X-ray polarization spectroscopy to study energy transport in ultra-high intensity laser produced plasmas

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Abstract. X-ray polarization spectroscopy was studied to derive directly the velocity distribution function (VDF) of hot electrons propagating in plasma created with a high intensity laser pulse. Polarization measurement was made at around $10^{18}$ W/cm² using a laser pulse (~10 J in ~1 ps) from Alisé facility at CEA/CESTA. Chlorinated triple-layer targets were irradiated, and Cl He D line was observed with an x-ray polarization spectrometer. Polarization degrees were measured as a function of the target overcoat thickness. It is found that the polarization is weakly negative for thin coating, but becomes positive, and finally zero for thick coating. This result is consistent with predictions made with a time-dependent atomic kinetics code developed to gain an insight into the generation of polarized Cl He D radiation.

1. Introduction
In the fast-ignitor plasma, there are two major components of electrons. The first component is hot electrons generated predominantly by collective processes in the laser–plasma interaction region [1], leading to initial distributions of hot electrons that are highly anisotropic. The second one is composed of cold bulk electrons. These form a return current for the hot electrons and will be heated mostly via ohmic and/or collisional processes [2]. Thus, the velocity distribution of cold electrons is isotropic. In terms of atomic processes, the fast electrons are mainly responsible for the inner-shell ionization, while the cold bulk electrons are responsible for the outer-shell ionization. This categorization is thus useful to derive the bulk electron temperature using x-ray spectroscopy [3, 4].

Hot electron spectra are usually measured with electron spectrometers, but resultant spectra are substantially affected by self-generated target potential so that the spectra observed do not adequately quantify the hot electron transport [5]. Transition radiation is proposed as another method to derive the...
hot electron velocity distribution function (VDF) [6, 7], but should be performed at the rear side of the target where the plasma has a very sharp boundary. However, since hot electrons distributions derived by this method are subject to transport through the target, the original information might be lost. As it is of great importance to clarify the energy deposition processes by directly observing the VDF of electrons, development of other methods is urgently required. To address the VDF of the electrons, x-ray-line polarization spectroscopy as a diagnostic method has been proposed [8-10]. Anisotropy of hot electron VDF can be derived by the observation of polarization degree $P$.

Polarized x-rays are generated due to the anisotropy of fast electron VDF and the alignment creation associated with magnetic atomic sublevels is essential [11-13]. Thus, polarization spectroscopy in a low density region is practically useful due to the small effect of alignment breaking by elastic electron impacts. By utilizing this principle, the anisotropy of hot electron VDFs can be determined by observing the polarization degree $P$ [8-10, 14]. In the case of a planar target irradiated by a high intensity laser pulse, hot electrons are so generated that they initially propagate nearly parallel to the density gradient, i.e., perpendicular to the target surface. Figure 1 shows similarity of polarized x-ray emission from an electron-beam ion trapping (EBIT) [15] to that in laser produced plasmas (see Fig.1). This direction is referred to as the quantization axis hereinafter. The observed polarization degree $P$ is defined as,

$$P = \frac{I_p - I_\perp}{I_p + I_\perp}$$

where $I_p$ and $I_\perp$ are respectively the intensities of the x-ray radiation whose electric fields are parallel and perpendicular to the quantization axis for an observer. This definition has been employed in the EBIT polarization spectroscopy.

2. Theoretical study on polarization of Cl He$\alpha$ line
A time dependent atomic kinetic code was developed for the polarization spectroscopy of He$\alpha$ transition ($1s^21S_0 - 1s2p\ ^1P_1$) of chlorine [16]. Atomic cross-sections with magnetic sublevels for helium-like atoms were obtained using the Breit-Pauli $R$-matrix method [17]. The details are described in the study by Kai et al. [18]. Figure 2 shows dependence of polarization degree $P$ on electron kinetic energy for Cl He$\alpha$ line obtained simply with the ratio of the cross-sections. The electron energy is normalized with the transition energy for $1s2p\ ^1P_1$->$1s^21S_0$. With increase in the electron energy, the polarization degree becomes smaller. This is an important feature of the polarization spectroscopy.

Radiative decay rates associated with $LSJ$-
states were obtained using the GRASP code [19], and the optical allowed transitions between \( JM \)-states were estimated using the Wigner-Eckert theorem [20]. For the polarized x-ray calculation, pre-process with a time-dependent atomic population kinetics code [21] must be separately carried out in advance. The basic calculation scheme to solve the population kinetics associated with the magnetic sublevels is given in Hakel et al. [22].

Figure 3 shows an example of calculation result. The polarization of above 10% can be expected at the ion density \( N_i = 4.5 \times 10^{21} \text{ cm}^{-3} \) (corresponding to \( \sim 0.05 \rho_s \) where \( \rho_s \) is the solid density), the fast electron temperature along the quantization axis \( T_{\text{Fast}-z} = 10-50 \text{ keV} \) and that perpendicular to the quantization axis \( T_{\text{Fast}-r} = 1 \text{ keV} \). The ratios \( f_2/f_0 \) (here \( f_n \) denotes the Legendre polynomial of order \( n \)) of the fast electrons with near the threshold of \( 1s2p \ ^1P_1^- \rightarrow 1s^2 \ ^1S_0 \) (about 2.79 keV) are 1.8–2.0, and those with the energies of 10–100 keV are 4.1–4.9. The anisotropy is high and the fast electrons with the energies of below 50 keV have a contribution to positive polarization [18]. With increase in \( T_{\text{Fast}-z} \) the polarization degree is reduced due to the increase in the number of the fast electrons with the energies of above 50 keV at about \( 0.05 \rho_s \). However, at the high density of greater than about \( 0.1 \rho_s \), the other atomic processes associated with \( 1s2p \ ^1P_1 \) may also affect the dependence.

3. Experiment

X-ray polarization was measured using a laser pulse (~10 J in ~1 ps) from Alisé facility at CEA/CESTA. Pedestal component arriving in prior to the main pulse grows linearly from the noise level to \( 5 \times 10^7 \) of the laser peak in 6 ns duration. Target used was a chlorinated triple-layer consisting of a 2x2x2 mm polyethylene substrate, a 0.5-\( \mu \text{m} \)-thick C$_2$H$_2$Cl$_2$ tracer layer, and a 0–6-\( \mu \text{m} \)-thick C$_8$H$_8$ parylene overcoat. It was irradiated with a laser spot of 58-\( \mu \text{m} \)-diam containing 50% of laser energy, yielding \( 2 \times 10^{18} \text{ W/cm}^2 \) average intensity. Laser was incident at 7 degrees from the target normal and Cl He \( \alpha \) line from the tracer layer was observed at 83 degrees from the target normal with an x-ray spectrometer having two orthogonal polarization channels. Assuming the quantization axis is along the laser axis, one channel detected the component in nearly parallel to the axis and the other channel the component perpendicular to it. Cross-calibration of mutual channels were made by rotating the whole body of the spectrometer around the line-of-sight by 45 degrees so that both channels detect the polarization components of the same amounts. In the calibration, a polyvinyl chloride (PVC: C$_2$H$_3$Cl) sheet was irradiated for various laser intensities. Calibration
factor of 4.16±0.14 was obtained, showing experimental uncertainties of 3.4% of averaged value.

Polarization degrees were measured as a function of the overcoat thicknesses. This corresponds to the depth along the pre-formed plasma generated with a leakage pulse from Alisé system. Figure 4 shows dependence of polarization on the depth to the tracer. Note here that the depth to the tracer layer is defined as the distance from the target surface to the tracer center. The polarization degree is weakly negative at the surface, becomes positive, and finally becomes zero with increase in the depth to the tracer. The result for thinner depth is consistent with the polarization measurement done at 10^{17} W/cm^2 [10] where the polarization changes from -7% to +33% with increase in the overcoat thickness. Furthermore the polarization tends to be from negative to positive with increase in the depth. This trend is identical to the predictions made with the time-dependent atomic kinetics code. The depolarization on the surface might be attributed to excessive bulk electron temperature and that in the deep region to the elastic-scattering processes by isotropic bulk electrons in dense region.

To the summary, x-ray polarization spectroscopy has been studied as a useful diagnostic tool to derive directly VDF of hot electrons propagating in the plasma created with a high intensity laser pulse. A new kinetic code dedicated for Cl He D line polarization spectroscopy was developed to investigate the properties of hot electron VDF. X-ray polarization of Cl He D was measured for the first time at above 10^{18} W/cm^2. The experimental results are consistent with the previous measurement at 10^{17} W/cm^2 and with the model predictions.

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