Study on anisotropic fast electron transport by polarized K-shell radiation in ultra-short intense laser produced plasmas

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Abstract. Polarized Heα of chlorine from ultra-intense laser produced plasmas was calculated. The experiment with 800 nm laser pulses of 100 – 130 mJ in 130 fs was also carried out, and the resultant polarization of time- and space-integrated Heα is so high (≥ 10%). A new time-dependent atomic kinetics code was developed to gain insight into the generation of polarized Heα by fast electron transport relevant to fast ignition. The polarized feature is due to anisotropic electron impacts by fast electrons, and the aspect ratio of fast electron temperatures associated with longitudinal and transverse directions is found to be essential with the numerical calculation. In the calculation, so small polarization (≤ 2 ∼ 3%) is predicted in dense plasma region (≥ 100 times the critical density), which is due to frequent elastic atomic transitions between magnetic atomic sublevels, while high polarization (≥ 10%) is observable in low density region (≤ 10 times the critical density). The collimated fast electrons are generated by electromagnetic instability, resulting in large anisotropy along the propagation direction in low density region.

1. Introduction

In fast ignition research, the transport of fast electrons generated by ultra-intense laser pulses is one of the critical issues [1]. Quantitative and/or qualitative understanding of the fast electron transport with a spectroscopic method is one of useful diagnostics, and the observation of Kα lines from partially ionized chlorine have been investigated for this purpose [2, 3, 4]. In the experiments, the Kα lines were diagnosed as a function of the thickness of an over-layered target, and a dramatic decrease in the radiation yield was found with an increase in the thickness at laser intensity of about 10^{17} W/cm². With an atomic kinetics code [3, 4], plasma creation with electron temperatures of 100 ~ 150 eV was predicted. The experimental results also indicate that the depth of heated plasma is located near the target surface and much shallower than the classical penetration depth of fast electrons. To understand well the energy deposition processes from fast electrons to a background plasma, direct observation of the fast electron
properties is indispensable. Optically allowed transition radiation was used to diagnose the velocity distribution function (VDF) of fast electrons [5]. However, the fast electrons were measured at the rear-side of an irradiated target, and the original features of the fast electrons may be lost for the sake of the long propagation in a target. To gain insight into the fast electron transport, polarized Heα radiation has been proposed as a useful diagnostic tool [6, 7, 8, 9]. At a laser intensity of about $10^{17}$ W/cm$^2$ (pulse energies: 100 $\sim$ 130 mJ, pulse width: 130 fs), the polarization spectroscopy of Heα radiation from a C$_8$H$_7$Cl plasma was carried out, and the anisotropic Heα radiation was obtained [7, 8].

Polarized x-rays are generated due to anisotropic electron impacts by fast electrons, and alignment creation associated with magnetic atomic sublevels is essential. The resultant alignment creation strongly depends upon the anisotropy of the fast electrons’ VDF. Since the bulk electron temperature is low (100 $\sim$ 200 eV) in the above experiment, the K-shell atomic transitions are attributed to electron impacts by fast electrons. Thus, the resultant polarization can reflect the VDF feature of fast electrons.

In this study, a new time-dependent atomic population kinetics code [9] was developed for the spectroscopy of polarized Heα (1s$^2$1S$_0$ - 1s2p$^1P_1$) of chlorine in a C$_8$H$_7$Cl plasma. In the calculation, because fast electrons give a minor contribution to the overall ionization property of plasmas [3], much effort is devoted to determining the polarization features on the VDF of fast electrons. The experimental results obtained using the T6 laser system [7, 8] are also discussed.

2. Atomic transition data with magnetic sublevels

Elastic- and inelastic-scattering cross-sections by an electron impact were obtained using the Breit-Pauli $R$-matrix method [10]. The details of the calculations are described in the study by Kai et al. [11, 12]. All the magnetic sublevels from the helium-like ground-state 1s$^2$ 1S$_0$ up to the 1s3d$^3$D$_{3,2,1}$, $^1$D$_2$ are considered.

![Collisional excitation cross-sections by an electron impact](image)

**Figure 1.** Collisional excitation cross-sections by an electron impact for 1s$^2$1S$_0$ (M = 0) $\rightarrow$ 1s2p$^1P_1$ (M = 0, 1). $a_0$ stands for the Bohr radius.

For instance, Fig.1 shows the collisional excitation cross-sections by an electron impact for 1s$^2$1S$_0$ (M = 0) $\rightarrow$ 1s2p$^1P_1$ (M = 0, 1). With the increase in the incident kinetic energy of a colliding electron, difference between the $M = 0 \rightarrow M = 0$ and the $M = 0 \rightarrow M = 1$ becomes small, and polarization shows negative if the electrons have an energy of above 50 keV, while those with the energies of below 50 keV have a contribution to positive polarization. The fast electrons generated by ultra intense laser pulses are energetically broad, so that positive polarization can be obtained even if fast electron temperature $T_{Fast} = 50$keV. However, with an increase in $T_{Fast}$, the polarization of Heα is reduced due to an increase in the number of the fast
electrons of above 50 keV at low plasma density. At high plasma density, miscellaneous atomic processes between $1s^2p^1P_1$ ($M = 0, \pm 1$) and higher atomic states may affect the dependence [9].

3. Theoretical results and discussions

$\pi$-light is defined as the x-ray component parallel to the direction of electron motion, which arises from the atomic transition $1s^2p^1P_1 \rightarrow 1s^21S_0 + h\nu$ with $\Delta M = 0$. $\sigma$-light is the component perpendicular to the electron motion for which $\Delta M = \pm 1$. In the calculation, since the directions of the fast electron motion are not initially well-collimated, a quantization axis can be defined as perpendicular to an irradiated target surface. Thus, the polarization $P$ can be defined as $P = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp}$, where $I_\parallel$ and $I_\perp$ are respectively the intensity of He $\alpha$ radiation of which electric fields are parallel and perpendicular to the quantization axis. For the polarized x-ray calculation, another time-dependent atomic population kinetics code [4] must be separately carried out in advance. The basic calculation scheme to solve the population kinetics is given in Hakel et al. [13].

To determine a time-history of background bulk electrons, the stopping range described by Batani [14] was adopted. The temporal evolution profile of fast electrons is assumed to be Gaussian with a full-width at half-maximum (FWHM) of 0.5 ps. The peak of fraction of fast electrons is the critical density for the laser wavelength of $\lambda = 800$ nm used in the experiment [8]. In the calculation, the VDF of the fast electrons is characterized by $T_{Fast-z}$ and $T_{Fast-r}$, where $T_{Fast-z}$ denotes the fast electron temperature along the quantization axis, and $T_{Fast-r}$ is that perpendicular to the axis.

In the study of Kawamura et al. [9], highly polarized He $\alpha$ radiation can be observed only at low density plasma, while there is no polarization at solid density $\rho_s$. It is expected that the polarized He $\alpha$ radiation experimentally obtained does not originate from the dense region, but rather from the low density region such as a corona plasma. In this study, the polarizations of above 10% can be expected at total ion density $N_i = 4.5 \times 10^{21}$ cm$^{-3}$ ($\approx 0.05\rho_s$), $T_{Fast-z} = 10 \sim 50$ keV and $T_{Fast-r} = 1$ keV. In the experiment, the resultant polarizations of time- and space-integrated He $\alpha$, however, are $10 \sim 30\%$ [8]. The fast electrons with a large transverse velocity component could be easily captured by self-induced magnetic field, resulting in the generation of a well-collimated fast electron beam. In Fig. 2, the calculations done with $T_{Fast-r} \leq 5$ keV are presented to demonstrate the effect of the narrow transverse thermal spread of the fast electron beam. The calculation results show that the polarization may reach up to

![Figure 2. Dependence of polarization on $T_{Fast-r}$ for $T_{Fast-z} = 10, 30, 50$ keV, and $N_i = 4.5 \times 10^{21}$ cm$^{-3}$.

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$\sim 20\%$ at $T_{\text{Fast} - r} \sim 100\,\text{eV}$, $T_{\text{Fast} - z} = 10\,\text{keV}$, and it is comparable to the experimental results. The temperature and density of fast electrons in our study are $10 \sim 50\,\text{keV}$, $\sim 10^{21}\,\text{cm}^{-3}$ respectively, and the corresponding beam current density is about $10^{12}\,\text{A/cm}^2$, which is greater than the Alfvén current with the assumption that the diameter of the electron beam is of the order of $1\,\mu\text{m}$, so that filamentation instability can be occurred. Since the fast electrons with a large transverse velocity component are captured by the magnetic field, the anisotropy of the VDF of the fast electrons is enhanced and so is the polarization at a plasma density of $\sim 4n_c$ [15], where $n_c$ is the critical density. Due to an increase in the number of elastic collisions in the dense region of greater than $10n_c$, the alignment can be broken, reducing the polarization.

4. Conclusions
In conclusion, a population kinetics code associated with magnetic atomic sublevels was developed for polarization spectroscopy relevant to fast ignition. The calculation results suggest that a VDF of fast electrons with large anisotropy along the propagation axis can be generated by the growth of filamentation instability, and that high polarization can be obtained. This study provides a qualitative understanding of polarized x-ray from highly charged atoms associated with fast electron transport in fast ignition plasmas, and it also demonstrates the potential of polarized x-ray spectroscopy to gain insight into fast electron transport in fast ignition plasmas.

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