High Energy Density & High Intensity Physics

High fidelity parameter scans in a 5 Hz plasma wakefield accelerator

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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.

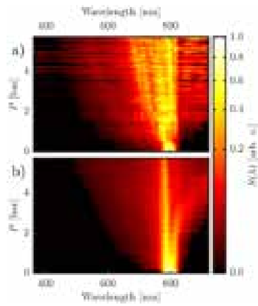

Figure 1

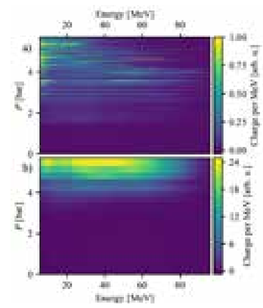

Figure 2

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.

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

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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.

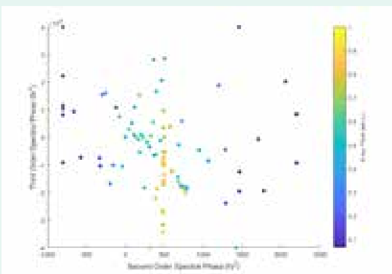

Figure 1: Every trial solution attempted by the genetic algorithm across all generations, with the colour representing the x-ray yield of each trial solution

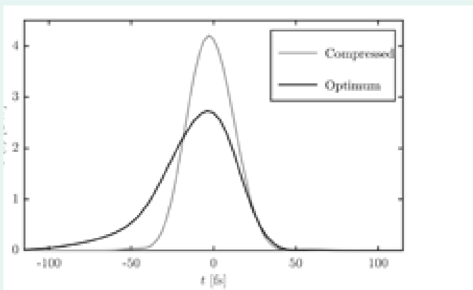

Figure 2: Temporal shape of the laser pulse that produced the highest x-ray yield

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

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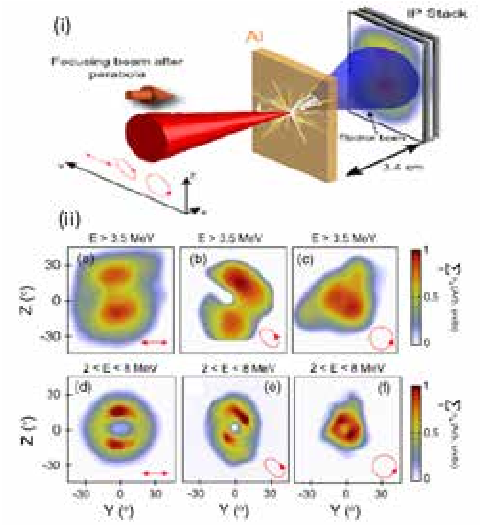
The collective response of electrons in an ultrathin foil target irradiated by an ultra-intense (~6 × 10^{20} W/cm^2) laser pulse is investigated experimentally and via 3D particle-in-cell simulations. It is shown that if the target is sufficiently thin that the laser induces significant radiation pressure, 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.

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

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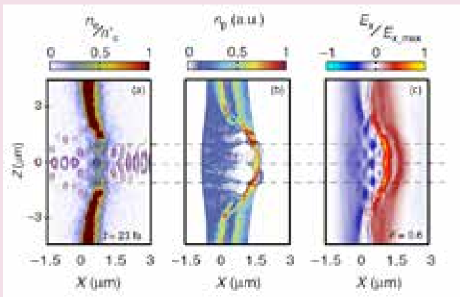
Control of the collective response of plasma particles to intense laser light is intrinsic to relativistic optics, the development of compact laser-driven particle and radiation sources, as well as investigations of some laboratory astrophysics phenomena. We recently demonstrated that a relativistic 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.

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

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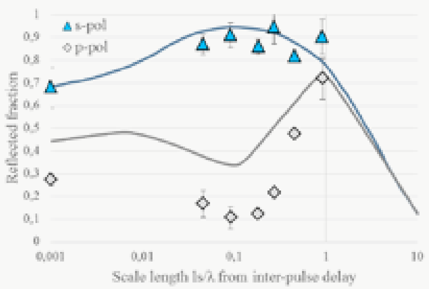
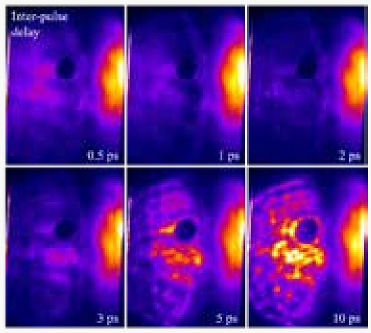
The characteristic absorption behaviour for radiation in laser-induced plasmas in the working intensity regime of plasma mirrors ($10^{14} – 10^{16}$ Wcm^{-2}) has been investigated as a function of polarisation, inter-pulse delay and angle of incidence. Resulting from the temperature of the plasma and 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.

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

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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.

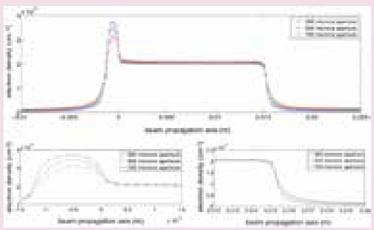

Figure 1: (a) Electron density distribution along the full gas cell, zero is the middle of the separation wall, depending on the aperture diameter; (b) density down-ramp between acceleration and injection stages; (c) density tail at the exit.

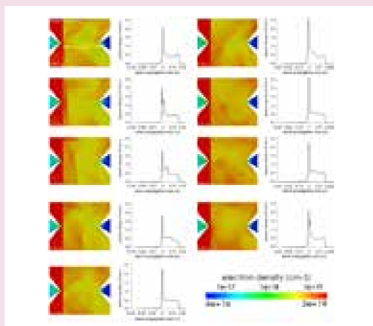

Figure 2: Density map and density plot at different time steps, which demonstrates the oscillations. The amplitude of the oscillation spike along the density profile reaches 35% of the plateau electron density for the high pressure and 20% for the medium pressure.

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

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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.

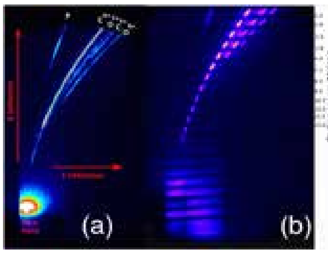

Figure 1 (a) MCP imaged on shot with Andor Neo CCD (false colour) (b) calibration shot using slotted CR-39 through which the carbon passes.

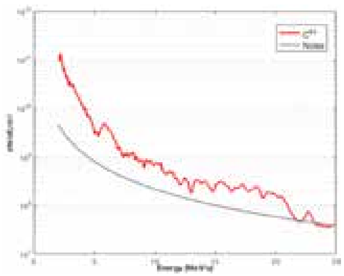

Figure 2: Spectra for a 15 nm foil with particle number/MeV/steradian plotted with the noise. Maximum energy is ~22 MeV/u.

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Spectral and spatial characterisation of laser-driven positron beams

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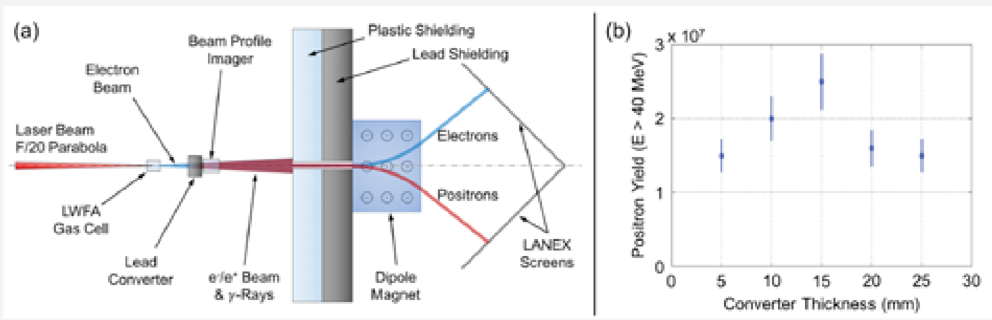
The generation of high-quality relativistic positron beams is a central area of research in experimental physics, due to their potential relevance in a wide range of scientific and engineering areas. There is now growing interest in developing hybrid accelerators, combining plasma-based and conventional 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.

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

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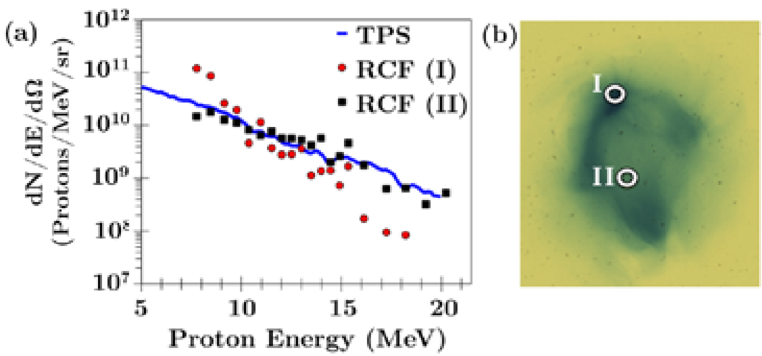

Methods and techniques used to capture and analyse beam profiles produced from the interaction of intense, ultrashort laser pulses and ultrathin foil targets using stacks of Radiochromic Film (RCF) and Columbia Resin #39 (CR-39) are presented. The identification of structure in the beam is particularly 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.

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Spin polarization of electrons interacting with ultra-intense laser pulses

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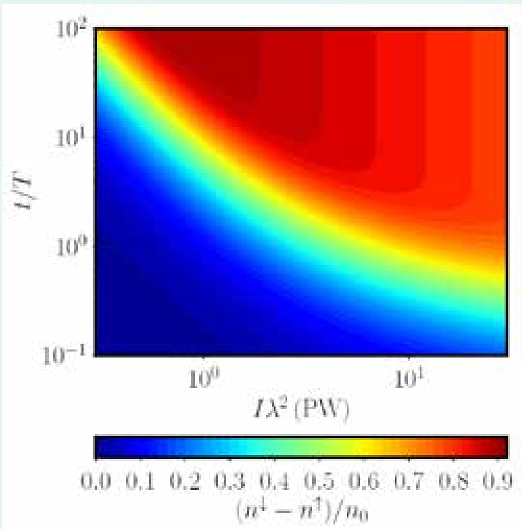

Degree of electron spin polarization, as a function of laser intensity and time normalized to the laser period.

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.

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Breaking of Dynamical Adiabaticity in Direct Laser Acceleration of Electrons

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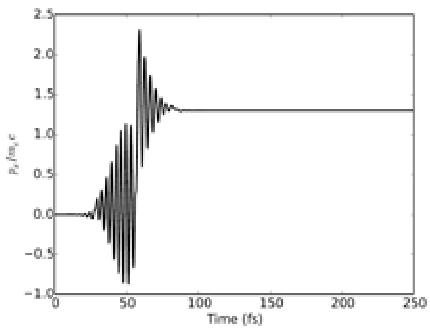
A key issue in fast electron generation in almost any aspect of ultra-intense laser-plasma interactions is what might be termed 'adiabaticity breaking', i.e. the irreversible transfer of energy from the electromagnetic (EM) field to the electrons. This is by no means a trivial matter: for example, a 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

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Experimental observation of thin-shell instability in a collisionless plasma

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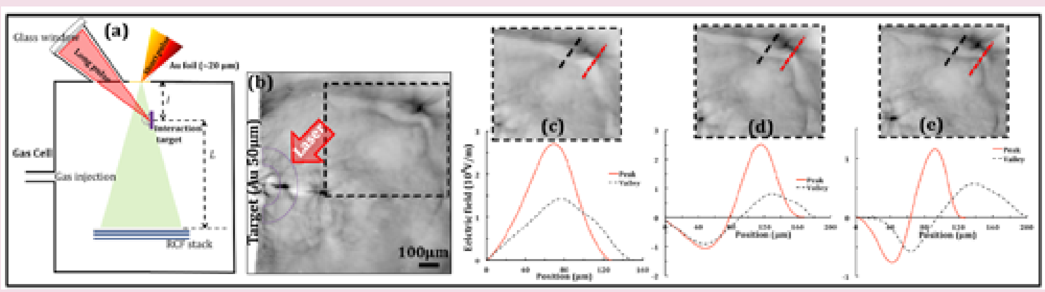
We report on the first experimental observation of a thin-shell instability in a collision-less plasma shell formed during the expansion of a laser ablated plasma into a rarefied ambient medium. By means of a proton radiography technique, the early stage evolution of the instability is temporally and 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.

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

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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.

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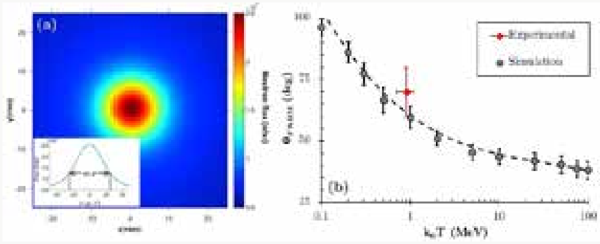

Simulated neutron beam. (a) Simulated profile of the neutron beam on a detector placed behind the catcher, as calculated considering the interaction of a deuteron beam with a deuterised plastic converter. Inset shows the lineout across the detector, indicating a neutron beam divergence of ~62 degree. (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

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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.

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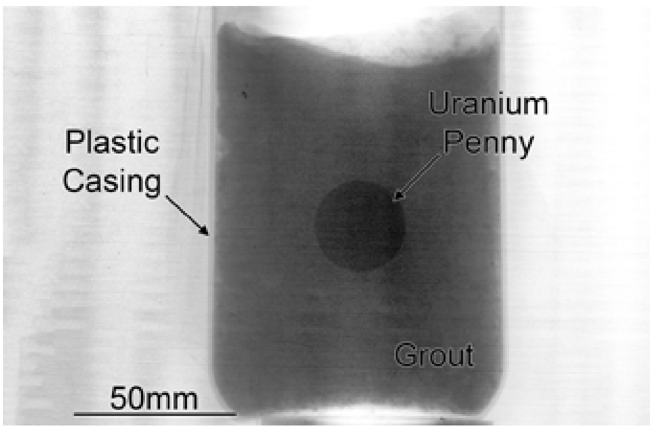

Radiograph of uranium penny encased in grout obtained using single pulse of a laser-driven x-ray beam.

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

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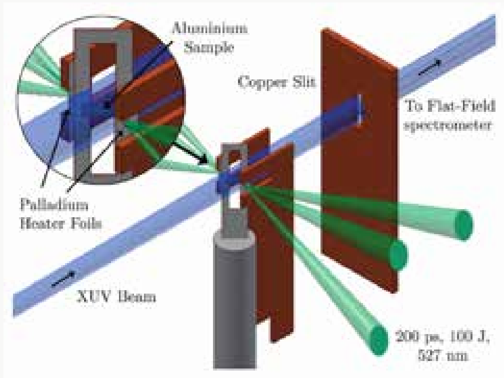
The collisional (or free-free) absorption of soft x-rays in warm dense aluminium remains an unsolved problem. Competing descriptions of the process exist, two of which we compare to our experimental data here. One of these is based on a weak scattering model, another uses a corrected classical approach. 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.



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.

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

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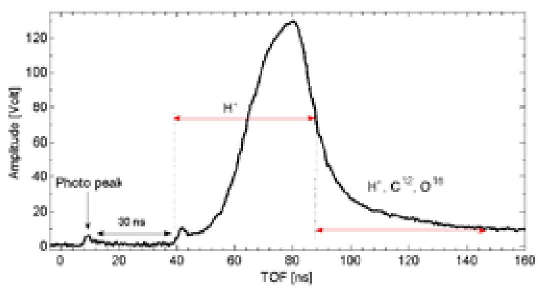
Time of Flight (TOF) measurements up to a proton energy cut-off around 30 MeV were performed for the first time, with a limited flight path, in the VULCAN Target Area Petawatt. Such results, together with the possibility of measuring the beam characteristics in real time, demonstrate how such a technique, 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.

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

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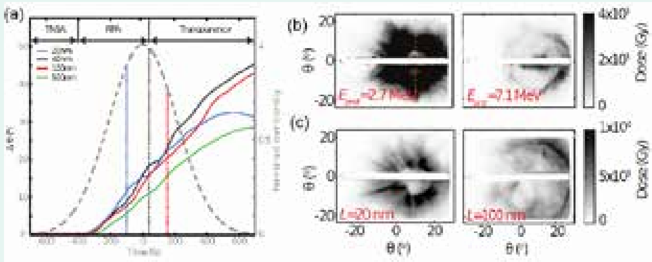
The Vulcan Petawatt laser was used to experimentally investigate ion acceleration from thin foils. A transition between ion acceleration mechanisms was observed over the duration of the pulse and characterised via measurements of the proton spatial-intensity distribution.

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.

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

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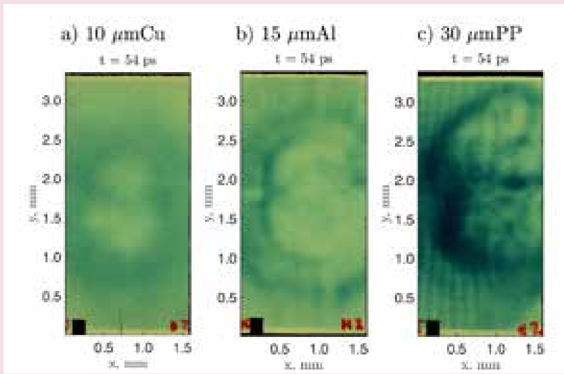
Magnetic reconnection is a process that contributes significantly to plasma dynamics and energy transfer in a wide range of situations, including inertial confinement fusion experiments, stellar coronae and compact, highly magnetised objects like neutron stars. There are many different models to describe 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.

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

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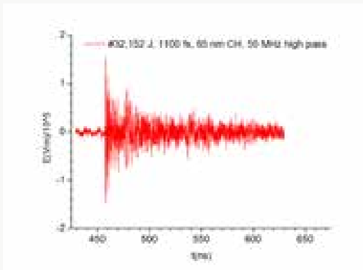
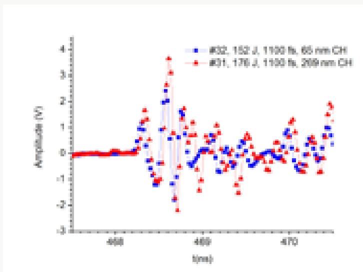
One of the effects accompanying the laser-target interaction at high laser intensities is the generation of strong electromagnetic pulses (EMP) with frequencies in the range of tens of MHz to few GHz. Such pulses may interfere with the electronics of the data acquisition systems and pose a threat to 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.

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

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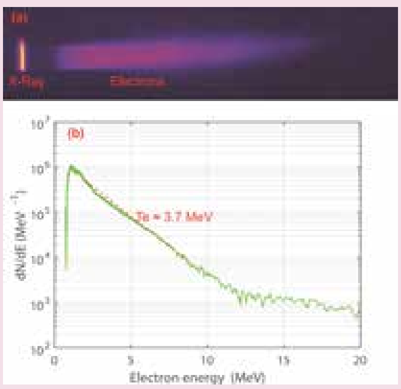

An electron spectrometer has been employed in measuring escaping electrons from laser-solid interactions. Electron spectra have been obtained in different laser pulse conditions. Dependence of escaping electron numbers and temperature on the pulse energy, intensity and duration is shown in this report.

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).

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