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## X-ray Polarization Spectroscopy from Ultra-Intense Interactions

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**Abstract.** Detailed knowledge of fast electron energy transport following the interaction of ultrashort intense laser pulses is a key subject for fast ignition. This is a problem relevant to many areas of laser-plasma physics with particular importance to fast ignition and X-ray secondary source development, necessary for the development of large-scale facilities such as HiPER and ELI. Operating two orthogonal crystal spectrometers set at Bragg angles close to 45° determines the X-ray s- and p- polarization ratio. From this ratio, it is possible to infer the velocity distribution function of the fast electron beam within the dense plasma. We report on results of polarization measurements at high density for sulphur and nickel buried layer targets in the high intensity range of  $10^{19} - 10^{21} \text{ Wcm}^{-2}$ . We observe at 45° the Ly- $\alpha$  doublet using two sets of orthogonal highly-orientated pyrolytic graphite (HOPG) crystals set in 1<sup>st</sup> order for sulphur and 3<sup>rd</sup> order for nickel.

### 1. X-ray Polarization Spectroscopy

Knowledge of fast electron energy transport within dense plasmas is a key area for the development of inertial confinement fusion [1], particularly with the current development of large scale facilities such as HiPER [2] and has bearing on secondary source production relevant to the development of ELI [3]. Fast electron generation is the primary method of energy transportation through solid density plasmas beyond the critical density. The propagation of fast electrons through the solid density plasma is mostly collision free. In order to sustain a high fast electron current the propagation of the relativistic electrons through the plasma is compensated by a cold electron return current [4] which collisionally ionizes the target plasma to the K-shell.

Magnetic sub-levels (with quantum numbers  $M_J$ ) within an atomic energy level are preferentially populated into  $M_J = \pm 1/2$  through excitation by the electron beam. Emission from the magnetic sub-levels is polarized ( $\Delta M_J = 0$  for  $\pi$ - polarization, and  $\Delta M_J = \pm 1$  for  $\sigma$ - polarization) [5], and only some  $M_J$ 's are populated, which produces a net polarization effect in the emission from the plasma. Polarized X-ray emission is associated with the strong anisotropy of the fast electron velocity distribution function [6]. This anisotropy is related to the mechanism responsible for the generation of fast electrons in intense laser-plasma interactions. In a study by Keiffer et al [7] the degree of polarization is shown to be given by  $P = (I_\sigma - I_\pi)/(I_\sigma + I_\pi)$ , and a number of further studies have been performed to observe polarization measurements of inner shell X-ray emission. These measurements have demonstrated the technique as a probe of hot electron velocity distributions at incident laser intensities up to  $2 \times 10^{19} \text{ Wcm}^{-2}$  [8]. Through the development of inertial confinement fusion and secondary source developments, there is a real need to expand these measurements into the highly relativistic regime at intensities above  $10^{19} \text{ Wcm}^{-2}$ .

This paper presents results of an experiment to perform polarization spectroscopy measurements in the relativistic regime at intensities from  $8.5 \times 10^{18} \text{ Wcm}^{-2}$  to  $1.0 \times 10^{21} \text{ Wcm}^{-2}$ , to analyze the Ly- $\alpha$  doublet,  $1s_{1/2} - 2p_{3/2}$  (Ly- $\alpha 1$ ) and  $1s_{1/2} - 2p_{1/2}$  (Ly- $\alpha 2$ ), X-ray emission from hydrogen-like sulphur and nickel and to determine if spectroscopic polarization measurements are possible at these high intensities and in a single shot. Ionizing Ni to the K-shell demands incident laser intensities of approximately  $10^{21} \text{ Wcm}^{-2}$ , and requires return current heating to high temperatures [9].

In order to observe both the p- and s- polarizations (with respect to the plane of incidence at the crystal) from the plasma in a single shot we demonstrate the use of a pair of Bragg reflecting crystals positioned at a Bragg angle of approximately  $45^\circ$ , where the intensity of the diffracted X-rays is given as  $I_p \sim R(\theta)\cos^2(2\theta_B)$ . By operating the crystals at an angle of  $45^\circ$  the p- polarized component is absent and only the s- component of the polarized X-rays is reflected. By positioning the HOPG crystals orthogonally to one another at  $45^\circ$  to the target, the crystals act as ideal polarizers and monitor the X-ray p- and s- polarized emissions. Percival and Seaton [10] have shown that the emission from the Ly- $\alpha 2$  line is unpolarized and as such act as a calibration between the two spectrometers. The ability to observe both the p- and s- polarizations in a single shot is critical as it removes the problems of analyzing data with inherent shot-to-shot differences in the plasma.

## 2. Experiment

The experiment was performed in the Vulcan Petawatt target area at the Central Laser Facility, UK. The Petawatt laser operates at a wavelength of  $\lambda = 1054 \text{ nm}$ , has a pulse duration of 600 fs and contained a maximum of 320 J of energy on target. The beam was focused to a best spot size of  $5 \times 6 \mu\text{m}^2$  using an f/3 off-axis parabola and incident at  $40^\circ$ , which achieved peak intensities on target of  $1.0 \times 10^{21} \text{ Wcm}^{-2}$ . The beam was defocused at the target position to a spot size of approximately  $50 \times 50 \mu\text{m}^2$  to reduce the intensity on target to  $8.0 \times 10^{18} \text{ Wcm}^{-2}$ .

The principal diagnostic used in this experiment was a pair of highly oriented pyrolytic graphite (HOPG) (002) crystals which had a mosaic spread of  $0.4 \pm 0.1^\circ$ . The two crystals were positioned above the target to view X-ray emission perpendicular to the fast electron quantization axis. Both crystals were positioned 200 mm from the target and both with Bragg angles of  $45^\circ$ . The high integrated reflectivity of HOPG crystals is essential in this experiment in order to record weak X-ray emissions from within a high level of noise. This will then enable accurate single shot polarization measurements to be performed.

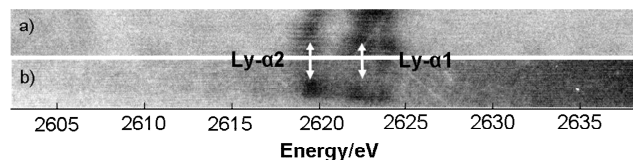
By using the spectrometers at  $\theta_B = 45^\circ$ , the number of transitions which are able to be observed is severely limited. Here we demonstrate the use of two crystal spectrometers with an identical set-up, which can be used to observe the emission from hydrogen-like sulphur viewed in first order and hydrogen-like nickel which is viewed in third order. The integrated reflectivity of HOPG crystals in the s- polarization is very high, whilst the p- polarization integrated reflectivity is significantly reduced, which allows the HOPG crystals to act as ideal polarizers.

Thin foil targets of polysulphane ( $\text{H}_2\text{S}_n$ ,  $n > 2$ ) and nickel of 25  $\mu\text{m}$  and 10  $\mu\text{m}$  thicknesses cut to 100  $\mu\text{m} \times 100 \mu\text{m}$  squares were mounted on copper stalks and placed in a rotational mount to enable fresh targets to be moved into position without the need to break the vacuum. Some targets were tamped on the front surface and/or the rear surface of the foils by 0.2 or 0.5  $\mu\text{m}$  thicknesses of an aluminum diagnostic layer.

Further diagnostics were also used in order to observe additional characteristics of the target plasma. An electron spectrometer [11] was used to observe the velocity distribution of the electrons, a single hit camera with a pinhole array [12] to observe the energy of absorbed photons in single events, and a high dispersion toroidal spectrometer to observe the K- $\alpha$  and K- $\beta$  emission from the surface coatings of aluminum.

### 3. Results

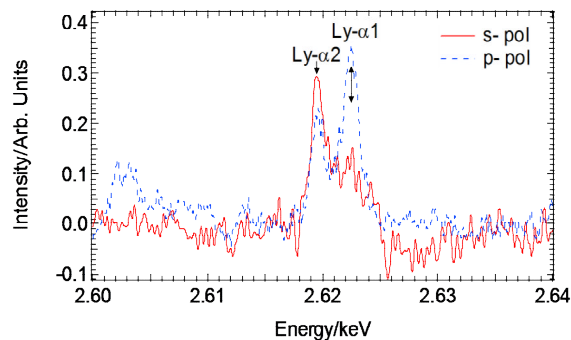
Figure 1 shows the sulphur X-ray emission of both the p- and s- polarizations from a polysulphane plasma recorded from two HOPG crystals operating orthogonally to each other and observing emission from the same shot. The target was polysulphane with no aluminum surface tamping, and was irradiated by the laser at an intensity of  $4.3 \times 10^{20} \text{ Wcm}^{-2}$ . The Ly- $\alpha$ 1 and Ly- $\alpha$ 2 are indicated in the figure, and demonstrates that it is possible to resolve the Ly- $\alpha$  doublet emission using two orthogonal spectrometers in a single shot.



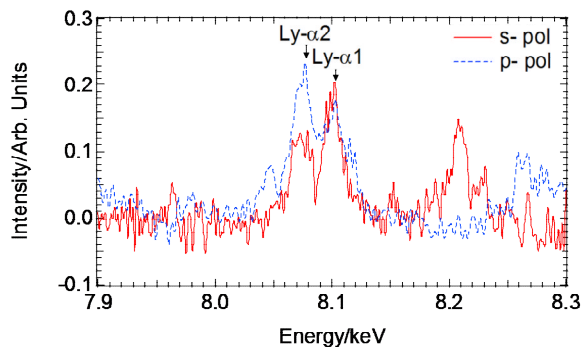
**Figure 1.** Sulphur Ly- $\alpha$  Emission spectra of a) the p- polarization and b) the s- polarization from the HOPG crystal spectrometers observing emission from a thin foil polysulphane target. The Ly- $\alpha$  doublet can be seen to be resolved in the centre of each spectrum. The background signal is different in each due to the different positions of the spectrometers and the shielding issues.

In order to process the recorded spectra from the HOPG crystals, lineouts are taken across the central region of the spectrum. The data is then processed to remove the wavelength dependent transmission of the spectrometer filtering [13]. In this case the filtering was 50  $\mu\text{m}$  and 25  $\mu\text{m}$  thicknesses of beryllium for the p- and s- polarizations respectively plus a 6  $\mu\text{m}$  thick CH foil. Digitisation noise and the background signal are also removed. Figure 2 shows the lineouts of the spectra shown in Figure 1, clearly resolving the two peaks of the Ly- $\alpha$  doublet of sulphur, with Ly- $\alpha$ 1 at 2622.6 eV and the Ly- $\alpha$ 2 at 2619.6 eV.

Lineouts of the emission from a thin (10  $\mu\text{m}$ ) foil Ni target also with no aluminum tamping layer is shown in Figure 3. The target was irradiated by the laser at best focus and full energy at an intensity of  $6.0 \times 10^{20} \text{ Wcm}^{-2}$ . The resolved Ly- $\alpha$  doublet is again clearly shown, with the Ly- $\alpha$ 1 emission line at 8101.4 eV and the Ly- $\alpha$ 2 emission line at 8072.8 eV. Further processing to calculate the integrated line intensities contained within the peaks will allow the calculation of the degree of polarization produced in the laser-target interaction from the formula given earlier.



**Figure 2.** Lineouts of the sulphur X-ray emission from a thin polysulphane target (as shown in figure 1). of the p- and s- polarization X-ray emissions recorded at the HOPG crystal spectrometers



**Figure 3.** Lineouts of the emission from a thin nickel target of the p- and s- polarization nickel X-ray emissions recorded at the HOPG crystal spectrometers.

#### 4. Conclusions

This paper presents measurements of the degree of polarization from inner shell X-rays produced during high intensity laser-plasma interactions between  $10^{19}$  and  $10^{21}$  Wcm<sup>-2</sup>. We have demonstrated that it is possible to observe both the p- and s- polarizations of the X-ray emission in a single shot by the use of two HOPG crystals positioned orthogonally to one another at a Bragg angle of 45°. Due to the high integrated reflectivity of the s- component at the crystal plane, the crystals act as ideal polarizers. The results presented here show the resolved Ly-α doublet X-ray emission from thin foil targets of sulphur and nickel, and further analysis of the relative peak intensities of the Ly-α1 emission will allow the degree of polarization of the plasma X-rays to be calculated.

This technique allows polarization spectroscopy from an X-ray emission line to be observed from a single shot at high laser intensities and provides new avenues for direct measurement of electron transport processes within a high density plasma, critical to inertial fusion energy and X-ray secondary source developments.

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