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Measuring fast electron distribution functions at intensities up to 10^{21} W cm^{-2}

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ABSTRACT

Here we present results from ultra-intense experiments demonstrating the viability of polarization spectroscopy as a diagnostic of the electron return current and spatial anisotropy and distribution function of the fast electron beam. The measurements extend to ultra-relativistic intensities of 10^{21} W cm^{-2}, including laser–plasma interaction regimes important for fast ignition studies, for example HiPER, and the development of secondary sources from next generation ultra-short pulse, ultra-intense laser facilities such as Astra-Gemini and ELI. As an *in situ* diagnostic, spectroscopic measurements are vital to understanding fast electron beams, enabling extrapolation of results to define fast ignition inertial confinement fusion and secondary source facilities.

1. Polarization spectroscopy

X-ray polarization measurements have been demonstrated as a suitable method for determining fast electron velocity distributions from intense laser–plasma interactions at intensities up to 10^{19} W cm^{-2} [1]. With the current drive towards inertial confinement fusion at NIF [2] and LMJ [3], the fast-ignition route to fusion [4] and secondary source development with ELI [5], the need to accurately determine electron transport within the plasma is of extreme importance. X-rays emitted from dense plasmas are a result of a strong anisotropy in the electron velocity distribution [6], and polarization studies offer an ideal method of observing the properties of fast electrons with fast-ignition relevant target geometries. By comparing results of ultra-intense experiments with a combination of 3D hybrid and atomic kinetic modeling it is possible to use plasma polarization spectroscopy as an *in situ* diagnostic of spatial anisotropy in the electron distribution functions.

In order to sustain a high fast electron current the propagation of the relativistic electrons in a plasma is compensated for by a cold electron return current that collisionally heats the plasma. Through a suitable choice of target and laser parameters, it is possible to use the return current to ionize the target material to the K-shell. As long as there is a local anisotropy in the cold electrons due to drawing a return current and the right temperature, polarized emission will be obtained. Refluxing of the hot electrons will alter the heating pattern that is obtained in the target, so this may alter the fine details of the measurement and would be observable if the emission was imaged, and as such is not essential for the observation of polarized emission.

Polarized X-rays arise from anisotropic components of the electron distribution function preferentially populating the $M_J = \pm ½$ magnetic sub-levels. The X-ray lines we observed in this report are the Ly-α doublet emission lines of sulfur (Ly-α_1 ($2p_{3/2}$–$2s_{1/2}$), $E=2622.6$ eV and Ly-α_2 ($2p_{1/2}$–$2s_{1/2}$), $E=2619.6$ eV) and nickel (Ly-α_1, $E=8101.4$ eV and Ly-α_2, $E=8072.8$ eV). We have particularly chosen these emission lines as the Ly-α_2 transition is unpolarized [7] and as such is suitable to use as a shot-to-shot calibration of the two spectrometers. The degree of polarization is given by $P=(I_\sigma-I_\pi)/(I_\sigma+I_\pi)$ [8] and is calculated using the integrated spectral line intensity of the Ly-α_1 emission lines.

2. VULCAN Petawatt experiment and simulations

The experiment took place using the Vulcan Petawatt laser at the central laser facility, Rutherford Appleton laboratory, UK [9].

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The laser has a wavelength of $\lambda = 1.053$ μm, a pulse duration of 600 fs and an ASE contrast of 10^{-6}, which was monitored on each shot. The laser was focused onto the targets with an f/3 off-axis parabola to a focal spot of approximately 5×6 μm leading to a laser intensity on target of 5×10^{20} W cm^{-2}. The targets used were thin foils of 25 μm of polysulfone ($C_{27}H_{26}O_6S$) and 10 μm of nickel mounted on copper stalks. The primary diagnostic for this experiment was a pair of flat, highly oriented pyrolytic graphite (HOPG) crystal spectrometers. The crystals were positioned 200 mm above the target, perpendicular to the fast electron quantization axis and orthogonal to one another. The experimental layout is shown in Fig. 1.

X-ray polarization spectroscopy uses the classical Thomson scattering to image the π- and σ-polarizations of the Ly-α emission individually, using two orthogonal crystal spectrometers. The intensity of the reflection of the p-polarized light (with respect to the crystal plane) is given as $I_p \sim R(\theta)\cos^2(2\theta_B)$ and so by positioning the crystals at approximately 45° the p-polarization reduces to zero ensuring that each crystal only sees either the π- or σ-polarized X-rays. In order to satisfy this condition we observe the nickel X-ray emission in third order and the sulfur emission in first order. The HOPG crystals also have a high integrated reflectivity that is essential to be able to perform spectroscopy in the noisy environment of the petawatt chamber.

Simulations are currently being performed using a 3D particle hybrid code (ZEPHYROS [10]) in combination with a sub-level atomic kinetics model (POLAR [11]). Using these two codes together it is possible to model the return current distribution with ZEPHYROS and feed in these results to POLAR to give the polarization of the spectral line emission. This modeling, when combined with the experimental measurements, will give us an *in situ* measurement of the return current and fast electron distribution functions.

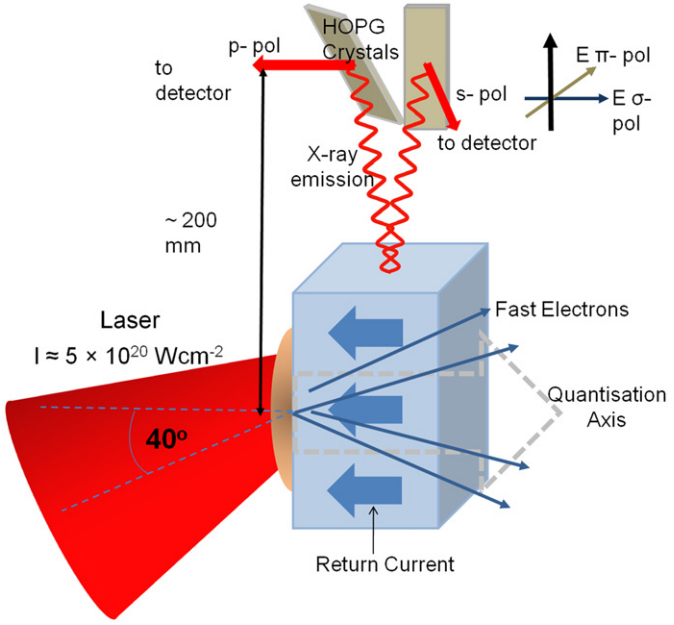

Fig. 1. Experimental layout and target geometry showing the angle of laser on target, fast electrons and return current, the fast electron quantization axis and the positioning of the crystals above the target.

3. Spectroscopy results

Lineouts from the experimentally observed X-ray spectra recorded using the HOPG spectrometers are shown in Fig. 2. The integrated line intensities of the Ly-α_2 emission for the two polarizations is used to calibrate each set of spectra, and the intensity of the Ly-α_1 line is then input into the equation given in Section 1 to give a value for the degree of polarization.

The degree of polarization from Fig. 2a is calculated to be $P = +0.22 \pm 0.04$ for sulfur and from Fig. 2b we obtain $P = -0.10 \pm 0.03$ for nickel. The polarization of the Ly-α_1 line is sensitive to both the isotropic and anisotropic parts of the collisional excitation processes [12] and as such will allow us to describe both the thermal and non-thermal electron distributions through ongoing modeling with ZEPHYROS and POLAR.

4. Conclusions

We have demonstrated the suitability of X-ray spectroscopy to measure the degree of polarization from X-rays emitted by plasmas created at ultra-relativistic intensities of 5×10^{20} W cm^{-2}. The degree of polarization is calculated for experimentally measured nickel and sulfur Ly-α_1 emission. Modeling work that is currently underway will enable us to show the sensitivity of the polarization to the thermal and non-thermal parts of the electron distribution. This will allow us to demonstrate the viability of X-ray polarization spectroscopy as an *in situ* diagnostic to measure electron distributions produced in ultra-intense interactions.

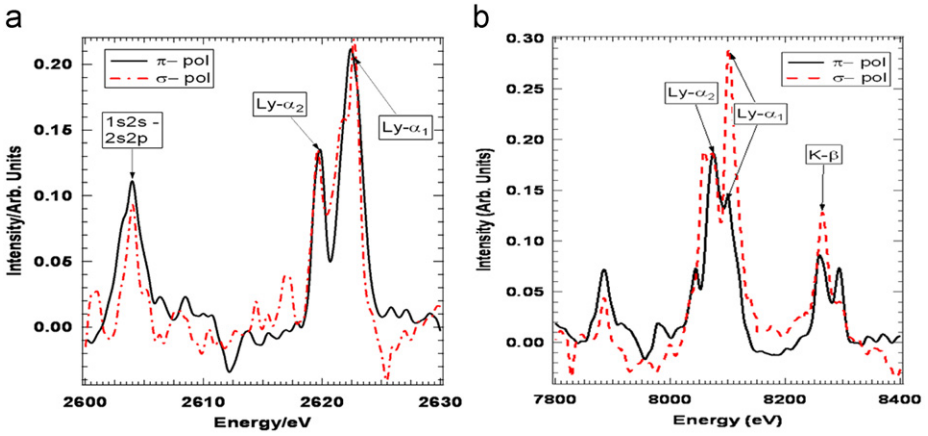

Fig. 2. X-ray spectra of emission from (a) polysulfone target showing the Ly-α doublet emission (Ly-α_1, $E = 2622.6$ eV and Ly-α_2, $E = 2619.6$ eV) and He-like emission of sulfur and (b) nickel target showing the Ly-α doublet (Ly-α_1, $E = 8101.4$ eV and Ly-α_2, $E = 8072.8$ eV)and K-β emission lines of nickel.

Acknowledgments

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