Diagnostics of anisotropic hot electron velocity distribution using x-ray polarization spectroscopy

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Abstract. X-ray polarization spectroscopy is a useful diagnostic tool for measuring the velocity distribution of electrons inside plasma. A new polarization measurement was performed at relativistic laser intensity using a laser pulse (10 J in ~1 ps) from Alisé facility at CEA/CESTA. Chlorinated triple-layer targets were irradiated, and polarization degrees of Cl-He line were measured. Obtained polarization degrees are negative in shallow region from the target surface and positive in deep region. This result is qualitatively consistent with the experimental results at non-relativistic intensity. Moreover, de-polarizations due to isotropic excitation and elastic collision, which were predicted by a model calculation and a time-dependent atomic kinetic code, were observed.

1. Introduction

Recent advances in ultra-short pulse, high-intensity lasers have opened up possibility of performing novel experiments in fields such as a fast-ignition [1, 2], particle accelerations [3-6], and short pulse x-ray generations [7]. Efficient energy transport from laser to dense plasma is a critical issue for all of these applications. There are two kinds of electrons in plasmas generated by ultra-high intensity lasers, namely hot electrons and cold bulk electrons. Hot electrons transfer absorbed laser energy to high-density region of plasma and are predominantly generated by collective processes in the laser-plasma interaction region [8]. Consequently, initial velocity distributions of hot electrons are highly anisotropic. Cold bulk electrons form a return current as a counter stream for hot electrons, and gain energy mostly via Ohmic process and collisional process [9]. Thus, velocity distributions of cold electrons are substantially isotropic. Investigation of the velocity distribution function (VDF) of hot electrons is critical for clarifying energy transport by these electrons in ultra-high intensity laser-produced plasmas.
X-ray polarization spectroscopy is a useful diagnostic tool for measuring the VDF of electrons. In general, polarized x rays are emitted due to anisotropic electron velocity distributions and/or an anisotropic electromagnetic field [10-12]. By utilizing this principle, the anisotropy of hot electron VDFs can be determined by observing the polarization degree $P$ [13-15]. In the case of plasma produced by a laser pulse at a relativistic intensity, hot electrons are predominantly generated by $\mathbf{J} \times \mathbf{B}$ acceleration and propagate along to the laser axis. This direction is referred to as the quantization axis hereafter. The observed polarization degree $P$ is defined as
\[
P = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp},
\]
where $I_\parallel$ and $I_\perp$ are the intensities of the x-ray radiation whose electric fields are parallel and perpendicular to the quantization axis, respectively. This definition accords with that employed by polarization spectroscopy that uses an electron beam ion trap [16]. Previously, some experiments of polarization spectroscopy have been performed at non-relativistic intensity [14, 15, 17, 19]. In this paper, a new experiment with a relativistic intensity laser pulse is reported. In this experiment, the distribution of polarization degrees of Cl-He$^+$ line emitted from helium-like chlorine ion was obtained at two different laser intensities.

2. Experimental setup
The experiment was carried out using Alisé laser system at CEA/CESA. This system provided a 1.053 µm laser pulse of ~10 J with ~1 ps duration. Pedestal component arriving in prior to the main pulse grows from the noise level to $5 \times 10^{-7}$ of the laser peak in 6 ns duration and generates pre-formed plasma. The s-polarized pulse was focused with an f/3 off-axis parabolic mirror. Measurements of x-ray spectra were performed at two different laser intensities which were changed by moving the off-axis parabolic mirror. Laser intensities were $4 \times 10^{17}$ W/cm$^2$ for low intensity shots and $3 \times 10^{18}$ W/cm$^2$ for high intensity shots.

Targets were triple-layer targets consisting of a 2×2×2 mm$^3$ polyethylene substrate, a 0.5 or 0.6-µm-thick C$_2$H$_2$Cl$_2$ tracer layer, and a 0–5-µm-thick C$_6$H$_{18}$ parylene overcoat. Two polarized components of Cl-He$^+$ line emitted from the tracer layer were simultaneously measured using a two-channel x-ray spectrometer. The spectrometer was designed by combining two equivalent toroidally-curved crystal spectrometers. Dispersion planes of two crystals were perpendicular to each other. Two cooled charge-coupled-device (CCD) cameras were used as detectors. These two channels had been

![Figure 1](image_url)

**Figure 1.** (a) Top view of the experimental setup. In this figure, the channel to measure a parallel component is omitted. (b) Side view of the experimental setup.
cross-calibrated beforehand with accuracy of ±3.4%. The energy range of this x-ray spectrometer was from 2600 eV to 2850 eV including Cl-Kα line, its shifted components and Heα line. Heα line was observed at the Bragg angle of 41.7°.

Figure 1(a) shows a top view of the experimental setup. The incident angle of the laser was 7° with respect to the target normal. The center axis of the spectrometer is 83° with respect to the target normal. Figure 1(b) shows a side view of the setup. One CCD camera whose line-of-sight was parallel to the laser axis detected a perpendicular component of Heα line (I⊥), and the other perpendicular to the axis detected a parallel component of Heα line (I||).

3. Experimental results and discussion

Figures 2(a) shows typical spectra, which were measured in the case of low intensity and the depth-to-the-tracer layer of 0.56 μm. The depth-to-the-tracer means the distance from the target surface to the center of the tracer layer. Heα line, its Li-like satellite lines and Kα line are seen. Polarization degrees were evaluated from integrated intensities of Heα line. Figures 2(b) shows a distribution of polarization degrees of Heα line in the cases of two different laser intensities. Uncertainties of polarization degrees were evaluated from the accuracy of calibration and the signal-to-noise ratios.

In the low intensity shots, the polarization degree is negative at shallow region, becomes positive, and finally becomes zero with increase in the depth of the tracer. This result except for zero qualitatively corresponds to the experiment at laser intensity of 10^{17} W/cm² [17] and the calculation using a 3-dimensional polarization spectroscopy model [20]. Negative polarization degrees are caused by electron oscillation in the electric field of the laser, and the reason of positive polarization degree is cigar-like electron VDF. Intensities of Heα line drastically decrease with the increase in the depth of the tracer. This indicates that the bulk electron temperature in the surface region is much higher than that in deep region. Slight de-polarization is seen in the surface region. Isotropic excitation by high energy bulk electrons in high temperature plasma induces this de-polarization [21]. Because the density at the depth-to-the-tracer of 5.3 μm is high, elastic collision of bulk electrons destroys the alignment and polarization becomes zero [22].

Although polarization degrees in the shallow region for high laser intensity are almost the same as that for low intensity, polarization degree in the deep region is zero. Hot electron temperatures calculated from the scaling of laser intensity [8] are 70 keV for low intensity and 300 keV for high intensity. In the high intensity shots higher energy electrons contribute to emission of Heα line than in the low intensity shots. Therefore polarization degree at the high intensity shots becomes low because

Figure 2. (a) X-ray spectra for the low intensity case at the depth-to-the-tracer layer of 0.56 μm. These measured spectra have different spectral resolutions due to slight difference of curvature of the crystals. (b) Dependence of polarization degrees on depths to the tracer.
polarization degree caused by electron-ion impact decrease with increase in the hot electron energy [23].

4. Summary

X-ray polarization spectroscopy is a useful diagnostic tool for measuring the VDF of electrons inside plasma. A new polarization measurement was performed at relativistic laser intensity. Measured polarization degrees are negative in shallow region from the target surface and positive in deep region. Distribution of polarization degree qualitatively corresponds to non-relativistic intensity case. Moreover, de-polarizations due to isotropic excitation and elastic collision, which were predicted by a model calculation and a time-dependent atomic kinetic code, were observed.

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References

[1] Tabak M, Hammer J, Glinsky M E, Kruer W L, Wilks S C, Woodworth J, Cambell E M, Perry M D, and Mason R J, 1994 Phys. Plasmas 1 1624
[2] Kodama R, et al., 2002 Nature 418 933
[3] Tajima T and Dawson J M, 1979 Phys. Rev. Lett. 43 267
[4] Mangles S P D, et al., 2004 Nature 431 535
[5] Geddes C G R, Toth C S, Tilborg J Van, Esarey E, Schroeder C B, Bruhwiler D, Nieter C, Cary J, and Leemans W P, 2004 Nature 431 538
[6] Faure J, Glinec Y, Pukhov A, Kiselev S, Gordienko S, Lefebvre E, Rousseau J P, Burgy F, and Malka V, 2004 Nature 431 541
[7] Rousse A, et al., 2001 Nature 410 65
[8] Wilks S C, Kruer W L, 1997 IEEE J. Quantum Electron 33 1954
[9] Sentoku Y, Mima K, Kaw P, and Nishikawa K. 2003 Phys. Rev. Lett. 90 155001
[10] Lombardi M and Pebay-peyroula J C, 1965 C. R. Acad. Sc. Paris 261, 1485
[11] Kallas Kh and Chaika M, 1969 Opt. Spectr. 27 376
[12] Carrington C G and Corney A 1969 Opt. COMM. 1 115
[13] Haug E, 1981 Solar Phys. 71 77
[14] Kieffer J C, Matte J P, Pepin H, Chaker M, Beaudoin Y, Johnston T W, Chien C Y, Coe S, Mourou G, and Dubau J, 1992 Phys. Rev. Lett. 68 480
[15] Kieffer J C, Matte J P, Pepin H, Chaker M, Beaudoin Y, Chien C Y, Coe S, Mourou G, Dubau J, and Inal M K, 1993 Phys. Rev. E 48 4648
[16] Beiersdorfer P, and Slater M, 2001 Phys. Rev. E 64 066408
[17] Inubushi Y, et al., 2006 J. Quant. Spectrosc. Radiat. Transf. 99, 305; Erratum, 2006 J. Quant. Spectrosc. Radiat. Transf. 101, 191
[18] Walden F, Kunze H J, Petoyan A, Urnov A, and Dubau J, 1999 Phys. Rev. E 59 3562
[19] Yoneda H, Hasegawa N, Kawana S, and Ueda K, 1997 Phys. Rev. E 56 988
[20] Inubushi Y, Kai T, Nakamura T, Fujioka S, Nishimura H, and Mima K, 2007 Phys. Rev. E 75 026401
[21] Inubushi Y, Kai T, Kawamura T, Fujioka S, Nishimura H,and Mima K, 2007 Plasma Fusion Research 2, 013
[22] Kawamura T, Kai T, Koike F, Nakazaki S, Inubuhi Y, and Nishimura H, accepted for publication in Phys. Rev. Lett.
[23] Kai T, Nakazaki S, Kawamura T, Nishimura H, and Mima K, 2007 Phys. Rev. A 75 012703