High Energy Density & High Intensity Physics

Plasma density optimisation of laser-wakefield acceleration for high-brightness bremsstrahlung emission applied to advanced manufacturing imaging

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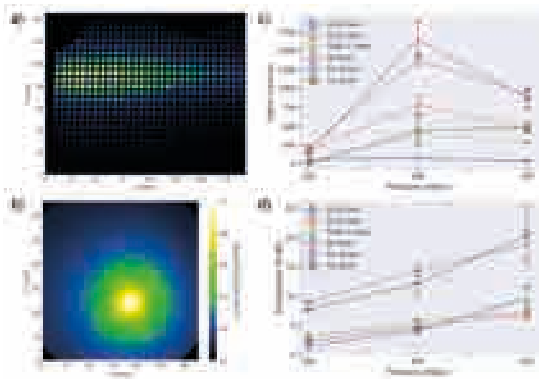
Laser-wakefield acceleration of electrons generates high-energy (GeV-scale) beams that, when propagated through solid materials, will stimulate bremsstrahlung x- ray emission that has both small (<50 μm) source size and high energy (>1MeV) for achieving high resolution penetrative radiography.
Laser-driven x-ray imaging requires bright beams for high signal-to-noise acquisition and therefore high-quality imaging.
X-ray emission is dependent on the electron beam charge and spectral distribution; therefore, mechanisms for optimising and tuning the electron beam properties are advantageous for development of this source for applications. Here we report on x-ray emission optimised for different material properties by varying the gas pressure of the wakefield accelerator.
Experimental results are presented of LWFA electron beam charge and x-ray emission after the beam is incident on a range of converter materials to produce bremsstrahlung. The x-rays were then used to image a number of high-density, industrially-relevant samples with sub-millimetre internal features, to demonstrate the capability of this new x-ray technology.



Bremsstrahlung x-ray beam generated from laser-accelerated electrons detected by (a) CsI scintillator array to measure divergence and energy and (b) LYSO scintillator screen for imaging. Effect of gas pressure and convertor material on (c) x-ray flux and (d) x-ray divergence.

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Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam

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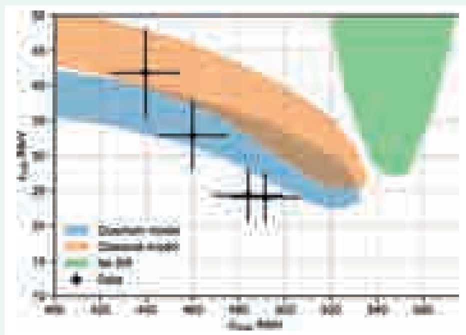
The dynamics of energetic particles in strong electromagnetic fields can be heavily influenced by the energy loss arising from the emission of radiation during acceleration, known as radiation reaction. When interacting with a high-energy electron beam, today's lasers are sufficiently intense to explore the transition between the classical and quantum radiation reaction regimes. We present evidence of radiation reaction in the collision of an ultrarelativistic electron beam generated by laser-wakefield acceleration (ε > 500 MeV) with an intense laser pulse (a_0 > 10). We measure an energy loss in the postcollision electron spectrum that is correlated with the detected signal of hard photons (γ rays), consistent with a quantum description of radiation reaction. The generated γ rays have the highest energies yet reported from an all-optical inverse Compton scattering scheme, with critical energy ε_{crit} > 30 MeV.



Experimentally measured ε_{crit} as a function of ε_{final} measured at the electron spectral feature (points). The shaded areas correspond to the results a hypothetical ensemble of identical experiments would measure 68% of the time under different assumed radiation reaction models for a uniform distribution of a_0 between 4 and 20.

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Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

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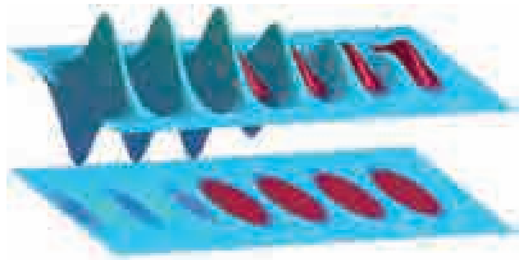
An experimental demonstration of a new method to drive a laser wakefield accelerator is presented. A train of laser pulses were generated to resonantly excite a plasma wave. This was achieved in Gemini Target Area 2 by spectrally filtering a stretched laser pulse using a Michelson interferometer, to generate a train of short pulses as shown in red in the figure. An important first step was experimentally shown in achieving an energy recovery plasma accelerator by proving that a plasma wave can be damped by an out-of-resonance trailing laser pulse.
The wakefields were measured using the Frequency Domain Holography (FDH) technique and are found to be in excellent agreement with analytical and numerical models of wakefield excitation in the linear regime. A further, simpler measurement method was also applied called Temporally Encoded Spectral Shifting (TESS) and was found to be an excellent analysis tool, that agreed well with the FDH analysis that was performed on the data.

These results indicate a promising direction towards achieving highly controlled, GeV-scale laser-plasma accelerators operating at multikilohertz repetition rates. A route towards achieving energy recovery, by dampening of the plasma wave, is shown experimentally for the first time.



Model of a train of pulses (in red) used to drive a plasma wave (in blue).

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Characterisation of a Laser Plasma Betatron Source for High Resolution X-ray Imaging

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We report on the optimisation of an x-ray source, generated by a laser-driven plasma wakefield accelerator for an imaging experiment in Gemini Target Area 3. The highest x-ray signal was observed at a plasma electron density of $(4.4 \pm 0.2) \times 10^{18}$ cm^{-3}. This coincided with the highest observed electron beam charge measured by the electron spectrometer. The peak electron energy at this density was limited by dephasing to 0.52 ± 0.12 GeV.
The spectra of the optimised source was consistent with an on-axis synchrotron spectra with a critical energy of 10.9 ± 0.4 keV and the number of photons incident on the detector was calculated to be $(3.7 \pm 0.1) \times 10^9$. The x-ray beam was used to image a resolution grid placed 37 cm from the source, which gave an estimated spatial resolution of 4 μm x 5 μm. A number of samples were also imaged radiographically as part of ongoing work to develop laser plasma generated betatron radiation as a viable industrial imaging tool.

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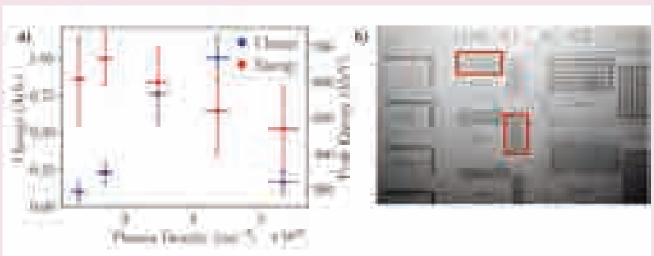

a) Plot showing the dependence of the electron bunch charge and maximum electron energy on the plasma density. The highest x-ray flux corresponds to the density of 4.4×10^{18} cm^{-3} that produces the highest charge beam. b) Radiographic image of a JIMA resolution grid. The red boxes highlight the smallest resolved features.

Radiation pressure-driven plasma surface dynamics in ultra-intense laser pulse interactions with ultra-thin foils

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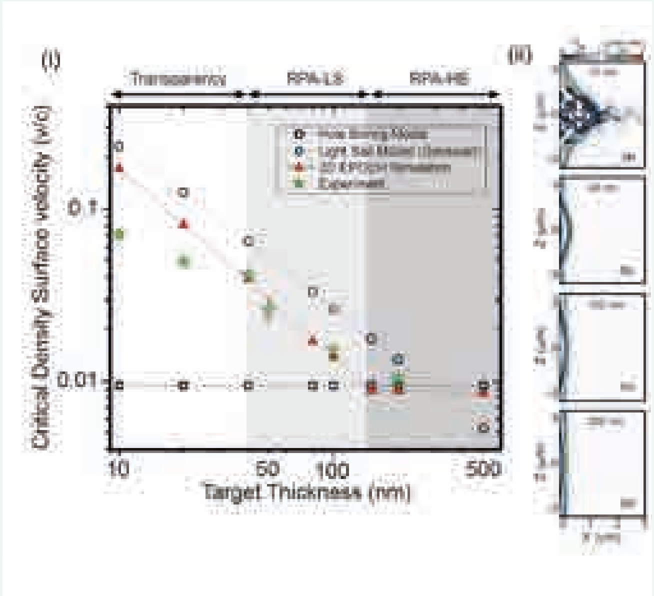
The dynamics of the plasma critical density surface in an ultra-thin foil target, irradiated by an ultra-intense pulse from the Gemini laser, are investigated both experimentally and numerically. Through variation of target thickness, from tens-to-hundreds of nanometres, the conditions for which hole-boring and light-sail models of radiation pressure acceleration dominate are investigated. It is shown that the onset of relativistic transparency limits the velocity of the critical surface, and the effectiveness of radiation pressure acceleration.



(i) Comparison of experiment and simulation results, and hole-boring and light-sail model calculations for the maximum plasma critical density surface velocity as a function of target thickness.
(ii) (a) Combined 2D plot of electron density and laser intensity, from a 2D particle-in-cell simulation with l = 10 nm, at the timestep corresponding to relativistic transparency. (b)-(d) Same, but for (b) l = 40 nm, (c) l = 100 nm and (d) l = 200 nm. The degree of target expansion increases with decreasing target thickness.

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Laser-wakefield accelerators for high-resolution X-ray imaging of complex microstructures

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Laser-wakefield accelerators (LWFAs) are high acceleration-gradient plasma-based particle accelerators, capable of producing ultra-relativistic electron beams. Within the strong focusing fields of the wakefield, accelerated electrons undergo betatron oscillations, emitting a bright pulse of x-rays with a micrometre-scale source size that may be used for imaging applications. Non-destructive x-ray phase contrast imaging and tomography of heterogeneous materials can provide insight into their processing, structure, and performance. To demonstrate the imaging capability of x-rays from an LWFA, we have examined an irregular eutectic in the aluminum-silicon (Al-Si) system. The lamellar spacing of the Al-Si eutectic microstructure is on the order of a few micrometres, thus requiring high spatial resolution. An upper bound on the resolving power of 2.7 μm of the LWFA source in this experiment was measured. These results indicate that betatron x-rays from LWFAs can perform high resolution imaging of eutectics and, more broadly, complex microstructures.

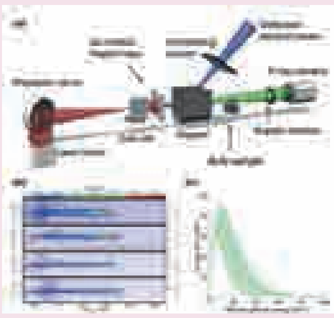

Fig 1. Experimental details for X-ray imaging using a laser wakefield accelerator. (a) Schematic of layout (b) Typical electron beams with a quasi-monoenergetic peak energy and broad low-energy tails (c) Best-fit to the betatron X-ray spectrum.

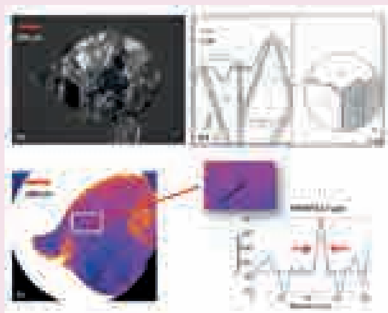

Fig 2. Al-Si sample investigated using a LWFA X-ray source. (a) Optical microscope image. (b) X-ray phase contrast (c) Schematic showing growth of irregular eutectics where ß represents the faceted phase (e.g., Si), α is the non-faceted, higher volume fraction phase (e.g., Al), and l is the melt ahead of the interface. The inset shows the α phase and the defect growth mechanism for the ß phase. *Retrieved with permission from D. J. Fisher and W. Kurz, Acta Metallurgica 28, 777 (1980).*

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Measurements of self-guiding of ultrashort laser pulses over long distances

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We report on the evaluation of the performance of self-guiding over extended distances with f/20 and f/40 focussing geometries. Guiding over 39 mm or more than 100 Rayleigh ranges was observed with the f/20 optic at n_e 1.5 x 10^{18} cm^{-3}. Analysis of guiding performance found that the extent of the exiting laser spatial mode closely followed the matched spot size predicted by 3D nonlinear theory. Self-guiding with an f/40 optic was also characterised, with guided modes observed for a plasma length of 90 mm and a plasma density of n_e 9.5 x 10^{17} cm^{-3}. This corresponds to self-guided propagation over 53 Rayleigh ranges and is similar to distances obtained with discharge plasma channel guiding.

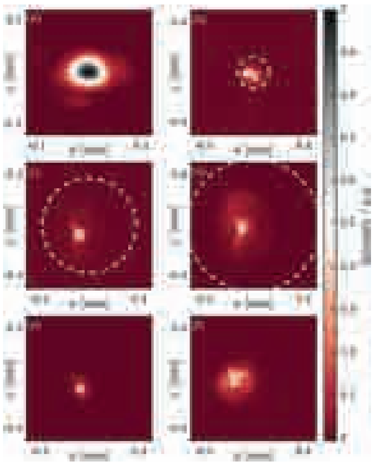

Figure 1: Measured laser focus from f/40 geometry before entering the plasma (a) and the plane of exit from the plasma (b)–(f) for different gas cell lengths and plasma densities. The white dashed line depicts the size of the laser nearfield for vacuum propagation over the same distance.

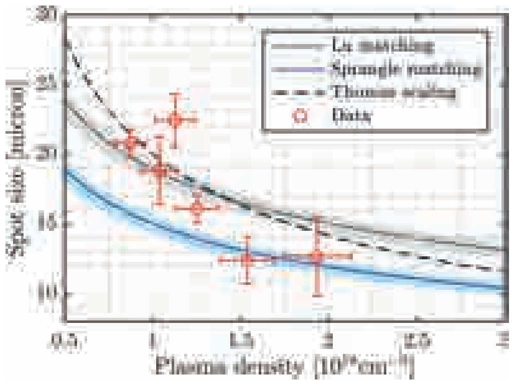

Figure 2: Variation of the measured exit mode size with plasma density for f/40 focussing optic with a 60 mm long gas cell.

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Comparative study of betatron radiation from different injection mechanisms in a gas jet

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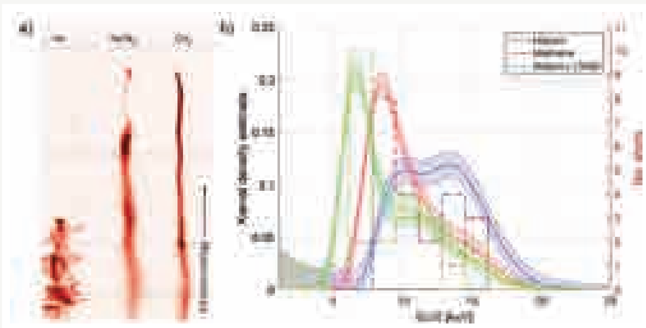
High power laser systems have enabled the development of compact particle accelerators, using plasma as the accelerating structure. Electron beams with energies in the GeV range are routinely produced using Gemini. A useful by-product of these accelerators is the generation of hard x-ray radiation, called betatron radiation, that is emitted as electrons oscillate in the focusing field present in the accelerator.

We investigate the generation of betatron radiation in three types of medium (helium, helium + 1% nitrogen, and methane clusters), and explore the various merits of each medium. The mechanism for electron injection into the wakefield is different in all these cases and influences the properties of the electron beams and radiation.

While self-injection produces betatron radiation with higher critical energies, ionisation and cluster injection achieves a higher x-ray flux. The critical energies for ionisation and cluster injected electron beams also exhibit a lower spread than self-injection.



a) Electron spectra generated by interaction with helium (self-injection), 1% nitrogen doped helium (ionisation injection) and methane (cluster injection).
b) Critical energy of emitted betatron radiation from the three targets.

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Polarization Dependence of Bulk Ion Acceleration from Ultrathin Foils Irradiated by High-Intensity Ultrashort Laser Pulses

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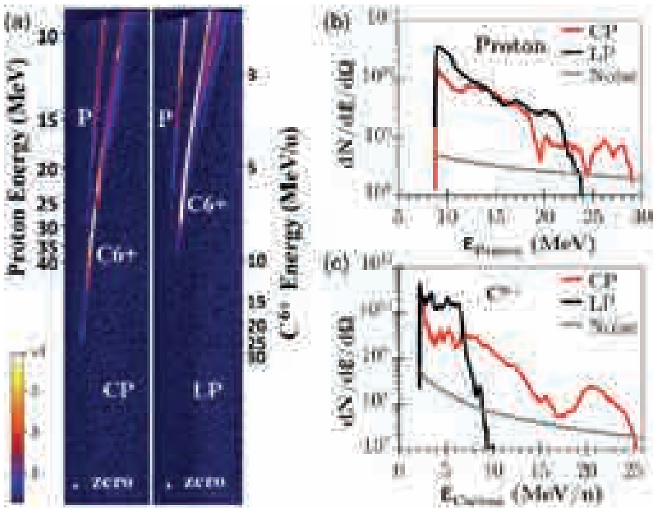
The acceleration of ions from ultrathin (10–100 nm) carbon foils has been investigated using intense (~6 × 10^{20} Wcm^{-2}) ultrashort (45 fs) laser pulses, highlighting a strong dependence of the ion beam parameters on the laser polarization, with circularly polarized (CP) pulses producing the highest energies for both protons and carbons (25 – 30 MeV/nucleon); in particular, carbon ion energies obtained employing CP pulses were significantly higher (~2.5 times) than for irradiations employing linearly polarized pulses. Particle-in-cell simulations indicate that radiation pressure acceleration becomes the dominant mechanism for the thinnest targets and CP pulses.



(a) Raw data from BAS-TR image plates for CP and LP laser pulses irradiating 10 nm amorphous carbon targets. The corresponding CP (red) and LP (black) background-subtracted proton (b) and C^{6+}spectra (c) with vertical axis units of particles/MeV/sr are also shown. The noise level of +2σ is also plotted.

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Low-Density Hydrodynamic Optical-Field-Ionized Plasma Channels Generated With An Axicon Lens

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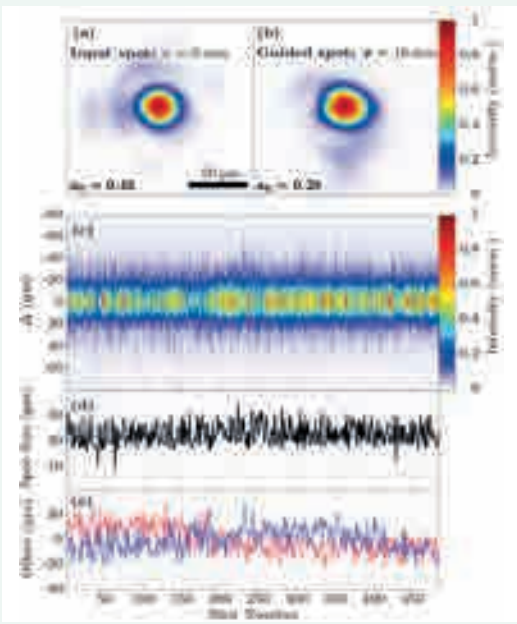
We demonstrate optical guiding of high-intensity laser pulses in long, low density hydrodynamic optical-field-ionized (HOFI) plasma channels. An axicon lens is used to generate HOFI plasma channels with on-axis electron densities as low as $n_e(0) = 1.5 \times 10^{17}$ cm^{-3} and matched spot sizes of a few tens of micrometres. 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 5Hz, 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 quasi-linear regime.



Transverse fluence profiles of the guided laser pulse at: (a) the entrance, and (b) the exit of a 16mm long HOFI channel. Panels (c)-(e) demonstrate the stability of the waveguides over 485 consecutive shots, showing (c) the transverse profile, (d) the D4σ spot size and (e) the vertical (blue) and horizontal (red) position of the spot centre.

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Experimental Observation of a Current-Driven Instability in a Neutral Electron-Positron Beam

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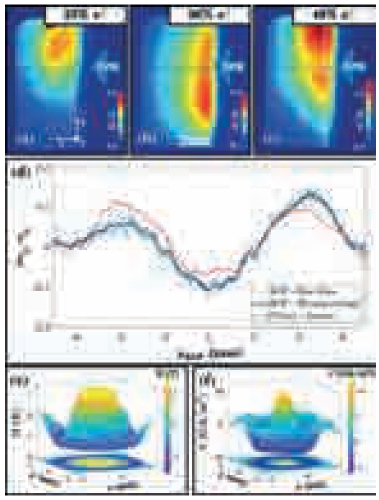
We report on the first experimental observation of a current-driven instability developing in a quasineutral matter-antimatter beam. Strong magnetic fields (≥ 1 T) are measured, via means of a proton radiography technique, after the propagation of a neutral electron-positron beam through a background electron-ion plasma. The experimentally determined equipartition parameter of $\epsilon_B \approx 10^{-3}$ is typical of values inferred from models of astrophysical gamma-ray bursts, in which the relativistic flows are also expected to be pair dominated. The data, supported by particle-in-cell simulations and simple analytical estimates, indicate that these magnetic fields persist in the background plasma for thousands of inverse plasma frequencies. The existence of such long-lived magnetic fields can be related to analogue astrophysical systems, such as those prevalent in lepton-dominated jets.



(a)–(c) Typical optical density of the proton radiographies of the background gas after the passage of the electron-positron beam for different percentages of positrons in the beam: 23% (a), 38% (b), and 48% (c). The beam propagates from right to left, as indicated by the arrow, with the main propagation axis represented by the dashed blue line. The spatial scale is common for all frames and refers to the interaction plane. Each radiograph is taken (280±30) ps after the transit of the EPB [corresponding proton energy of (1.1±0.5) MeV]. (d) Comparison between the experimental proton distribution and the output of the particle-tracing simulation for frame (c). The lineout position is highlighted by the white dashed rectangle in frame (c). and it is taken at the detection plane, with the spatial scale thus magnified by a factor M≃8. (e) Distribution of the azimuthal magnetic field used as an input for the particle-tracing simulation and (f) related current density.

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General features of experiments on the dynamics of laser-driven electron–positron beams

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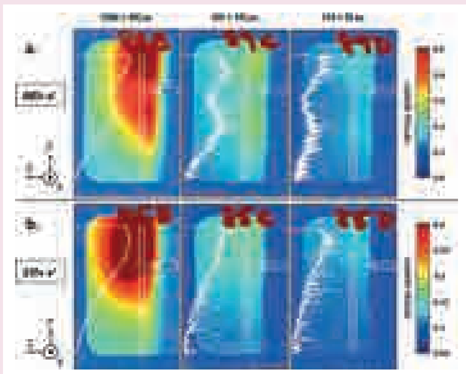
The experimental study of the dynamics of neutral electron–positron beams is an emerging area of research, enabled by the recent results on the generation of this exotic state of matter in the laboratory. Electron–positron beams and plasmas are believed to play a major role in the dynamics of extreme astrophysical objects such as supermassive black holes and pulsars. For instance, they are believed to be the main constituents of a large number of astrophysical jets, and they have been proposed to significantly contribute to the emission of gamma-ray bursts and their afterglow.
However, despite extensive numerical modelling and indirect astrophysical observations, a detailed experimental characterisation of the dynamics of these objects is still at its infancy. Here, we will report on some of the general features of experiments studying the dynamics of electron–positron beams in a fully laser-driven setup.



Proton radiographs of the background plasma after the propagation of a quasi-neutral EPB with 48% e+ population in row (a.), and a non-neutral EPB with 23% e+population in row (b.). Different columns correspond to different proton energies, and therefore, different probe times after the passage of the EPB (as labelled). Each row corresponds to a single shot, highlighting the multi-frame capability of this radiographic technique. The colour-bars represent the optical density on the RCFs for the respective rows, with a higher number corresponding to higher proton density). Lineouts (white solid line) are taken from the regions between the white-dashed lines. For an EPB with 23% e+ population (row b.), no clear modulation is seen on the proton radiographs (smooth monotonically decreasing profile, corresponding to the initial proton beam distribution). A pronounced modulation is observed for an EPB with 48% e+ population (row a.). The modulation can be seen on all three layers of RCF indicating that the magnetic fields responsible for modulation are long-lived within the background plasma.

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Simulated Optimisation of a 10 mJ Class, mid-IR Driven Laser Wakefield Accelerator Demonstrating a High Charge, MeV Electron Source Created via Extreme Laser Redshifting

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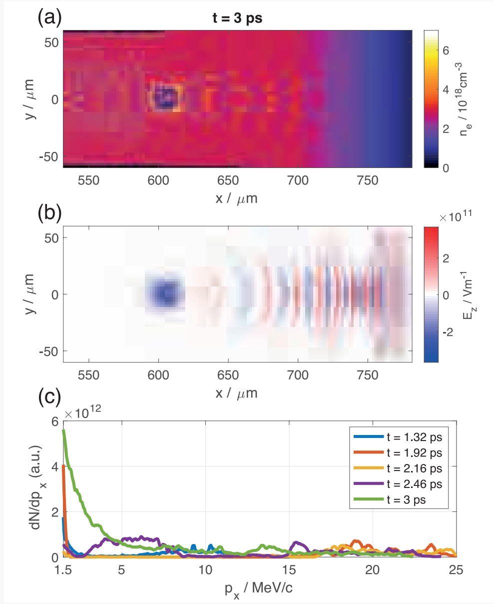
LWFA scalings were reviewed for mid-IR laser pulses, which must be more energetic for the same electron energy, but this is compensated for by a higher charge. A larger wakefield can be driven, which would be beneficial for diagnostics. 2D PIC simulations of LWFAs driven by a 25 mJ, 30 fs, 4 μm laser pulse (based on the Chimera system at Imperial College London) showed potential for a table-top source of 20-40 MeV electron beams, accelerated in easy to produce, millimetre-scale targets. For high ratios of electron to critical density there was a large redshift of the laser. Some of the light became so redshifted that the plasma was opaque to it and it became trapped, resembling the formation of a postsoliton. A large population of electrons was injected in to the approximately stationary postsoliton bubble and was accelerated up to 5 MeV. This effect was confirmed in 3D simulations.



A 2D PIC simulation of a Laser Wakefield Accelerator showing extreme laser red-shifting, causing some light to be trapped in the plasma. (a) shows the plasma density and (b) the laser electric field. (c) shows the electron momentum spectra at various times in the simulation. The stationary bubble driven by very long wavelength light, at t = 3 ps, is a bright source of few MeV electrons.

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Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme

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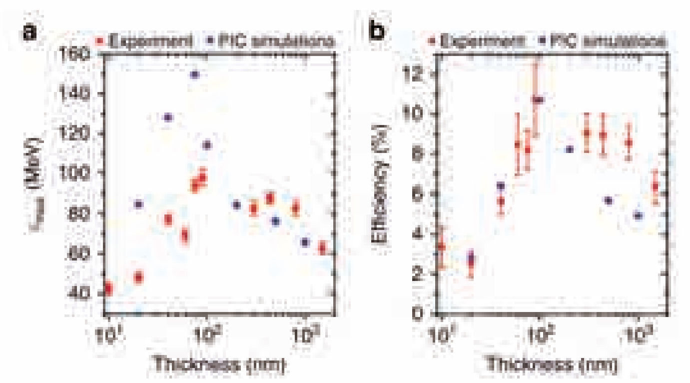
Laser-plasma ion acceleration offers several applications based on the compact and efficient nature of the interactions. This motivates research into novel acceleration schemes to improve the achievable ion energies.

In the ultrathin target regime, several acceleration mechanisms occur over the course of one laser pulse. Operating in this hybrid-acceleration regime allows for greater control of the ions accelerated through optimisation of the experimental conditions. Here we present experimental results of high-energy proton acceleration, exceeding 94 MeV, utilising radiation pressure and sheath acceleration processes. Via 2D particle in cell simulations, we find that target transparency leads to a double-peaked electrostatic field structure at the target rear. A jet of super-thermal electrons is then accelerated, which enhances the maximum energy that protons contained within that target can reach.



(a) Proton maximum energy scaling and (b) conversion efficiency scaling with target thickness.

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Reflection of intense laser light from microstructured targets as a potential diagnostic of laser focus and plasma temperature

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The spatial-intensity profile of light reflected during the interaction of an intense laser pulse with a microstructured target is investigated experimentally, and the potential to apply this as a diagnostic of the interaction physics is explored numerically.

Diffraction and speckle patterns are measured in the specularly reflected light in the cases of targets with regular groove and needle-like structures, respectively, highlighting the potential to use this as a diagnostic of the evolving plasma surface.

Ray-tracing and numerical modelling shows that, for a laser focal spot diameter smaller than the periodicity of the target structure, the reflected light patterns can potentially be used to diagnose the degree of plasma expansion and, by extension, the local plasma temperature at the focus of the intense laser light. The reflected patterns could also be used to diagnose the size of the laser focal spot during a high intensity interaction, when using a regular structure with known spacing.

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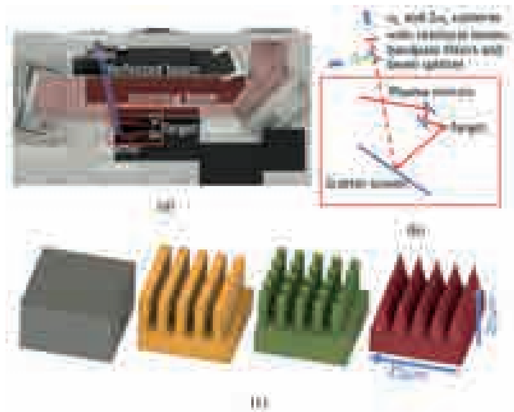

Figure1: (a) Plan view of the experiment arrangement. The incoming laser beam is shown in red and light reflecting out of chamber to the CCDs is shown in blue. (b) Schematic showing the path of the incoming laser beam (solid red line), from the double plasma mirror onto target and finally onto the scatter screen. The imaging line is shown by the dashed red line. (c) Schematic illustrating the four types of targets employed; From left to right: flat foil, grooves, pillars and needles.

Observation of extremely strong shock waves in solids launched by petawatt laser heating

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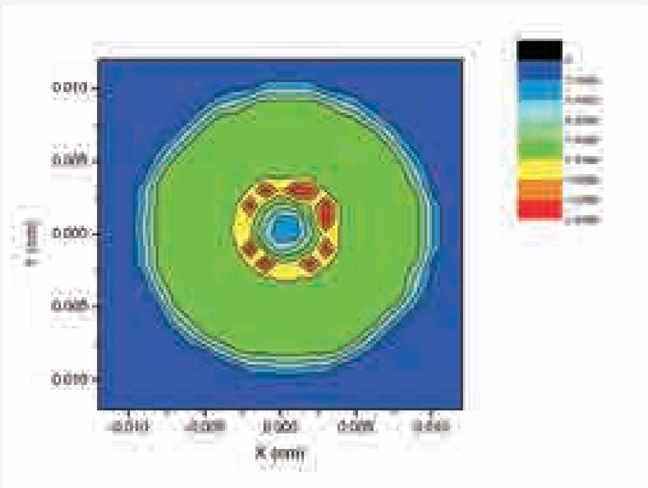
Understanding hydrodynamic phenomena driven by fast electron heating is important for a range of applications, including fast electron collimation schemes for fast ignition and the production and study of hot, dense matter. In this work, detailed numerical simulations modelling the heating, hydrodynamic evolution and XUV emission in combination with experimental XUV images indicate shock waves of exceptional strength (200 Mbar) launched due to rapid heating of material via a petawatt laser. In our recent publication in Physics of Plasmas (PoP 24, 083115, 2017), we discuss in detail the production of synthetic XUV images and how they assist us in interpreting experimental XUV images captured at 256 eV using a multi-layer spherical mirror. Experimental work was conducted at the VULCAN PW facility.



A synthetic time-integrated XUV image obtained by post processing the baseline radiation-hydrodynamic simulation output using the SPECT3D code (colour scale is in arbitrary units). The imager is assumed to look at the target's rear surface along the target normal.

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Experimental demonstration of a compact epithermal neutron source based on a high power laser

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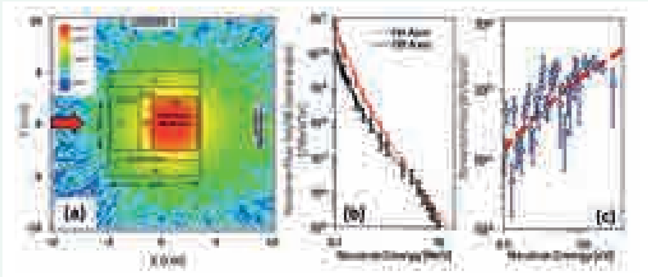
The current trend in the development of laser-driven fast neutron sources warrants investigation of producing sources with lower neutron energies. While fast neutrons are useful in applications such as radiography, most of the applications can be realised at wavelengths closer to materials scattering/diffraction lengths. In particular, sources of epithermal neutrons (eV-100keV) are of high interest for a wide range of applications, from material science to nuclear waste transmutations and healthcare.

An experiment was performed employing the Beam 7 arm of Vulcan laser to moderate the fast neutrons (~MeV), produced via pitcher-catcher technique, into the epithermal region (0.5 eV-0.1 keV) employing a compact moderator. Using ^{3}He proportional counters, the epithermal flux of ~ 10^5 n/Sr/pulse in the energy range 0.5-300 eV was measured in the experiment. While these proof-of-principle results are encouraging, there is significant scope for further optimisation of the epithermal neutrons flux by optimising the moderator design as well as the fast neutron source.



(a) The design of the moderator superimposed on the neutron (in the range 1eV-1keV) flux distribution across the mid-plane of the moderator, obtained from MCNPX simulation for 1 MeV neutrons entering the moderator from the left side (shown by red arrow). (b) A typical spectrum of fast neutrons produced in the experiment, measured by two scintillator detectors, one along the axis and the other 35° off axis. (c) Epithermal neutron spectrum generated by the moderator, averaged over 16 measurements, where the red line is an eye-guide to the data points.

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An ultra-high gain and efficient amplifier based on Raman amplification in plasma

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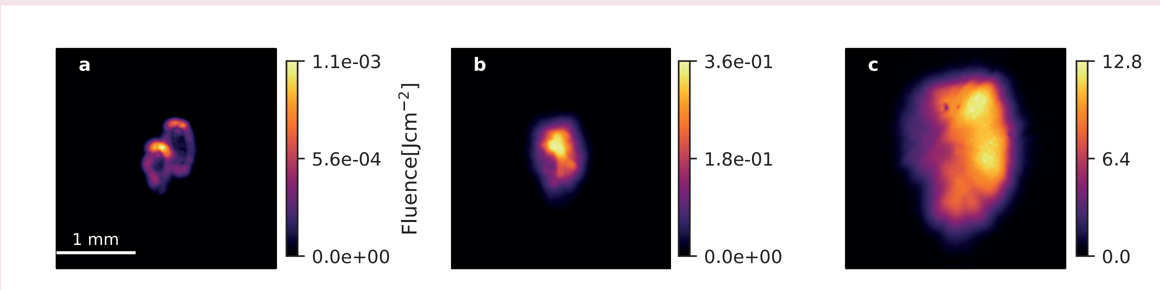
Raman amplification arising from the excitation of a density echelon in plasma could lead to amplifiers that significantly exceed current power limits of conventional laser media. Here we show that 1 – 100 J pump pulses can amplify picojoule seed pulses to nearly joule level. The extremely high gain also leads to significant amplification of backscattered radiation from "noise", arising from stochastic plasma fluctuations that competes with externally injected seed pulses, which are amplified to similar levels at the highest pump energies. The pump energy is scattered into the seed at an oblique angle with 14 J sr^{-1}, and net gains of more than eight orders of magnitude. The maximum gain coefficient, of 180 cm^{-1}, exceeds high-power solid-state amplifying media by orders of magnitude. The observation of a minimum of 640 J sr^{-1} directly backscattered from noise, corresponding to ≈10% of the pump energy in the observation solid angle, implies potential overall efficiencies greater than 10%.



Transverse profile of the Raman signal. Recorded beam profiles for three different nominal pump energies: (a) 3 J, (b) 20 J, (c) 70 J.

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Development of focusing plasma mirrors for ultraintense laser-driven particle and radiation sources

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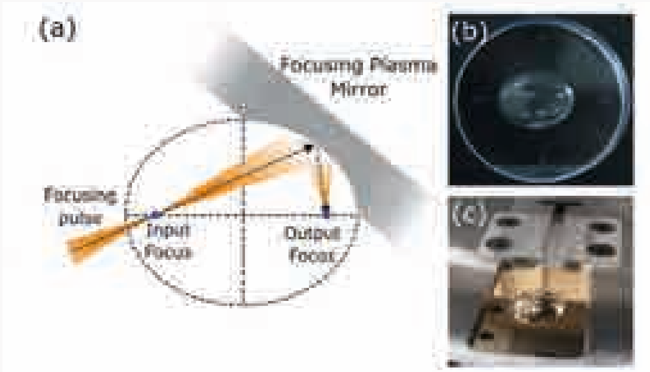
Increasing the achievable peak intensity of high power laser pulses opens up new regimes of laser-plasma interactions, resulting in enhanced ion energies and more efficient photon generation. Here we report on a programme of work to design, manufacture and optimise a small F-number focusing plasma mirror concept, capable of increasing the peak intensity of the Vulcan-PW laser system. This optic form, which re-images and demagnifies the laser focus, is small, enhances pulse intensity contrast and eliminates the requirement to expose conventional optics directly to target debris. It is thus an attractive approach for achieving higher intensities, without requiring significant alteration to the laser. Two approaches for manufacturing this innovative optic are described, namely diamond machining and injection moulding, and the results of characterisation tests are presented. The method developed to align these optics on the Vulcan-PW laser is outlined, together with initial results from their deployment.



(a) Illustration of ellipsoidal focusing plasma mirror concept. Images of (b) the manufactured diamond machined optic and (c) the injection moulding tool.

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