High energy density and high intensity physics

Generation of Intense Second Harmonic Light from Aperture Targets

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This report provides a summary of the development of experimental methodologies to enable the investigation of a novel plasma-based mechanism for the generation of higher order mode (HOM) at relativistic intensities, using the Gemini laser system in early 2022.

This mechanism involved the interaction between a high intensity (>10^{18} W/cm^2) laser pulse and a micron-diameter aperture target, leading to several obstacles to overcome experimentally.

These obstacles included mitigating the on-shot spatial jitter of the laser pointing, locating and accurately aligning the aperture to laser focus and a target design which would facilitate high repetition rate operation through automated or precision target placement.

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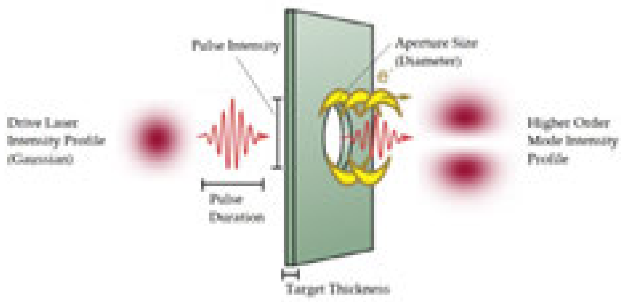

Figure 1: Schematic of the plasma-based HOM generation mechanism, adapted from [1].

[1] E.F.J. Bacon et al. High order modes of intense second harmonic light produced from a plasma aperture. Matter and Radiation at Extremes} **7***, 5 (2022)*

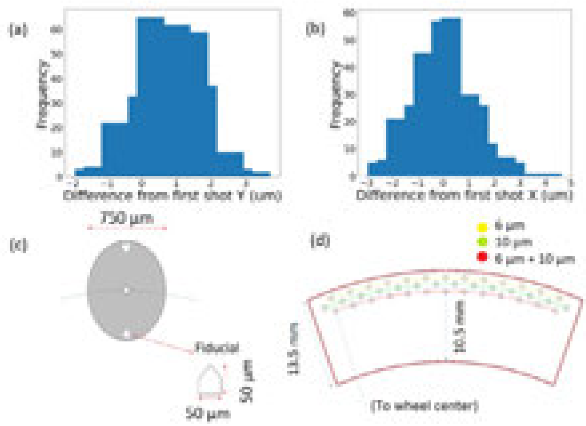

Figure 2: (a) and (b) are histograms of the movements of the focal spot between each shot in Y and X directions, respectively. (c) placement of a fiducial relative to an aperture. (d) segment of the target wheel developed for this experiment.

Effect of laser temporal intensity skew on enhancing pair production in laser—electron-beam collisions

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Recent high-intensity laser experiments (Cole *et al.* *2018 Phys. Rev. X* **8** 011020; Poder *et al.* 2018 *Phys. Rev. X* **8** 031004) have shown evidence of strong radiation reaction in the quantum regime.

Experimental evidence of quantum effects on radiation reaction and electron–positron pair cascades has, however, proven challenging to obtain and crucially depends on maximising the quantum parameter of the electron (defined as the ratio of the electric field it feels in its rest frame to the Schwinger field). The quantum parameter can be suppressed as the electrons lose energy by radiation reaction as they traverse the initial rise in the laser intensity.

As a result the shape of the intensity temporal envelope becomes important in enhancing quantum radiation reaction effects and pair cascades. Here we show that a realistic laser pulse with a faster rise time on the leading edge, achieved by skewing the temporal envelope, results in curtailing of pair yields as the peak power is reduced. We find a reduction in pair yields by orders of magnitude in contrast to only small reductions reported previously in large-scale particle-in-cell code simulations (Hojbota *et al. 2018 Plasma Phys. Control. Fusion* **60** 064004). Maximum pairs per electron are found in colliding 1.5 GeV electrons with a laser wakefield produced envelope 7.90×10^{-2} followed by a short 50 fs Gaussian envelope, 1.90×10^{-2}, while it is reduced to 8.90×10^{-5}, a factor of 100, for an asymmetric envelope.

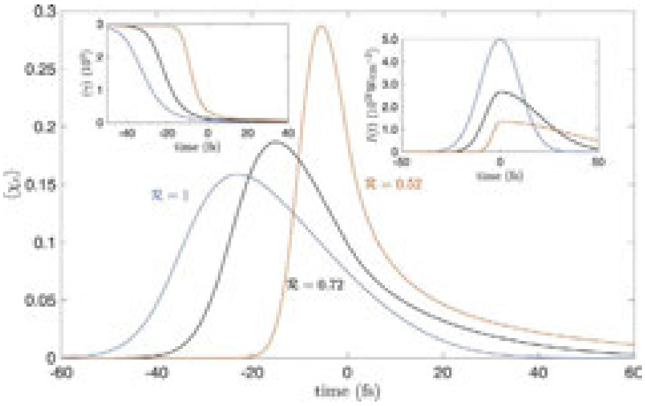

Figure 1: Average electron quantum parameter $\chi_e(t)$ for a Gaussian with different amounts of skew (right inset) using the closed form solution in equations (7) (left inset) and (8) with different reduction factors R. The equations can be found in the published paper.

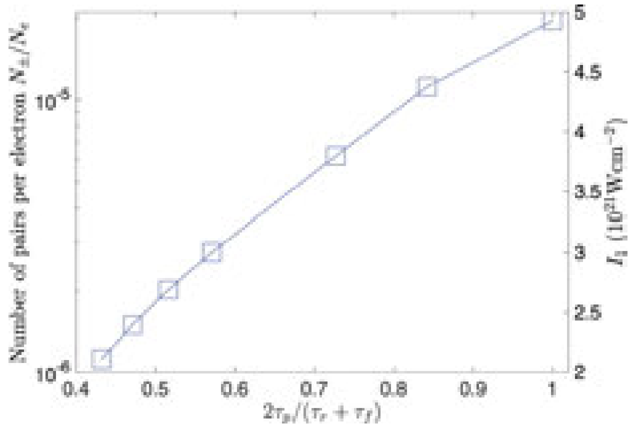

Figure 2: PIC code results showing the electron–positron pair yields per electron $N_{\pm}/N_e$ as the laser envelope is skewed. As the rising edge of a $I_0 = 5 \times 10^{21}$ W cm^{-2} Gaussian laser pulse becomes faster, the peak intensity drops by a factor R giving the new peak intensity $I_1 = RI_0$ displayed on the right-hand axis.

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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 characterisation of an x-ray source, generated by a laser-driven plasma wakefield accelerator. The spectrum of the optimised source was consistent with an on-axis synchrotron spectrum with a critical energy of $13.8^{+2.2}_{-1.9}$ keV and the number of photons per pulse generated above 1 keV was calculated to be $6^{+1.2}_{-0.9} \times 10^9$. The x-ray beam was used to image a resolution grid placed 37 cm from the source, which gave a measured spatial resolution of 4 µm × 5 µm. The inferred emission region had a radius and length of 0.5 ± 0.2 µm and 3.2 ± 0.9 mm respectively. It was also observed that laser damage to the exit aperture of the gas cell led to a reduction in the accelerated electron beam charge and a corresponding reduction in x-ray flux due to the change in the plasma density profile.

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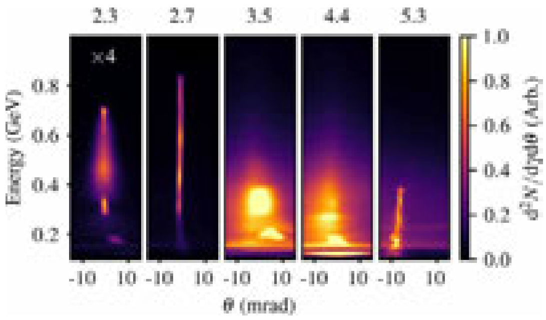

Figure 1: Angularly resolved electron spectra for different plasma densities. The plasma density given on top of each image is given in units of 10^{18} cm^{-3}. The spectrum in the left-most panel has been multiplied by 4 to make it visible on the same colour scale.

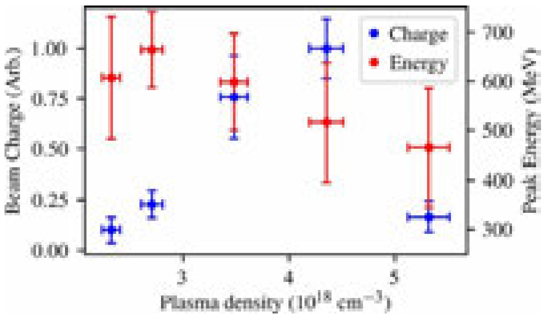

Figure 2: Dependence of the electron bunch charge and maximum electron energy on the plasma density. Each point shows the mean and standard deviation of between 16 and 21 electron spectra.

Industrial imaging using bremsstrahlung generated by a laser-plasma accelerator

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Laser-plasma accelerators can generate bright x-ray beams with attractive properties for imaging applications. They have the potential to surpass the image quality and acquisition rates achievable with commercially available machines – a major motivation for the Extreme Photonics Applications Centre (EPAC), under construction at the CLF. In collaboration with Rolls-Royce, we performed a proof of principle experiment in Gemini Target Area 3 to explore the capability of laser-driven bremsstrahlung x-rays to provide high quality imaging of large, high-density components.

The sample was a rotor that has been used on a demonstrator project for developing high power density electric machines. Rolls-Royce need to analyse the internal features of this rotor without disassembly because this would disturb the underlying structure. This type of non-destructive inspection (NDI) is difficult to achieve with conventional sources, and is a perfect test-case for the unique properties of the radiation beams that will be generated using EPAC.

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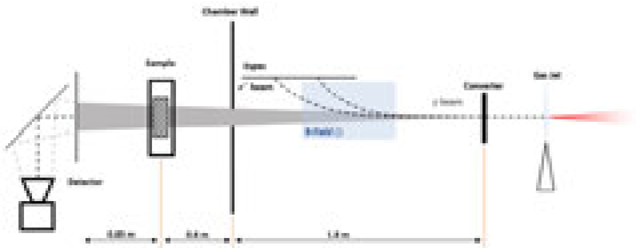

Figure 1: Experimental layout for production and use of bremsstrahlung radiation from laser wakefield acceleration.

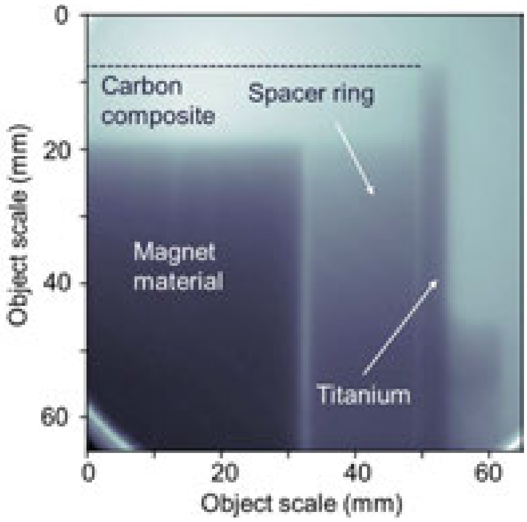

Figure 2: Radiograph of Rolls Royce rotor obtained using bremsstrahlung generated with Gemini.

Investigation of the ejected mass during high-intensity laser solid interaction for improved plasma mirror generation

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The interaction of very intense and ultrashort laser pulses with solid targets is a topic that has attracted a large amount of interest in science and applications. This interest is boosted by the large progress made in the development of high repetition rate, high-power laser systems. With the significant increase in average power, there is concern about how to deal with ablated debris that may lead to contamination and damage during interaction experiments with solid targets.

This issue is also highly relevant in experiments that include plasma mirrors. These are often employed to increase the contrast ratio of the intense laser pulse to unwanted laser pre-pulses from the amplifier chain and/or the background of amplified spontaneous emission.

For this reason, the present work investigates the mass ejected from the target into vacuum for different conditions, particularly those present when plasma mirrors are introduced. The total amount of ablated mass can be reduced by making use of a temporally controlled plasma expansion that enhances the plasma mirror reflectivity. In this way, high intensity laser interaction experiments can be carried out with efficient and clean plasma mirrors significantly reducing the degradation of the laser optics and plasma diagnostics placed near the interaction.

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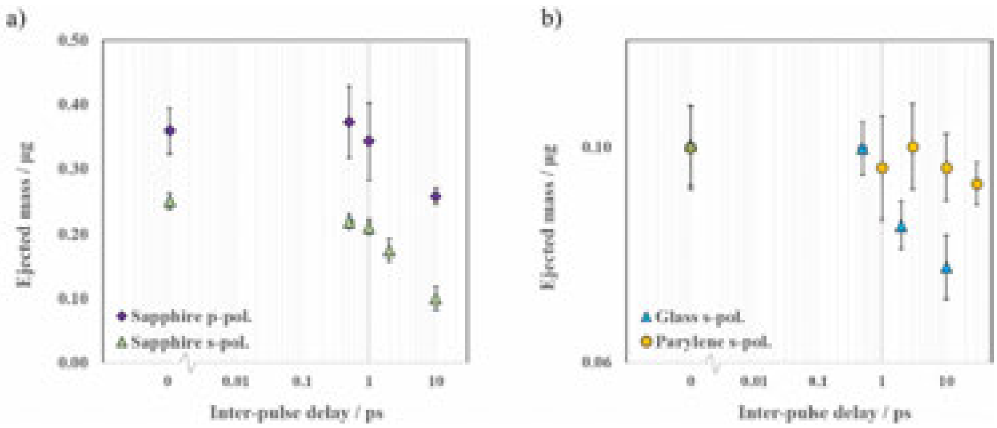

Experimental results showing the ablated mass m_{abl} from the target material ejected into the vacuum as a function of the inter-pulse delay. The first data point in both graphs at 0 ps inter-pulse delay represents a single pulse ablation. (a) Results on the ablation of sapphire showing variation with polarisation. (b) Difference between ablation of glass and parylene, both data sets were obtained in s-polarisation.

A laser–plasma platform for photon–photon physics: the two photon Breit–Wheeler process

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We describe a laser–plasma platform for photon–photon collision experiments to measure fundamental quantum electrodynamic processes. As an example we describe using this platform to attempt to observe the linear Breit–Wheeler process.

The platform has been developed using the Gemini laser facility at the Rutherford Appleton Laboratory. A laser wakefield accelerator and a bremsstrahlung convertor are used to generate a collimated beam of photons with energies of hundreds of MeV, that collide with keV x-ray photons generated by a laser heated plasma target.

To detect the pairs generated by the photon–photon collisions, a magnetic transport system has been developed which directs the pairs onto scintillation-based and hybrid silicon pixel single particle detectors (SPDs).

We present commissioning results from an experimental campaign using this laser–plasma platform for photon–photon physics, demonstrating successful generation of both photon sources, characterisation of the magnetic transport system and calibration of the SPDs, and discuss the feasibility of this platform for the observation of the Breit–Wheeler process. The design of the platform will also serve as the basis for the investigation of strong-field quantum electrodynamic processes such as the nonlinear Breit–Wheeler and the Trident process, or eventually, photon–photon scattering.

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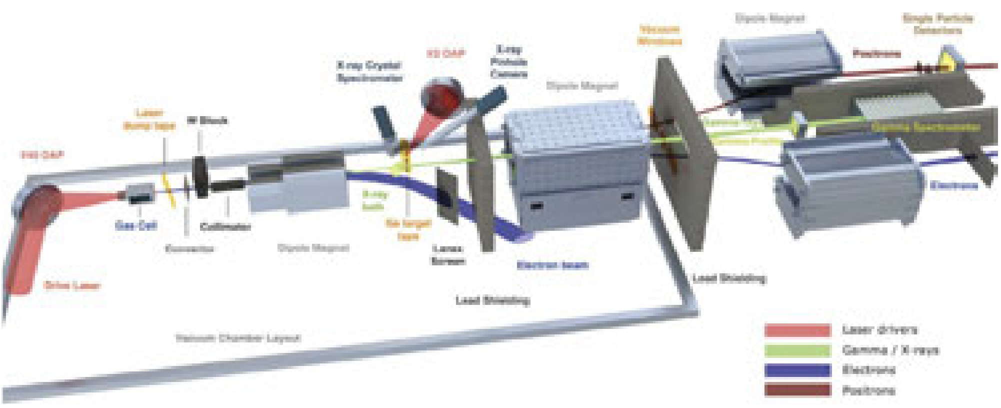

The experiment setup. An f/40 laser pulse was used to drive a laser-wakefield accelerated electron beam in a gas cell. This high-energy electron beam was used to create on axis γ-rays before being swept away by a magnet. A second laser pulse was incident on a germanium target tape, driving an x-ray bath through which the γ beam passed. Any particle pairs created in this interaction region propagate on axis and are swept away to SPDs using a magnetic transport system.

Parametric study of high-energy ring-shaped electron beams from a laser wakefield accelerator

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Laser wakefield accelerators commonly produce on-axis, low-divergence, high-energy electron beams. However, a high charge, annular shaped beam can be trapped outside the bubble and accelerated to high energies. Here we present a parametric study on the production of low-energy-spread, ultra-relativistic electron ring beams in a two-stage gas cell. Ring-shaped beams with energies higher than 750 MeV are observed simultaneously with on axis, continuously injected electrons.

Often multiple ring shaped beams with different energies are produced and parametric studies to control the generation and properties of these structures were conducted. Particle tracking and particle-in-cell simulations are used to determine properties of these beams and investigate how they are formed and trapped outside the bubble by the wake produced by on-axis injected electrons. These unusual femtosecond duration, high-charge, high-energy, ring electron beams may find use in beam driven plasma wakefield accelerators and radiation sources.

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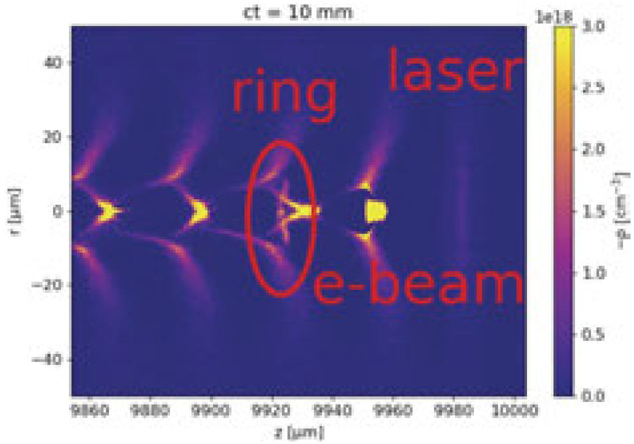

Figure 1: Electron density distribution obtained using FBPIC shows both the ring-shaped and the on-axis electron beams produced by a laser pulse with an initial a_0 = 1.35 focused inside the gas cell (at z = 3 mm). This snapshot is taken after 10 mm propagation.

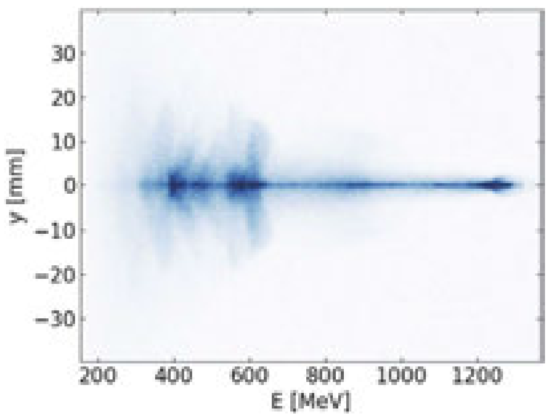

Figure 2: Electron spectrum obtained from FBPIC simulations reported in figures 9(b) and 10(b) (see published paper) transported using GPT through a set up reproducing the experimental one.

Selective Ion Acceleration by Intense Radiation Pressure

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We report on the selective acceleration of carbon ions during the interaction of ultrashort, circularly polarized and contrast-enhanced laser pulses, at a peak intensity of 5.5×10^{20} W/cm^2, with ultrathin carbon foils. Under optimized conditions, energies per nucleon of the bulk carbon ions reached significantly higher values than the energies of contaminant protons (33 MeV/nucleon vs 18 MeV), unlike what is typically observed in laser-foil acceleration experiments.

Experimental data, and supporting simulations, emphasize different dominant acceleration mechanisms for the two ion species and highlight an (intensity dependent) optimum thickness for radiation pressure acceleration; it is suggested that the preceding laser energy reaching the target before the main pulse arrives plays a key role in a preferential acceleration of the heavier ion species.

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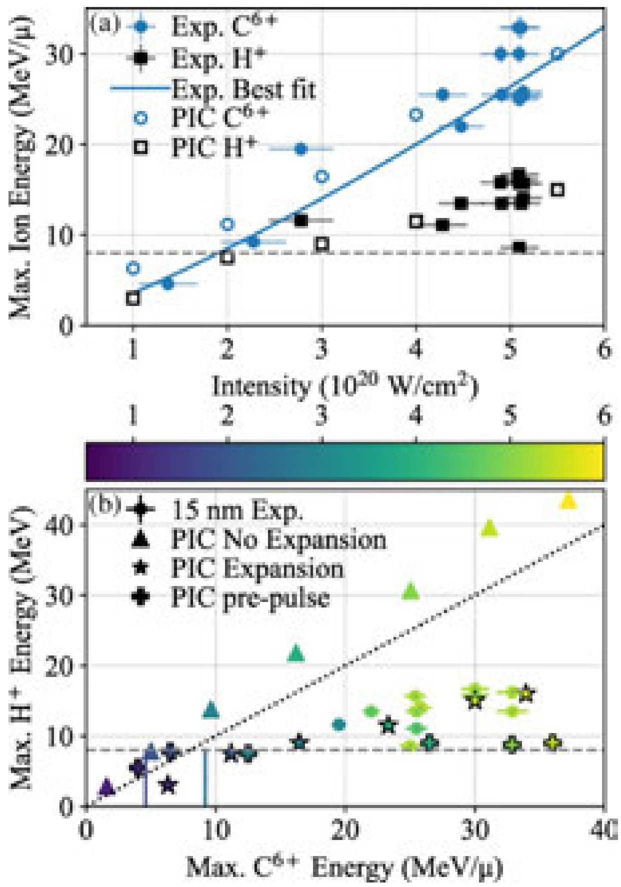

(a) Maximum ion energy as a function of laser intensity for experimental measurements of C^{6+} (filled blue circles) and H^+ (filled black squares). 2D PICs with expansion included are also shown with the same markers but empty. The solid line represents the best fit line to the C^{6+} experimental data, $\propto I^{1.2\pm0.2}$. (b) Correlation between C^{6+} and H^+ maximum energies for experimental and simulation data (marker colors indicate the laser intensity). Dotted line indicates where C^{6+} and H^+ energies are equal. The dashed line at y = 8 MeV in (a) and (b) represents the detection threshold for protons, and the maximum proton energy did not meet this threshold for the two lowest intensity shots. Crosses indicate simulations which included a prepulse with a peak intensity of 10^{17} W/cm^2 arriving on target 2.5 ps before the peak of the main pulse.

Kinematics of femtosecond laser-generated plasma expansion: Determination of sub-micron density gradient and collisionality evolution of over-critical laser plasmas

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An optical diagnostic based on resonant absorption of laser light in a plasma is introduced and is used for the determination of density scale lengths in the range of 10 nm to >1 µm at the critical surface of an overdense plasma. This diagnostic is also used to extract the plasma collisional frequency, allowing inference of the temporally evolving plasma composition on the tens of femtosecond timescale. This is found to be characterized by two eras: the early time and short scale length expansion (L < 0.1λ), where the interaction is highly collisional and target material dependent, followed by a period of material independent plasma expansion for longer scale lengths (L > 0.1λ); this is consistent with a hydrogen plasma decoupling from the bulk target material. Density gradients and plasma parameters on this scale are of importance to plasma mirror optical performance and comment is made on this theme.

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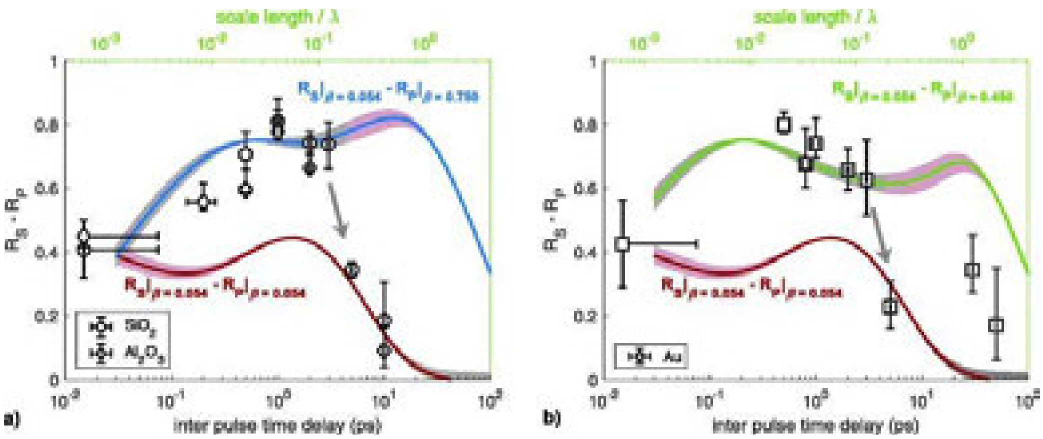

[(a) and (b)] The difference in reflected energy fraction between s- and p-polarized interactions for three different collisionality ratios as calculated from the analytic model is shown by lines. This is compared to the experimentally measured values for (a) BK7 glass and sapphire, and (b) gold. (a) $\beta_P > \beta_S$, represented by the blue line, best fits the data for scale lengths less than around 125 nm, whilst for scale lengths longer than this, the red line representing $\beta_P = \beta_S$ better fits the experimental data. (b) Qualitatively the same trend is observed for gold. In both cases, the error bar in the model represents the effect of changing the collision frequency by 10% and its colour is intended to guide the eye to its region of validity, grey being where the model fits the data, and red being where it does not. A summary of the best fitting parameters for the model is presented in Table I in the published paper.

Measuring multi-tesla, transient magnetic fields in laser-driven coils using dual-axis proton deflectometry

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In this paper, we show that quantitative measurements using perpendicular probing are complicated by the presence of GV/m electric fields in the target that contribute to the proton deflection and can produce significant errors in the magnetic field measurement. Probing parallel to the coil axis with fiducial grids, we demonstrate that electric and magnetic field measurements can be reliably separated by recording the rotation of the grid shadow in the proton images.

Comparing our experimental proton data with particle-in-cell simulations, we estimate that currents of order I ≈ 5 kA were generated in 1 mm- and 2 mm-diameter wire loops using a ~550 J, ns-duration laser drive from Vulcan West.

We also present an analytic model of proton deflection in electric and magnetic fields that can be used to benchmark results from particle-in-cell codes and help deconvolve the magnetic and electric field deflections using a proton energy scaling.

Building on these results, a new experimental platform for measuring multi-tesla, laser-generated magnetic fields is proposed using a single-plate target with a miniature coil integrated into the target support.

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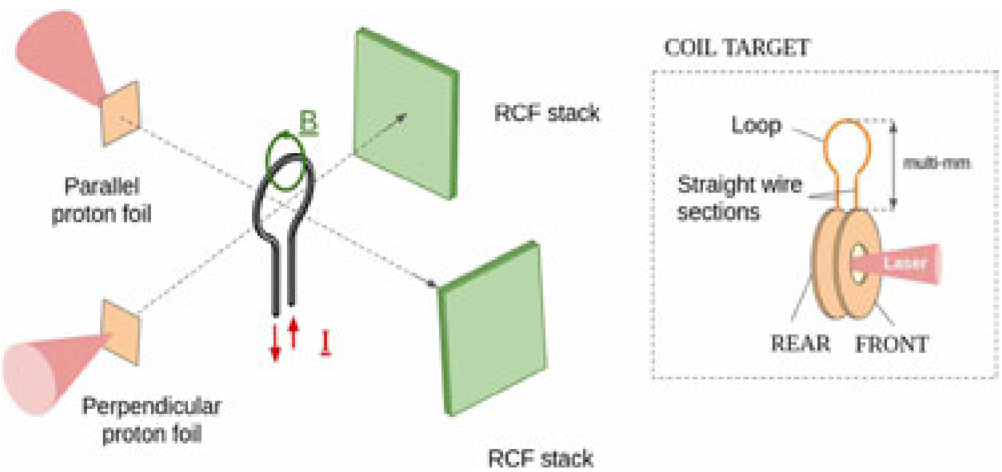

Schematic representation of the dual-axis experiment.

Measuring the principal Hugoniot of inertial-confinement-fusion-relevant TMPTA plastic foams

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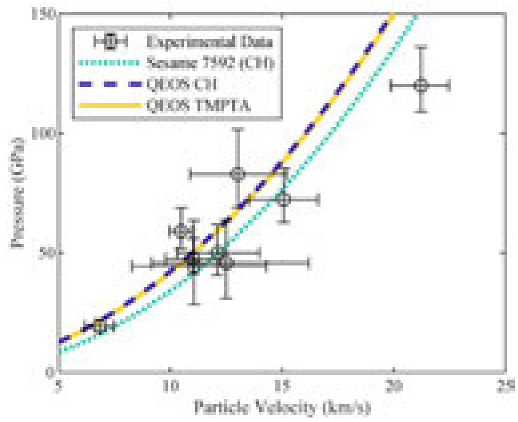
Simulations involving foam materials (such as those of ICF capsules with DT-wetted-foam layers) often describe the foam using EOS models for homogeneous materials. To test the accuracy of this approximation, an experiment was performed at the CLF to measure principal Hugoniot data of TMPTA foam at 0.26 g/cm^3 (the density of DT-wetted foams, and of the foam in recently proposed 'hydrodynamic-equivalent' capsules).

Vulcan was used to drive a shock through a multi-layer target containing an α-quartz reference and the TMPTA foam. VISAR was used to measure the average shock velocity in these two materials, and an impedance matching calculation performed to determine the foam shock state achieved in each shot. SOP was used to estimate the temperature of the shocked foam. The results suggest that, for the 20 – 120 GPa pressure range accessed, this material can be reasonably well described using existing EOS models for homogeneous plastics.



Experimentally determined principal Hugoniot states in the TMPTA foam, compared to a range of EOS models for homogenous plastics. These models well describe the data to within the accuracy of the experiment.

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Generation of photoionized plasmas in the laboratory of relevance to accretion-powered x-ray sources using keV line radiation

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In this paper we describe an experiment to generate x-ray photoionized plasmas in the laboratory, of relevance to accretion-powered x-ray sources such as neutron star binaries and quasars, which includes significant improvements over similar previous work. One of the key astrophysical plasma properties of interest is the photoionization parameter, $\xi=4\pi F/n_e$ where F is the x-ray flux and n_e the electron density. We demonstrate that we can achieve values of ξ >100 erg-cm s^{-1} using laser-plasma x-ray sources, in the regime of interest for several astrophysical scenarios.

In particular, we show that our use of a keV line source, rather than the usual quasi-blackbody radiation fields normally employed in such experiments, has allowed us to generate the same ratio of inner-shell to outer-shell photoionization as that expected from a blackbody source with ~keV spectral temperature. This is also a key factor in allowing experiments to be compared to the predictions of codes employed to model astrophysical sources.

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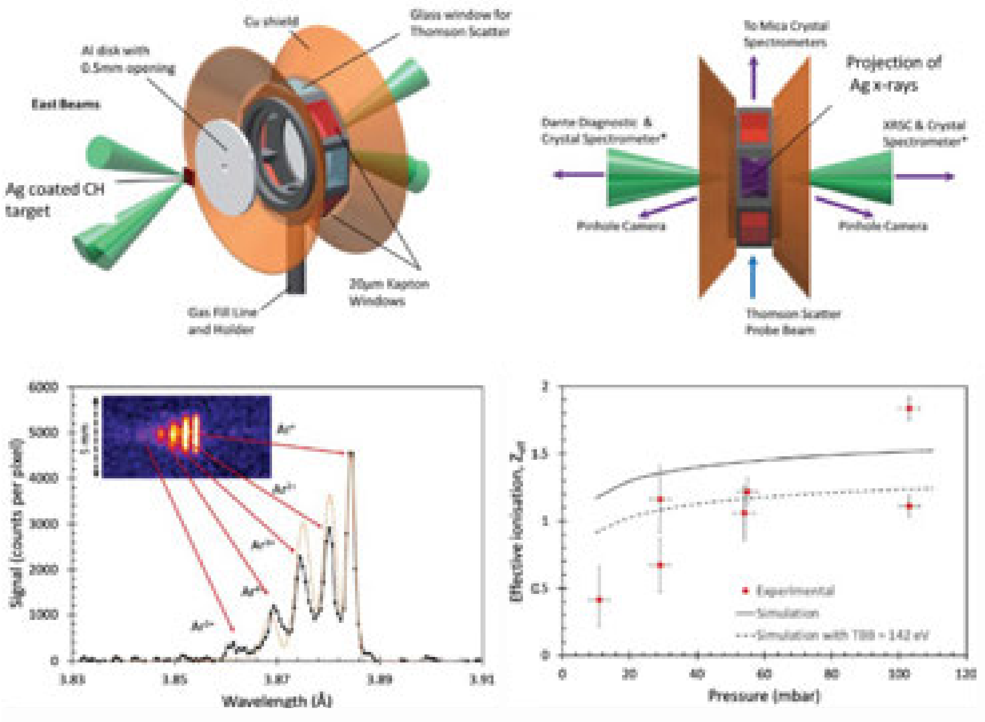

Top: Gas cell target for photoionisation experiment. The Ar gas fill varied from 10-500 mbar. The end windows were CH coated with Ag. L-shell x-rays from the Ag photoionised and heated the Ar plasma.

Below Left: A spherical crystal spectrometer was used to spatially resolve the K- β fluorescence.

Below right: The fluorescence was used to estimate an effective ionisation state that could be compared to simulation using an in-house time dependent code.

Triggering and probing electromagnetic stochasticity in a low-density magnetized plasma irradiated by a multi-speckled laser beam

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The triggering of electromagnetic stochasticity in magnetized plasmas via high-power lasers is investigated by sending a nanosecond-duration, multi-speckled laser pulse into a low-density gas, coupled with a strong, initially homogeneous, external magnetic field perpendicular to the laser pulse. Detailed characterization of the induced electromagnetic structures is realized through proton radiography, in addition to Thomson scattering measurements for the background plasma heating.

The experiment is performed using an intense short-pulse laser and several long-pulse lasers, at the Vulcan Target Area West laser facility at the Rutherford Appleton Laboratory. Additionally, the energy spectrum of MeV protons propagated through the plasma is registered with a Thomson parabola. This allows us to assess the impact of the stochastic EM structures in the plasma on the transport of the collisionless proton beam.

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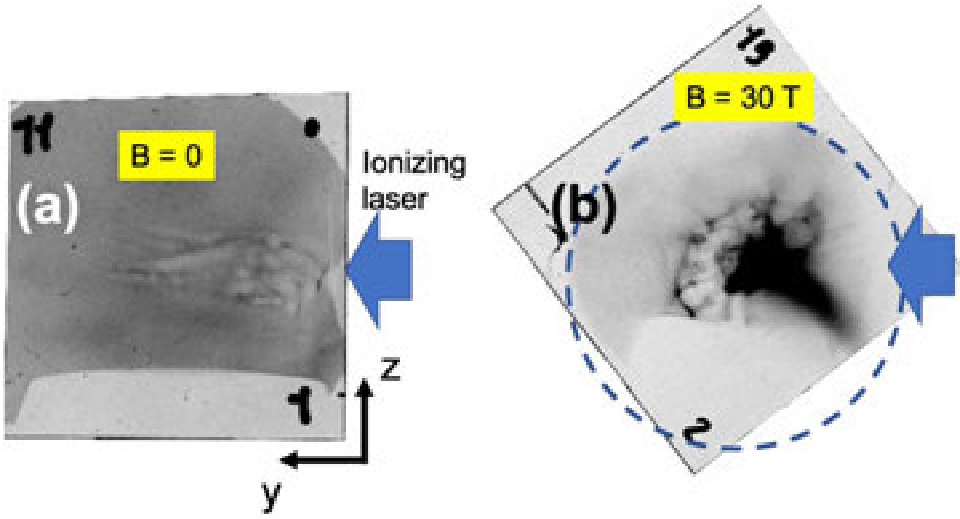

Proton radiography results (a) without and (b) with external applied magnetic field. In both cases the gas pressure is 25 bars, and the time delay (between the long, ionizing beam and the short pulse beam that drives the probing protons) is 0.7 ns.