Multi MegaGauss magnetic field and electron anisotropy measurements in ultra-relativistic plasmas

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Abstract

The magnetic fields created in ultra-intense laser plasma interactions and the effect that they have on the electron distribution and transport through the plasma is a fundamental question which has so far gone unanswered. Little is known of the magnetic fields generated in plasmas beyond the critical density layer, where the primary method of energy transport is via fast electrons. However, probing this energy deposition is extremely difficult due to the solid densities of the plasma generated in these ultra-intense interactions. Here, we show that anisotropy in electron beam distribution can be studied combining optical and x-ray spectroscopic measurements.

Magnetic fields in laser produced plasmas are generated by hot electron currents generated at the interaction. Since the absorption is at a maximum at the critical density layer, the amplitude of hot-electron generated magnetic fields are maximised around the critical layer. The magnetic fields and the return currents from the solid density material behind the critical layer, in turn influence the propagation of hot electrons through the target. The distribution of hot electrons is a central to the fast-ignition-based laser fusion studies as they are the primary means of energy transport to the fusion pellet. However, conventional probing techniques are not capable of accurately measuring this, due to the solid density material involved. Here we show that, by combining x-ray and optical polarimetry, the hot electron propagation through solid targets can be inferred. X-rays originated by inner shell transitions within the target material carry signatures of electron distribution within the target. The effect of propagation on hot electron distribution can be inferred by measuring the magnetic field-induced birefringence in the plasma at the rear of the target. Here we provide the preliminary experimental results of this unique combination of probing techniques.

Both probing techniques are based on the influence of hot electron beams on the surrounding plasma. The hot electron and cold return currents [2,3], generate magnetic fields inside the solid density plasma, which in turn controls the electron beam distribution inside the target. A beam of electrons can excite ground state ions and anisotropically populate atomic magnetic sub-levels. Radiation emitted during de-excitation from these sub-shells is polarised, and by measuring the degree of polarisation of the radiation with X-ray spectroscopy it is possible to ultimately infer properties of the exciting electron beam [4] including the directional anisotropy of the exciting electrons and the magnetic fields inside a solid target.

The effect of propagation on hot electron beams can be monitored by optical polarimetry at the rear side of the target. The magnetic fields generated by hot electrons can induce birefringence in the plasma at the rear side of the target. An optical probe reflecting from the critical layer can acquire polarisation changes from this birefringence. By measuring the Stokes parameters of the reflected probe, it is therefore possible to infer details about spatial distribution the magnetic fields and in turn the hot electron distribution [1]. By changing the delay between the driving pulse and the probe, it is possible to study the temporal evolution of the magnetic fields at the rear surface.

The experiments were undertaken using the Vulcan Petawatt facility of the Central Laser Facility, UK. The beam contained a maximum of 420 J on target in pulse durations between 600 fs and 2.5 ps, with focal spots of 3×3 μm and 6×6 μm diameters, leading to on target irradiances of $2 – 5 \times 10^{20}$ Wcm^{-2}. The targets consisted of thin foils (25 μm thick, 100 × 100 μm^2) of polysulphone ($C_{27}H_{26}O_6S$) for polarisation measurements and polished aluminium and mylar targets of varying thickness in 1×1 mm^2 for the magnetic field measurements.

Measurements of the degree of polarisation are recorded using an orthogonal pair of HOPG crystals (grade ZYA with a mosaic spread of 0.4° ± 0.1°) positioned at 200 mm ± 5mm above the target parallel to the fast electron quantisation axis. HOPG crystals are ideal diagnostics in the noisy environment of the petawatt interaction chamber, as their high reflectivity allows single shot spectroscopy measurements. The Ly-α doublet ($2p_{3/2,\,1/2}$ - $1s_{1/2}$) is observed for the polarisation measurements, with the advantage of these lines being that Ly-α_2 ($2p_{1/2,}$ - $1s_{1/2}$)

emission is unpolarized [5], which allows us to use this emission line as an on-shot calibration of the spectrometer pair. Figure 1 shows a lineout of the X-ray emission spectra from the two spectrometers, the degree of polarization is given by $P = \frac{I_\pi - I_\sigma}{I_\pi + I_\sigma}$ [6] and is calculated from the calibrated line intensities of the Ly-α_1 spectra. From the Ly-α_1 spectra in figure 1, a degree of polarisation of $P = +0.16 \pm 0.04$ is calculated. This degree of polarisation implies that exciting electron population is relatively cold and arises from low energy electrons from the return current distribution [9].

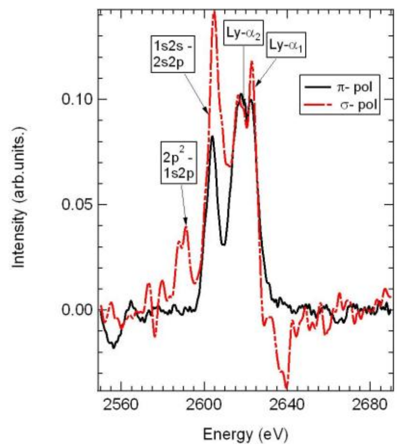

Figure 1. Single shot lineouts of the σ- and π-polarisations of the X-ray emission from polysulphone target interaction with the petawatt laser.

Magnetic field measurements were made by the use of a frequency doubled, 532nm, optical probe. Less than 1J of energy was focussed to an approximately 50 μm spot on the rear surface of the target, which, after reflection from the rear surface of the target was recollimated and was split into three arms. Two arms were relayed through polarisers and the third was directly imaged to a CCD in order to measure three of the four Stokes' parameters through polarimetric measurements of the probe beam [1,10]. By adjusting the delay between the main pump pulse and the probe, we can infer the temporal evolution of magnetic fields. The probe itself is not intense enough to produce plasma on the target so the non-uniformities in the near field do not alter the magnetic field measurements.

The magnetic fields generate birefringence in the target which induces ellipticity and polarisation rotation in a probe beam reflected from the plasma critical surface due to Cotton-Mouton effects and Faraday rotation [2]. The magnetic field-induced birefringence splits the incident light field to ordinary and extra ordinary waves. While the refractive index for the ordinary wave depends just on the plasma frequency, that of the extra-ordinary beam is a function of the electron cyclotron frequency —. Depending on the direction of magnetic field, this results in a polarization rotation or additional ellipticity in the incident probe light. By iteratively solving the evolution of Stoke's vector, in comparison with the incident polarisation, the magnetic field values can be obtained numerically.

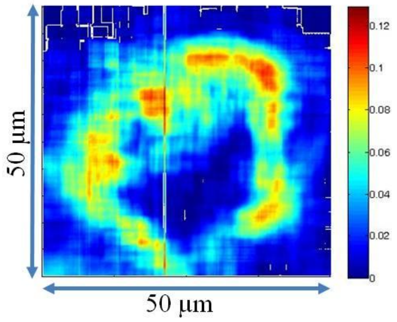

Figure 2. Ellipticity profile of the probe beam after reflection at the rear of a CH target, 5ps after the arrival of the main interaction pulse.

In our case, most of the measured polarisation change is additional ellipticity. Figure 2 (b) shows the ellipticity images of the probe beam reflected from the rear of a mylar target at 5ps after the arrival of the main pulse. The target was flash coated with 2 µm Al to provide a reflective surface for the probe. Post-processing of the data using a code based on the results of [10] will provide calculations of the generated magnetic fields from the measurements of the ellipticity in the reflected probe beam [11]. It is interesting to note that the magnetic field-induced ellipticity at the rear of the plastic target is not uniform but is in annular shape. This means that the magnetic fields themselves are in annular shape indicating a beam-like hot electron distribution. To deduce the exact magnitudes of the magnetic field, hydrodynamic simulations are necessary to estimate the plasma density profile and are underway.

In conclusion, we have demonstrated that through spectroscopic and optical probing of dense plasmas it is possible to make in situ measurements of the anisotropy in the fast electron beams and the magnetic fields generated as a result of fast electron transport through the plasma.

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