibly into the UV range. Progress has been hampered by the requirement for a short, powerful seed pulse with a wavelength approximately 10% longer than the counter-propagating pump pulse. Here we investigate the generation of an effective seed pulse using Raman forward scatter in a pre-amplifier stage. The subsequent light was well characterised and had many desirable properties for a seed, once the remaining fundamental light has been spectrally filtered out. Furthermore, this technique allows a single laser system to generate both pulses. The feasibility is also assessed using a particle-in-cell simulation.



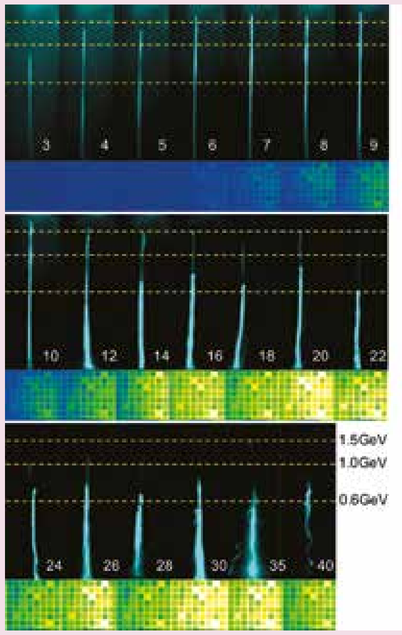
Schematic of the backwards Raman amplifier scheme, with seeding from forward scatter of a short pulse in an under-dense plasma.

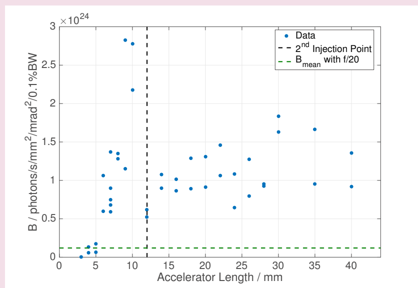
Contact: J. D. Sadler (james.sadler@physics.ox.ac.uk)

Enhanced Betatron Radiation from a Laser Wakefield Accelerator in a Long Focal Length Geometry

J. C. Wood, K. Poder, N. C. Lopes, J. M. Cole, S. Alatabi, C. Kamperidis, S. P. D. Mangles, A.Sahai, Z. Najmudin *(The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, UK)*
O. Kononenko, C. A. J. Palmer *(Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany)*
P. Foster, D. Rusby, D. R. Symes *(Central Laser Facility, STFC Rutherford Appleton Laboratory, UK)*
J. R. Warwick, G. Sarri *(Centre for Plasma Physics, Queen's University Belfast, Belfast, UK)*

By using a double focal length optic, a 6 m focal length *f*/40 optic compared to a 3 m *f*/20, it was shown that electrons from a self-guiding, self-injecting laser wakefield accelerator, driven by a 120 TW laser pulse, could be accelerated to 1.9 GeV while maintaining a source size below 0.5 µm. Dynamic evolution of the bubble size led to a secondary injection of a high charge per unit bandwidth electron bunch which increased the number of betatron radiation photons by a factor of five at moderate photon energies (~ 16 keV critical energy). By increasing the laser power to 240 TW the peak brightness of the betatron beam was increased to 3.8×10^{24} photons/s/mm^2/mrad^2/0.1%BW at 18 keV, with the whole beam containing 3×10^{10} photons above 1 keV.





Top: Electron spectra (black/blue) and betatron x-ray images (green) from an accelerator length scan, with length in mm denoted by the white numbers. The electron beam is dispersed vertically by energy. At 12 mm length a high charge per MeV electron beam was injected, which was correlated with a large increase in x-ray flux.

Bottom: Brightness as a function of accelerator length. The green dashed line shows the mean peak brightness with an f/20 geometry, which has been exceeded by a factor of more than 10 in this experiment.

Contact: J. C. Wood (jonathan.wood08@imperial.ac.uk)