1

X-ray polarisation of fast electron heated dense plasmas

Contact **nb505@york.ac.uk**

N. Booth, J. Pasley*, E. Wagenaars, J. N. Waugh and N. C. Woolsey
Department of Physics, University of York, Heslington, York YO10 5DD, UK

G. Gregori and B. Li*
Department of Physics, University of Oxford, Oxford, OX4 1PJ, UK

L. Gizzi, P. Koester, L. Labate and T. Levato
ILIL-IPCF, Consiglio Nazionale delle Ricerche, PISA, Italy

R. J. Clarke and P. P. Rajeev
Central Laser Facility, STFC, Rutherford Appleton Laboratory, HSIC, Didcot, Oxon OX11 0QX, UK

M. Makita and D. Riley
Department of Physics and Mathematics, Queens University Belfast, Belfast BT1 4NN, UK

S. B. Hansen
Sandia National Laboratory, Alberquerque, New Mexico, USA

*Also at Central Laser Facility, STFC, Rutherford Appleton Laboratory, HSIC, Didcot, Oxon OX11 0QN, UK

Introduction

Detailed knowledge of fast electron energy transport following the interaction of high-intensity, ultra-short laser pulses with a plasma is a key requirement for the successful application of the fast ignition approach to inertial confinement fusion [1]. As light cannot penetrate beyond the critical density in plasma, the generation and transport of fast electrons is a possible method for transporting energy beyond the critical density to an imploded core. Fast electron data, such as current density, velocity distributions and so forth are required to constrain models of future fast ignition schemes.

Here we study fast electrons generated as the PW laser interacts with solid density plasma. The fast electron-plasma interaction is mostly collision free, and the intense fast electron currents are balanced by a collisional electron return current [2]. This return current heats the target. Resistive heating results in ionisation up to the K-shell. The fast electrons excite the K-shell ions into spatially anisotropic atomic magnetic sub-levels. The resulting X-ray emission is polarised. This is due to the net difference in magnetic sub-levels populations [3]. The degree of polarisation, P, is related to the velocity distribution of the fast electrons and is given by [4]

$$P = \frac{I_\sigma - I_\pi}{I_\sigma + I_\pi} \quad (1).$$

Polarisation spectroscopy has been demonstrated at laser intensities < 10^{19} Wcm^{-2}, as an effective probe of fast electron velocity distributions [5,6]. In this report we demonstrate the measurement of the degree of polarisation in the highly-relativistic regime of I > 10^{19} Wcm^{-2}.

The aim of this experiment is to demonstrate at high intensity the polarisation spectroscopy in the Ly-$_\alpha$ doublet emission of sulphur (Z = 16) and nickel (Z = 28) by comparing the integrate intensity in the doublet components. Figure 1 shows calculations of

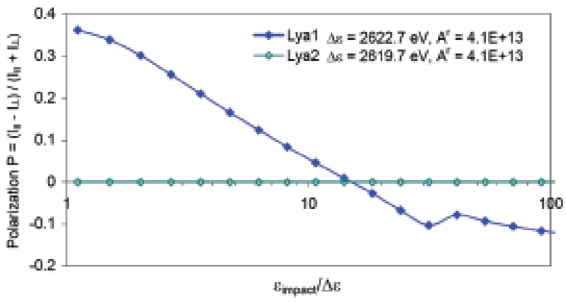

Figure 1. Simulations of polarisation of emission from H-like sulphur.

the degree of polarisation of the Ly-$_{\alpha1}$ and Ly-$_{\alpha2}$ lines of H-like sulphur as a ratio of the fast electron temperature (ε_{impact}) and the excitation potential ($\Delta\varepsilon$). Calculation shows the Ly-$_{\alpha2}$ component is unpolarised, and as such acts as a calibration source between spectrometers. The Ly-$_{\alpha1}$ component polarises, the polarisation is $\varepsilon_{impact}/\Delta\varepsilon$ dependent. In general, P is strongest when the ratio is approximately 1. This motivates the use of both sulphur and nickel. However, reaching the nickel K-shell requires high temperatures. It has been shown that emission from the Ni Ly-$_\alpha$ reduces rapidly at lower temperatures [7].

The different polarisations of emission are observed using a pair of highly oriented pyrolytic graphite (HOPG) Bragg reflecting crystals positioned at a Bragg angle, θ_B = 45°. The reflectivity of the crystals is given by

$$R = R_0\left[\frac{1}{\sin 2\theta_B} - \frac{\sin 2\theta_B}{2}\left(1+P\right)\right] \quad (2)$$

where R_0 is a constant based on crystal properties. By positioning the HOPG crystals orthogonally to one another, both at 45° to the target, the crystals act as ideal polarisers and monitor the X-ray π- and σ-polarised emissions.

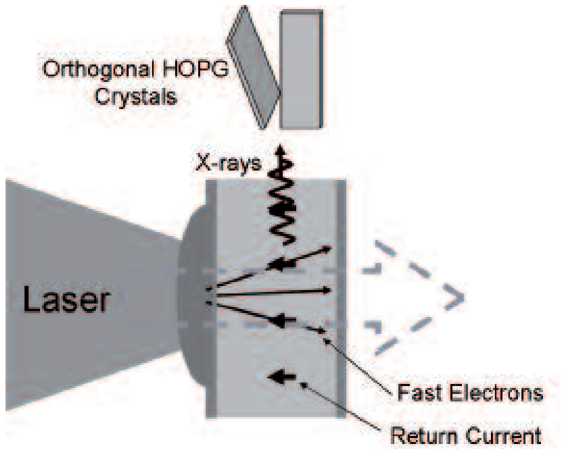

Figure 2. Schematic diagram of the experimental layout, include fast electron generation and return current heating within the target.

Experiment

The experiment was carried out using the petawatt arm of the Vulcan laser system. The laser pulse delivered ~ 450 J of energy before the compressor, with a pulse duration of ~ 600 fs. The beam was focused using an f/3 off-axis parabolic mirror to a focal spot at the target of either ~ 5 μm^2 or ~ 50 μm^2, resulting in focused intensities of ~ $10^{19} - 10^{21}$ Wcm^{-2} on target. The targets used in this experiment were thin foils of Ni and polysulphane (PS), 10 µm and 25 µm thick respectively, each of 100 μm^2 surface dimension and mounted on a copper stalk. Some targets were coated with a thin layer of Al on either the front surface, rear surface or both, which ranged in thickness from 0.2 µm to 0.5 µm.

The primary diagnostics used to observe the emission of the Ly-$_\alpha$ doublet from the targets were a dual pair of HOPG crystal spectrometers. Other diagnostics used include an electron spectrometer, a pinhole array, single hit camera and a high dispersion and a low dispersion crystal spectrometer, to observe emission from the aluminium coatings on the front surface of the target. The HOPG spectrometers were positioned to view the X-ray emission from directly above the top edge of the target which were operated orthogonally to each other in order to observe the ratio between the X-ray π- and σ- polarisations. The experimental layout of the HOPG spectrometers is shown in figure 2. At a Bragg angle of 45°, the Ni Ly-$_\alpha$ doublet is detected in third order, and the S Ly-$_\alpha$ doublet is detected in first order.

Preliminary results of Ly-$_\alpha$ polarisation spectroscopy

In this section, some of the preliminary results and observations from the HOPG spectrometers will be discussed.

Lineouts have been taken through the centre of the HOPG spectrometer images in order to observe the Ly-$_\alpha$ doublet peaks of the Ni and the PS thin foil targets. Figure 3 shows a sample image from one of the HOPG spectrometers from a PS target irradiated with I ≈ 10^{19} Wcm^{-2}, in which the two separate line peaks of the Ly-$_\alpha$ doublet can be observed.

Figure 3. Sample of HOPG spectrometer image from 25 µm thick polysulphane (PS) target, with Ly-$_\alpha$ doublet resolved at the centre of the image.

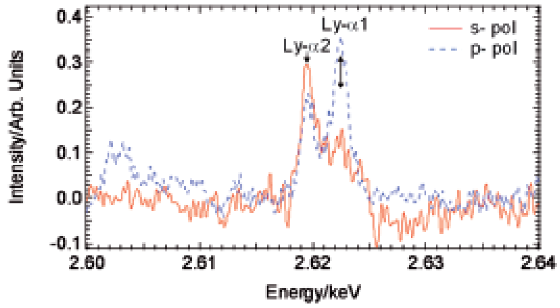

Figure 4. Lineouts of the HOPG spectrometer images recorded from a PS foil target with 0.2 µm Al tamping on the front surface irradiated by I ≈ 10^{19} Wcm^{-2}.

Figure 4 shows two lineouts from the orthogonal HOPG spectrometers, the σ- polarisation lineout is from the image shown in figure 3. The polysulphane target used in this shot was tamped by 0.2 µm of aluminium on the front surface, which allows the selection of the fast electron energy range by varying the thickness. It is possible to see that the relative intensities of the Ly-$_{\alpha 1}$ line at 2622.6 eV and Ly-$_{\alpha 2}$ line at 2619.6 eV between the two polarisations has reversed. Further processing of these images will allow the intensities in each peak to be analysed, in order to calculate the degree of polarisation between the two Ly-$_\alpha$ lines.

Emission from thin Ni foils was also observed with the orthogonal HOPG spectrometers on this occasion operating in third order. Figure 5 shows emission from a thin (10 µm) Ni foil, which had no tamping on either surface. From this image it is also possible to see the reversal of the Ly-$_{\alpha 1}$ (8101.4 eV) and Ly-$_{\alpha 2}$ (8072.8 eV) doublet between the two spectrometers as it was from the tamped PS target. Again further analysis will allow the degree of polarisation to be calculated.

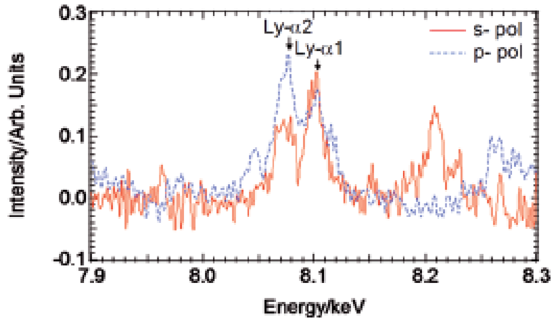

Figure 5. Lineouts of HOPG spectrometer images recorded from a Ni foil target with no tamping irradiated by I ≈ 10^{21} Wcm^{-2}.

Further data has been obtained for both target types with varying levels of tamping on each surface (ranging from 0 – 0.5 μm of Al) which all also demonstrate this same reversal of the Ly-α doublet peak intensities.

Discussion

Simulations have shown that the opacity effects on the Ly-α lines are significant in targets larger than 50 μm in spherical diameter along with collisional broadening of the lines. Further work is needed to account for these depolarising effects along with the effects of the cold electron return current. Analysis is required from the single-hit pinhole array and the electron spectrometer, in order to calculate fast electron energies, to allow further processing of the data.

Conclusions

Initial raw results have been presented which demonstrate that a pair of HOPG crystal spectrometers operating in orthogonal directions simultaneously and at a Bragg angle of $\theta_B = 45°$ can resolve the X-ray Ly-α doublet emission from Ni and PS thin foil targets. The Ly-α_2 emission is unpolarised therefore by calculating the intensity of emission of each peak between the σ- and π- polarisations, it will be possible to calculate the degree of polarisation due to the fast electron velocity distribution in the target.

Acknowledgements

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