High energy density and high intensity physics

Computer tomography with laser-generated X-rays at Gemini

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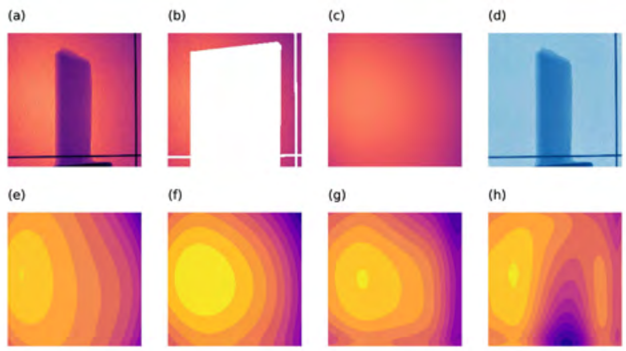
We describe recent CT imaging work at Gemini. We focus on aspects of the scanning and reconstruction processes that are needed to deal with the poor repeatability of current laser-driven x-ray sources. In particular, we describe golden ratio scanning, a useful technique employed with sources of degrading quality, and a custom beam profile correction step, applied to correct for the pulse-to-pulse changes in the x-ray beam profile and direction. The beam profile is inferred by fitting a polynomial function based on the border regions of the image. A regularisation method ensures that this fit accurately represents the beam, as shown in the figure. After image processing has been performed, standard CT reconstruction techniques can be applied to the data-set to produce a 3D visualisation of the object. Integrating these processing steps into a standardised software package used by other imaging facilities is a key objective for developing CT capability for the EPAC facility.



An example of the beam profile correction process applied to x-ray images obtained using Gemini: (a) the original image; (b) the image after removing the sample and alignment wires; (c) the reconstructed x-ray beam profile; (d) the transmission map, obtained by dividing (a) by (c). The second row shows how the regularisation parameter $\propto$ affects the fitting process: (e) $\propto = 10^{-3}$ is too large failing to fit to the beam profile correctly; (f) $\propto = 10^{-4}$ provides a good fit and is used for (c-d); (g) $\propto = 10^{-5}$ and (h) $\propto = 10^{-6}$ overfit the data.

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Laser wakefield acceleration with active feedback at 5Hz

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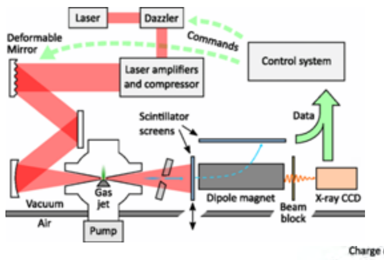
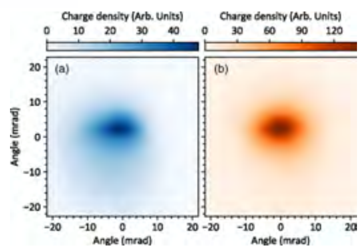
We describe the use of a genetic algorithm to apply active feedback to a laser wakefield accelerator at a higher power (10 TW) and a lower repetition rate (5 Hz) than previous work. The temporal shape of the drive laser pulse was adjusted automatically to optimize the properties of the electron beam. By changing the software configuration, different properties could be improved. This included the total accelerated charge per bunch, which was doubled, and the average electron energy, which was increased from 22 to 27 MeV. Using experimental measurements directly to provide feedback allows the system to work even when the underlying acceleration mechanisms are not fully understood, and, in fact, studying the optimized pulse shape might reveal new insights into the physical processes responsible. Our work suggests that this technique, which has already been applied with low-power lasers, can be extended to work with petawatt-class laser systems.



Schematic diagram of the experimental set-up.



Images of the electron beam spatial profile (a) before and (b) after optimization.

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High order mode structure of intense light fields generated via a laser-driven relativistic plasma aperture

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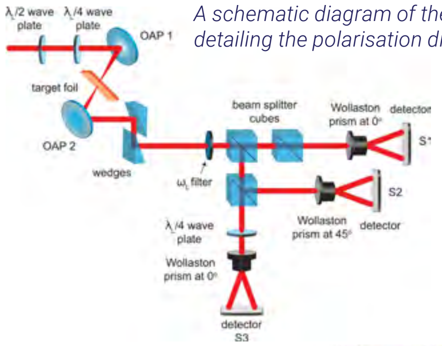
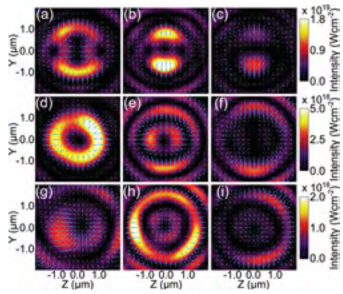
The spatio-temporal and polarisation properties of intense light is important in wide-ranging topics at the forefront of extreme light-matter interactions, including ultrafast laser-driven particle acceleration, attosecond pulse generation, plasma photonics, high-field physics and laboratory astrophysics. Here, we experimentally demonstrate modifications to the polarisation and temporal properties of intense light measured at the rear of an ultrathin target foil irradiated by a relativistically intense laser pulse.

The changes are shown to result from a superposition of coherent radiation, generated by a directly accelerated bipolar electron distribution, and the light transmitted due to the onset of relativistic self-induced transparency. Simulations show that the generated light has a high-order transverse electromagnetic mode structure in both the first and second laser harmonics that can evolve on intra-pulse time-scales. The mode structure and polarisation state vary with the interaction parameters, opening up the possibility of developing this approach to achieve dynamic control of structured light fields at ultrahigh intensities.



A schematic diagram of the experimental set-up detailing the polarisation diagnostic.



Right: Spatial intensity distributions and electric field vectors (blue arrows) for $2\omega_L$ light, from the full laser-foil simulations, measured 10 μm behind the target rear. Three values of target thickness are compared; (a–c), 5 nm; (d–f), 20 nm; and (g–i), 30 nm.

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Low-density hydrodynamic optical-field-ionized plasma channels generated with an axicon lens

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We demonstrate optical guiding of high-intensity laser pulses in long, low-density hydrodynamic optical-field-ionized (HOFI) plasma channels. An axicon lens is used to generate HOFI plasma channels with on-axis electron densities as low as $n_e(0) = 1.5 \times 10^{17}$ cm^{-3} and matched spot sizes in the range 20 μm $\lesssim W_M \lesssim$ 40 μm. Control of these channel parameters via adjustment of the initial cell pressure and the delay after the arrival of the channel-forming pulse is demonstrated. For laser pulses with a peak axial intensity of 4×10^{17} W cm^{-2}, highly reproducible, high-quality guiding over more than 14 Rayleigh ranges is achieved at a pulse repetition rate of 5 Hz, limited by the available channel-forming laser and vacuum pumping system. Plasma channels of this type would seem to be well suited to multi-GeV laser wakefield accelerators operating in the quasilinear regime.

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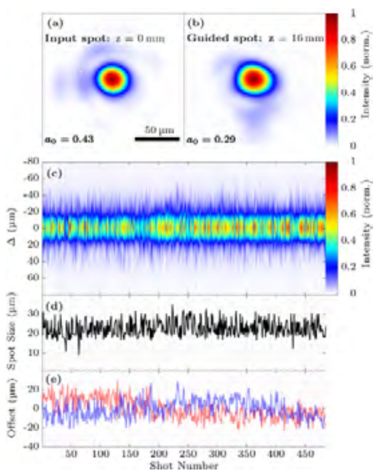

Transverse fluence profiles of the guided laser pulse at (a) the entrance and (b) the exit of a 16-mm-long HOFI channel, at τ = 1.5 ns. (c) shows, for each shot, the average of the horizontal and vertical fluence profiles through the center of mass; the coordinate Δ has its origin at the center of mass. In (d), the D4σ spot size of the transmitted beam (averaged along the principal axes of the spot) is shown for each of the 485 shots; (e) shows the vertical (blue) and horizontal (red) offsets of the spot center. In (a)–(c), the peak fluence has been normalized to the highest value in each plot.

Single-shot multi-keV X-ray absorption spectroscopy using an ultrashort laser-wakefield accelerator source

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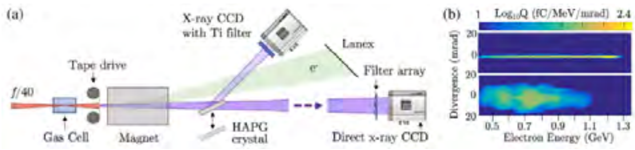
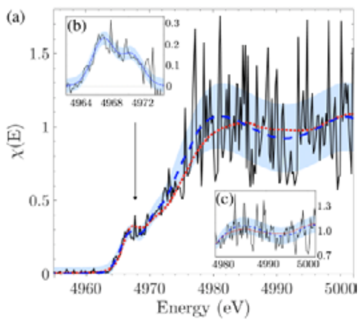
Single-shot absorption measurements have been performed using the multi-keV X-rays generated by a laser-wakefield accelerator. A 200 TW laser was used to drive a laser-wakefield accelerator in a mode which produced broadband electron beams with a maximum energy above 1 GeV and a broad divergence of ≈15 mrad FWHM. Betatron oscillations of these electrons generated 1.2 ± 0.2 × 10^6 photons/eV in the 5 keV region, with a signal-to-noise ratio of approximately 300:1. This was sufficient to allow high-resolution X-ray absorption near-edge structure measurements at the *K* edge of a titanium sample in a single shot. We demonstrate that this source is capable of single-shot, simultaneous measurements of both the electron and ion distributions in matter heated to eV temperatures by comparison with density functional theory simulations. The unique combination of a high-flux, large bandwidth, few femtosecond duration X-ray pulse synchronized to a high-power laser will enable key advances in the study of ultrafast energetic processes, such as electron-ion equilibration.



(a) Experiment setup. The LWFA x rays can be measured on axis or with a high-resolution crystal spectrometer. (b) Electron spectra where, for the first stage of the gas cell, $n_e = 1.2 \times 10^{18}$ cm^{-3} (top) and ne = 2.6 × 10^{18} cm^{-3} (bottom).



(a) Single-shot normalized absorption data (solid black curve) compared to a synchrotron reference measurement (dotted red curve). The fitted profile for our data is given (dashed blue curve) with the light blue area indicating the measurement error. (b) Double Gaussian fit to the preedge features. (c) The same result as in (a), but averaged over 11 shots.

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Dosimetry of laser-accelerated carbon ions for cell irradiation at ultra-high dose rate

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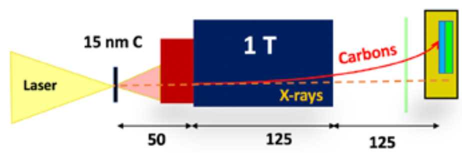
Carbon ions are particularly attractive for the treatment of radioresistant tumours, thanks to their higher Linear Energy Transfer (LET) and Relative Biological Effectiveness (RBE). Recent developments in ion acceleration have allowed to investigate for the first time the biological effects of carbon ions at ultra-high dose-rate (10^{10} Gy/s) using the Gemini laser system at the Rutherford Appleton Laboratory (RAL). Carbon ions were accelerated from ultrathin (10-20 nm) carbon foils and energy selected by a magnet allowing to irradiate the cells with an average carbon energy of 10 MeV/nucleon ± 8%. The details of the dosimetry arrangement as well as the measurement of the dose distribution at the cell plane are reported.



Schematic of the experimental setup.

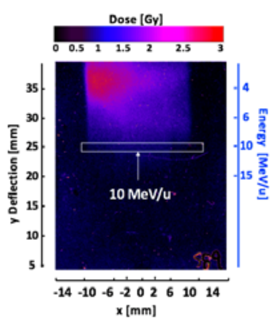


Image of the unlaminated EBT3 irradiated with carbon ions during one shot. The region corresponding to 10 MeV/nucleon carbon ions is also shown (white square).

Figures adapted from G. Milluzzo et al. Dosimetry of laser-accelerated carbon ions for cell irradiation at ultra-high dose rate, J. Phys.: Conf. Ser. 1596 012038 (2020), published by IOP Publishing Ltd, under the terms of the Creative Commons Attribution 3.0 Licence (CC BY 3.0). doi: 10.1088/1742-6596/1596/1/012038

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Characteristics of ion beams generated in the interaction of ultra-short laser pulses with ultra-thin foils

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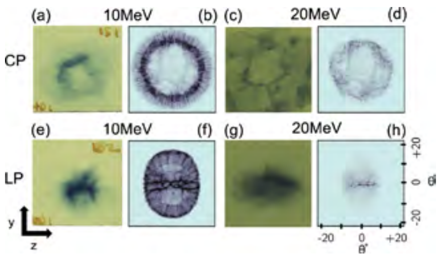
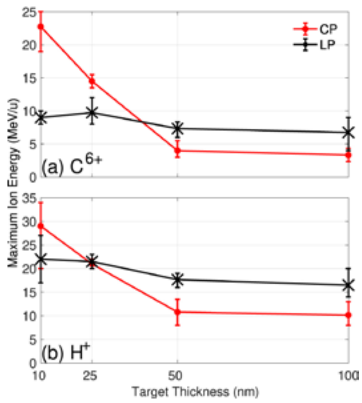
Experiments investigating ion acceleration from laser-irradiated ultra-thin foils on the Gemini laser facility at the Rutherford Appleton Laboratory indicate a transition to 'light sail' radiation pressure acceleration when using circularly polarised, high contrast laser pulses. This paper complements previously published results with additional data and modelling which provide information on the multispecies dynamics taking place during the acceleration, and provides an indication on expected scaling of these processes at higher laser intensities.



Average maximum ion energy measured from the Thomson Parabola Spectrometer. A target thickness scan showing maximum ion energies for (a) C^{6+} and (b) protons for linear (LP) and circular polarisation (CP) is displayed.



CP (a)–(d) and LP (e)–(h) proton beam profiles a 10 MeV (left) and 20 MeV (right) obtained experimentally from RCF (a), (c), (e), (g) and through 3D PIC simulations (b), (d), (f), (h).

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doi: 10.1088/1361-6587/ab7d26

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Selective ion acceleration by intense radiation pressure

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We report on preferential acceleration of heavy ions in an inherently multi-species target by the intense radiation pressure of the Gemini laser incident on ultra-thin foils with circular polarization. At the optimum thickness of 15 nm, heavy ion C^{6+} energies were detected up to 33 MeV/nucleon and protons with a maximum energy cut off of 18 MeV. This difference, the opposite to what is typically observed with laser-foil interactions, is attributed (via multi-dimensional Particle in Cell simulations) to the removal of contaminant protons (and their subsequent thermal acceleration) by the laser's coherent contrast, with the carbon ions being accelerated via Radiation Pressure Acceleration in the Light Sail regime. This is supported by the experimental measurement of different scaling of the maximum ion energy with laser intensity for the two species.

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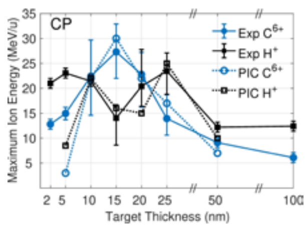
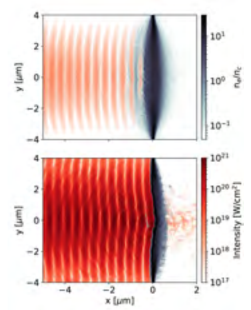


Maximum ion energy along the laser axis for C^{6+} (blue) and protons (black) for circular polarisation. The experimental data is shown with solid lines (and solid markers) and simulations with dotted lines (and empty markers). Preferential acceleration of carbon ions over protons is observed at 15 nm.



2D PIC maps of electron density (grey scale) and laser intensity (red scale) at -83 fs (top) and -23 fs (bottom) with respect to the peak of the pulse hitting the target at 0 fs (each colour-bar refers to both images). The laser enters from the left and is centred at y = 0 μm. Moderate target expansion prior to the peak of the pulse arriving is responsible for the removal of contaminant protons and allows for the acceleration of carbon ions only by radiation pressure.

Generation of electron high energy beams with a ring-like structure by a dual stage laser wakefield accelerator

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The laser wakefield accelerator (LWFA) traditionally produces high brightness, quasi-monoenergetic electron beams with Gaussian-like spatial and angular distributions. In the present work we investigate the generation of ultra-relativistic beams with ring-like structures in the blowout regime of the LWFA using a dual stage accelerator. A density down-ramp triggers injection after the first stage and is used to produce ring-like electron spectra in the 300 – 600 MeV energy range. These well-defined, annular beams are observed simultaneously with the on-axis, high energy electron beams, with a divergence of a few milliradians. The rings have quasi-monoenergetic energy spectra with an RMS spread estimated to be less than 5%. Particle-in-cell simulations confirm that off-axis injection provides the electrons with the initial transverse momentum necessary to undertake distinct betatron oscillations within the plasma bubble during their acceleration process.

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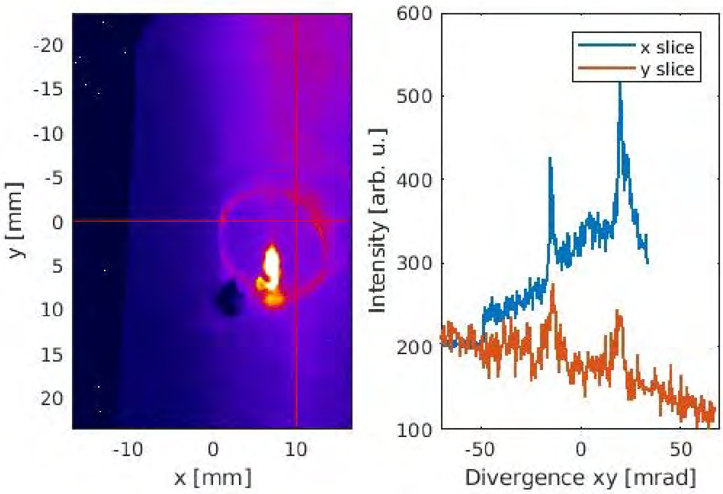
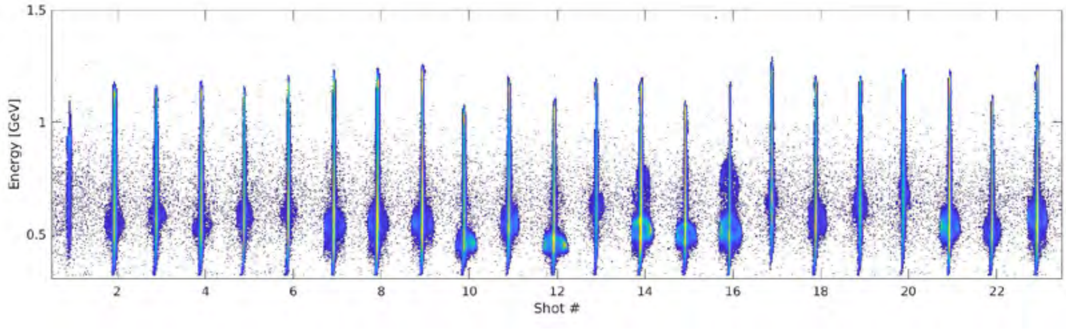


Electron beam profile measured on a LANEX electron profile monitor with cross-sections taken along the indicated lines.



Electron energy spectrum measurements showing a broad energy distribution as well as a quasi-monoenergetic ring structure.

Absolute calibration of microchannel plate detector for carbon ions up to 250 MeV

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S.D.R. Williamson, P. McKenna *(SUPA, Department of Physics, University of Strathclyde, Glasgow, UK)*
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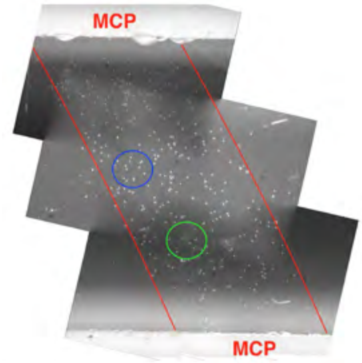
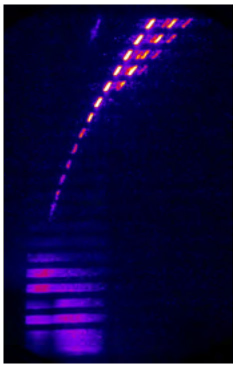
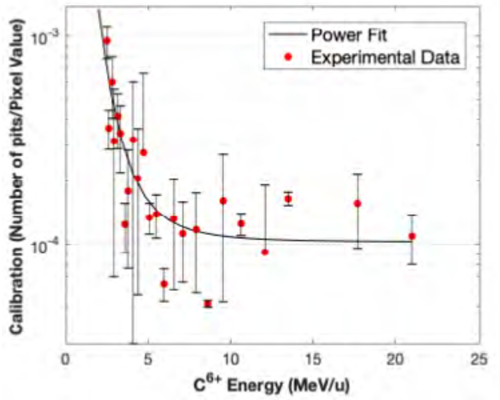
A 375 TW 40 fs pulse was used at the Gemini facility for investigating novel ion acceleration regimes employing ultrathin foil targets. An online detection system consisting of a Thomson Parabola Spectrometer (TPS) with a Microchannel Plate (MCP) was used to determine maximum energies and spectra per species. The response of the MCP was calibrated for absolute particle (carbon) number per steradian using CR-39 up to 21 MeV/nucleon. This calibration provides a useful reference for a widely used diagnostic arrangement.





Left: Mosaic image of CR-39 at X10 magnification showing the width of the parabolic ion trace (red lines) and the CR-39–MCP interface at 4.1 MeV/nucleon (top) and 4.4MeV/u (bottom). The blue circle represents C^{6+} and green represents noise from damage particles. Right: Image of MCP with slotted CR-39 placed in front of it forming regular interfaces between the two.



Calibration function for each energy bin for the Thomson Parabola Spectrometer at 0° (red dots):
Calibration = $1.257 \times 10^{-2} \times energy^{-3.331} + 1.028 \times 10^{-4}$ (black line).

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Wakefields in a cluster plasma

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K. Glize, N. Bourgeois, D.R. Symes, R.M.G.M. Trines, P.P. Rajeev *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*
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R.A. Fonseca *(ISCTE - Instituto Universitário de Lisboa, Portugal; GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Tecnico, Lisbon, Portugal)*
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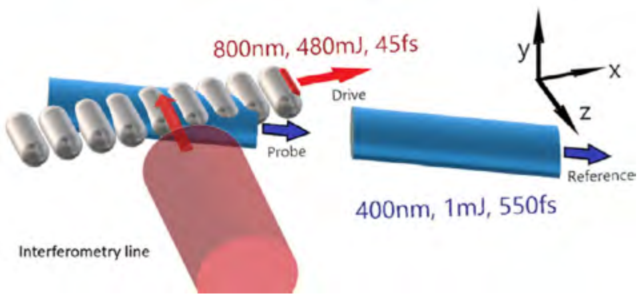
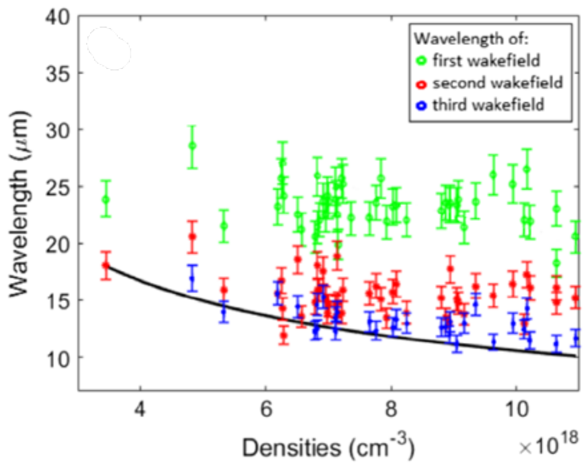
We report the first comprehensive study of large amplitude Langmuir waves in a plasma of nanometre-scale clusters. Using an oblique angle single-shot frequency domain holography diagnostic, the shape of these wakefields is captured for the first time. The wavefronts are observed to curve backwards, in contrast to the forwards curvature of wakefields in uniform plasma. Due to the expansion of the clusters, the first wakefield period is longer than those trailing it. The features of the data are well described by fully relativistic two-dimensional particle-in-cell simulations and by a quasianalytic solution for a one-dimensional, nonlinear wakefield in a cluster plasma.



Schematic of the experimental set-up, including a single-shot oblique-angle frequency domain holography diagnostic and a transverse optical probe.



Measurement of the first (green), second (red), and third (blue) wakefield wavelengths as a function of the average plasma electron density measured by the transverse interferometry, with data from 30 separate laser shots.

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Calorimetry techniques for absolute dosimetry of laser-driven ion beams

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N. Lee, A. Subiel *(National Physical Laboratory, Medical Radiation Science, Teddington, UK)*
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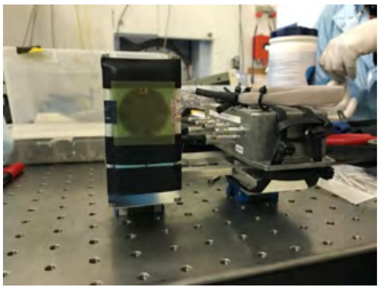
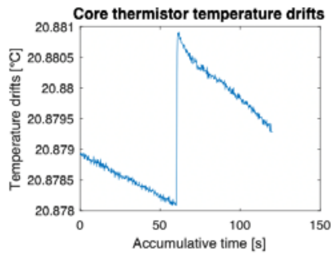
Laser-driven particle acceleration based on the use of intense, ultra-short laser pulses is emerging as a novel technique for the compact generation and delivery of energetic ion beams, particularly in view of the possible future use of these beams as a source for particle therapy of cancer. Precise measurement of the dose delivered to a given volume is essential to ensure safe delivery of treatment. Therefore, reliable methods allowing beam characterization and accurate dosimetry need to be established to first ensure reliable pre-clinical studies and, in a future perspective, optimal treatment. Absolute dosimetry of laser-driven ion beams, using a small portable graphite calorimeter developed at National Physical Laboratory is presented, with a first proof of principle experiment demonstrating the use of calorimetric techniques in a laser environment.



Left: The SPGC assembled in a makeshift holder dedicated for the measurement using Vulcan, and electronics close by. The calorimeter indicated is composed of a sensitive core containing 4 thermistors.



Right: Measured radiation induced temperature rise of the SPGC core for a shot performed with the Vulcan laser system. This represents the first laser-driven proton beam captured by through calorimetry.

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Multi-species hybrid ion acceleration from ps, PW interactions with ultra-thin foils

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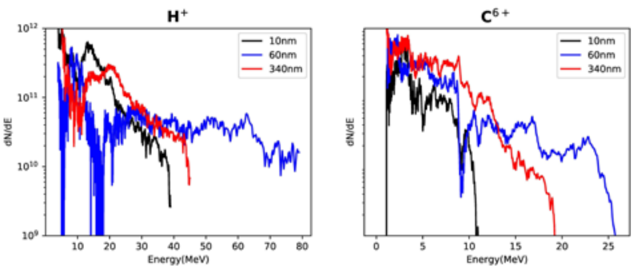
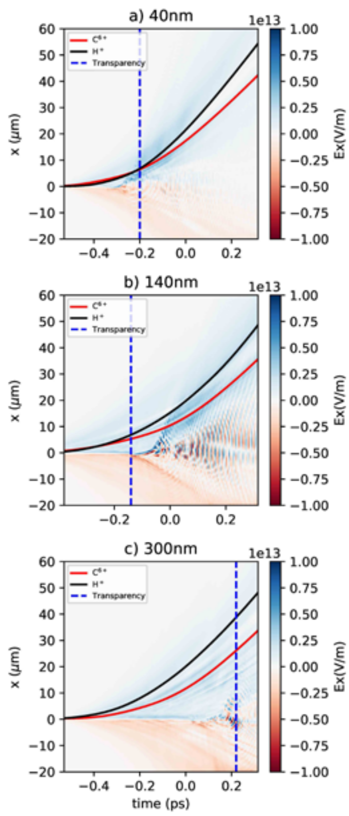
J. Jarrett, M. King, P. McKenna *(SUPA Department of Physics University of Strathclyde, Glasgow, UK)*

The optimisation of heavy and light ion acceleration from intense laser interactions was investigated experimentally. Ultra-thin (10 - 340 nm) plastic (CH) foils were irradiated with intense, short (750 fs) laser pulses with maximum energies of 75 MeV and 25 MeV/μ obtained for H^+ and C^{6+} ions, respectively. Species resolved spectra suggest differences in the acceleration mechanism for each species. Further analysis through Particle in Cell simulations, identifies a hybrid acceleration scheme, which is enhanced by the onset of relativistically induced transparency. This report presents the analysis of the interplay of the different mechanisms and how it affects each species' acceleration dynamics.



Spectra obtained for both H^+ (left) and C^{6+} (right) ions at TPS1 (+6.5°) for three target thicknesses, 10 nm, 60 nm and 340 nm.



2D colour-maps of average electric field at each time-step for three thicknesses, a) 40 nm, b) 140 nm, c) 300 nm. X positions of highest energy ions (H^+ (black) and C^{6+} ions (red)) for each thickness are tracked. The times at which transparency occurs are marked with a blue vertical line for each thickness.

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Light-sail acceleration from two moderate intensity pulses

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D. Doria *(ELI NP, Magurele, Romania)*
J. Jarrett, P. McKenna *(Department of Physics, University of Strathclyde, UK)*
S. Zhai *(ELI Beamlines, Dolní Břežany, Czechia)*

The acceleration of ions from ultrathin deuterated plastic foils is demonstrated by implementing two pulses with intensities on the order of 10^{19} W/cm^2, which could be spatio-temporally separated by varying degrees. At the optimal arrangement of the two pulses, maximum proton and deuteron energies of 45 MeV and 33 MeV/u, respectively, were accelerated from 85 nm foils, exceeding what was achieved from a single pulse irradiating the same target at ~5 × 10^{20} W/cm^2, despite the double pulse setup sacrificing a ~60% average reduction in total laser fluence on target.

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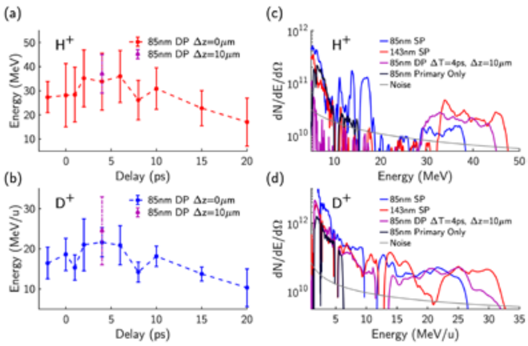

(a) Proton, and (b) deuteron central bunch energies along target normal direction vs time delay between the two beams in the double pulse setup. Also shown in purple is the highest energy reached when the secondary beam is focused 10 μm further along the laser axis. The bars on each data point represent bunch widths of individual shots. The maximum limit of the bars corresponds to the spectrum cut-off energies. (c) Proton and (d) deuteron TPS spectra, for selected single pulse (SP) and double pulse (DP) shots from the campaign, taken along the laser axis.

Extending proton energy gain in laser-driven helical coil targets

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H. Ahmed, J. Green *(Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK)*

Laser driven helical coil targets post-accelerate and focus TNSA beams to form a quasi-collimated, narrow energy band of protons. Increasing the length of helical coil extends the duration protons remain in phase with the strong electric fields formed by the helical coil target. Therefore, longer helical coils are expected to enhance the acceleration and focussing effects, which was observed in our recent experiment at Vulcan's target area west with helical coil length up to ~12 mm. Particle tracing simulations closely resemble the experimental data and reveal that the helical coil effectiveness is significantly reduced after ~12 mm. The reduced effectiveness is attributed to accelerated protons outrunning, thus de-phasing with the strong electric field region produced by helical coils of fixed pitch and radius.

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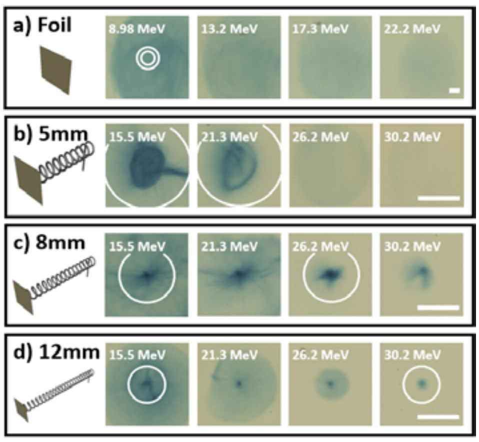
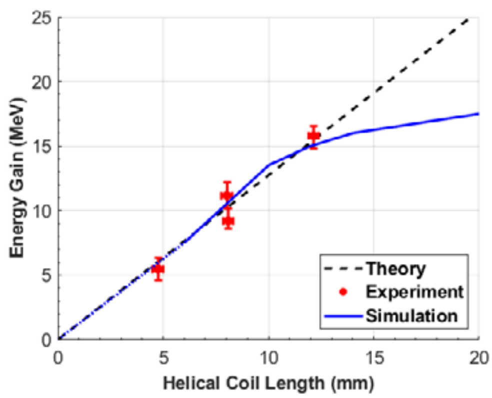


(a-d) Proton beam spatial profiles at different energies produced from helical coils of varying lengths, obtained from an experimental campaign at Vulcan's target area west. HCs had 0.5 mm pitch, 0.7 mm diameter. RCF was deployed 75 mm from the proton source and scale bars correspond 5 mm at the RCF plane. White circles represent the helical coil apertures with half-angle divergences (b) 4.0°, (c) 2.5° and (d) 1.7°. As a reference, 4.0° and 2.5° divergences are also shown in (a).



Energy gain as a function of helical coil length for experimental data (red dots) and PTRACE particle tracing simulations (blue line). Energy gain remains uniform at ~1.25 MeV/mm for the first 12 mm of the helical coil length, as expected from theory (black dashed line). However, the de-phasing between accelerated protons and EM field saturates energy gain beyond 12 mm, as studied through PTRACE simulations.

Field reconstruction from proton radiography of intense laser-driven magnetic reconnection

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L. Willingale *(Center for Ultrafast Optical Science, University of Michigan, USA; Cockcroft Institute, Daresbury, UK; Physics Department, Lancaster University, UK)*
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A.F.A. Bott, G. Gregori, A.A. Schekochihin *(Clarendon Laboratory, University of Oxford, UK)*
J. Halliday, S.V. Lebedev, E.R. Tubman, M.J.V. Streeter *(Blackett Laboratory, Imperial College London, UK)*
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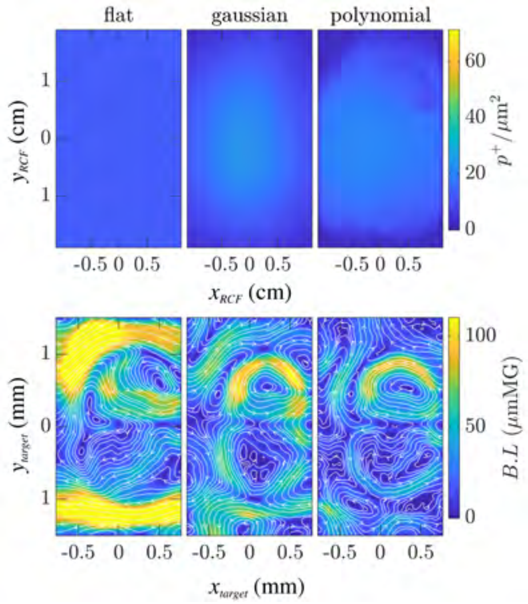
Relativistic magnetic reconnection is a potential source of particle energisation in extreme astrophysical environments. Non-thermal particle populations have been produced in laboratory reconnection events driven by two high intensity laser pulses (A. E. Raymond *et al.*, PRE, 98, 043207 (2018)). Here proton radiography was used to map the field evolution around two such laser foci. The azimuthal magnetic fields around each focus is established rapidly (<6 ps) and are distorted as the fields of each focus meet in the midplane region. The measurements reveal that these continue to grow for 10s ps after the laser drive before decaying. An algorithm developed by A. F. A. Bott *et al.*, JPP, 83, 905830614 (2017), was used to retrieve the fields and multiple initial proton fluxes are tested to determine the sensitivity of the retrieval to initial beam profile.



Field retrievals (bottom row) at the interaction plane of proton radiography at t = 33 ps using different assumed 'undisturbed' proton flux distributions shown at the detector plane (top row) including, from left to right, a flat mean-field, a σ=150-pixel Gaussian filter with 200-pixel kernal size, and a custom 2D 3rd-order polynomial, masked with the beam edge, in which the low flux regions are replaced with the original image. Taken from Palmer et al., PoP, 26, 083109 (2019)

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Collisionless shock acceleration from laser-irradiated foam targets

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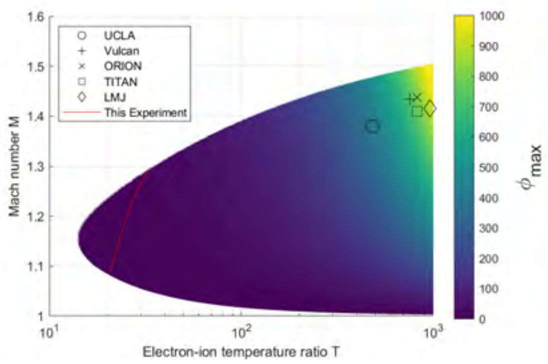
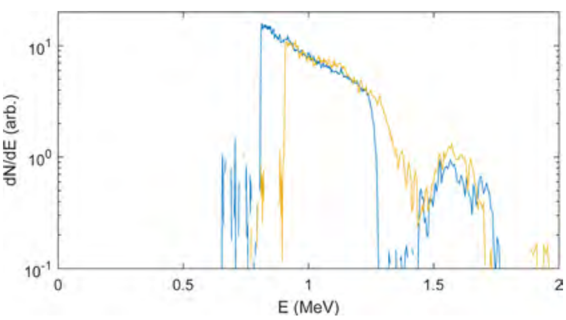
An experiment was carried out at the Vulcan 100 TW laser facility to investigate the potential for collisionless shock acceleration in low-density plastic foam targets. To assist in interpretation of the spectra obtained, advances are made in the kinetic theory approach to collisionless shock theory first presented by Cairns *et al.* in 2014. Experimental signatures consistent with acceleration from a collisionless shock were detected and parameter values which fit the form of the ion spectra are found. The parameter values found correspond to somewhat sub optimal plasma conditions that arose due to experimental constraints.



Above: The parameter space compatible with this experiment's results. The red line is produced by varying the ion temperature while keeping the maximum energy and energy FWHM of the reflected ions constant. Shown with markers are predictions for the parameter space attainable at Vulcan and other facilities under ideal conditions.



Left: Ion spectra collected on two representative shots, showing the quasi-monoenergetic ion feature indicative of acceleration by a collisionless shock.

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Supersonic plasma turbulence in the laboratory

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M. Kühn-Kauffeldt *(Universität der Bundeswehr München, Germany)*
A.F.A. Bott, A.R. Bell, J. Meinecke, F. Miniati, S. Sarkar, A.A. Schekochihin, G. Gregori *(Department of Physics, University of Oxford, UK)*
L.N.K. Döhl, N. Woolsey *(York Plasma Institute, University of York, UK)*
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J. Squire *(Theoretical Astrophysics, 350-17, California Institute of Technology, USA; Physics Department, University of Otago, Dunedin, New Zealand)*

The Universe is full of turbulent plasmas. The characteristic large scales and small viscosities drive chaotic motion that governs the dynamics of the interstellar medium, molecular clouds, stars, supernovae, and accretion disks. However, unlike most terrestrial-based turbulence, in these astrophysical scenarios, the motions are often supersonic, i.e., faster than the speed of sound. The additional complexity has hampered our understanding compared to the subsonic case. In our latest paper, published in *Nature Communications*[1], we study the behaviour of turbulence generated from the collision of two supersonic plasma jets driven by high-energy lasers. We were able to use TAW laser to generate jets up to Mach 6, which is at velocities comparable to those found in star-forming molecular clouds. By passing these jets through a pair of grids and colliding them in the centre, we produced a region of supersonic turbulence. Utilizing a suite of diagnostics, we observed the formation of small shockwaves, a characteristic of supersonic turbulence. We ultimately watched the turbulence transition away from being Kolmogorov-like at low Mach number to matching what is seen in molecular clouds at higher Mach number.

1. White, T.G., Oliver, M.T., Mabey, P. et al. Supersonic plasma turbulence in the laboratory. Nat Commun 10, 1758 (2019). https://doi.org/10.1038/s41467-019-09498-y

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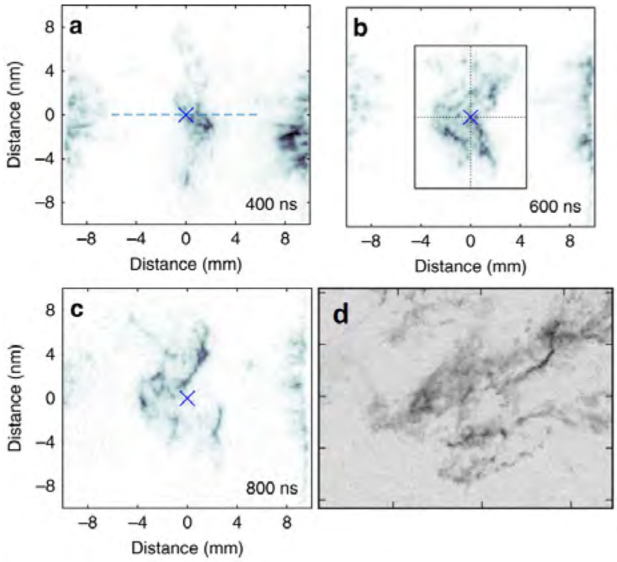

Schlieren images of the supersonic plasma generated in the experiment (a – 400 ns, b – 600 ns, c – 800ns) and CO integrated intensity map of the Taurus Molecular Cloud (d). Notice the formation of thin features in both, a characteristic of shock-wave formation and supersonic turbulence. The image in d is reproduced from Brunt, C. M. The density variance–Mach number relation in the Taurus molecular cloud. Astronomy & Astrophysics 513 (2010): A67. doi: 10.1051/0004-6361/200913506

Proton acceleration from a cryogenic hydrogen ribbon

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We report on the interaction of an intense (~5 × 10^{20} W/cm^2) picosecond pulse with thin (75 – 100 µm) ribbons of cryogenically-cooled solid hydrogen. Beams of protons exhibiting the broadband TNSA-like spectrum seen in typical higher-density target types were observed, in addition to quasi-monoenergetic bunches, at energies exceeding the TNSA cutoff, directed predominantly along the laser axis. This suggests a significant hole boring radiation pressure contribution to the acceleration dynamics. 2D PIC simulations are also presented, which demonstrate a strong relativistic self-focusing and channelling of the pulse inside the target, enhancing proton energies via the hole boring mechanism.

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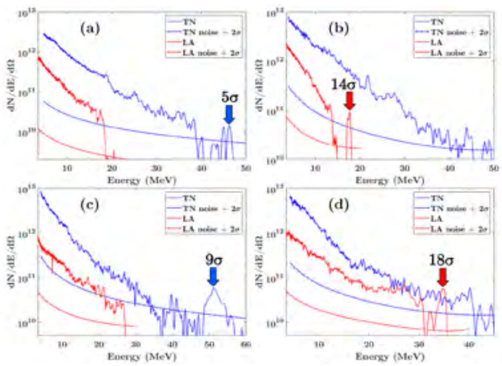

Proton spectra and the detection threshold taken along the target normal (TN) and laser axis (LA) TPS for solid hydrogen targets of (a) 75 µm and (b,c,d) 100 µm thickness. Quasi-monoenergetic bunches at high energy are indicated by the arrows, seen along target normal in (a) and (c), and laser axis in (b) and (d). The statistical heights of each peak above the noise level are displayed on the plots.