Large anisotropy of the electron distribution function in the high-density plasma produced by an ultrashort-pulse UV laser

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Anisotropy of the electron distribution function in a high-density plasma was measured with x-ray polarization spectroscopy. A prepulse controlled KrF laser was used to produce a plasma with a density of up to 10^{22} cm^{-3}. In the high-density plasma, a large beamlike anisotropy was observed when the collision time was less than the laser pulse length. The direction of this anisotropy was aligned with the polarization of the incident laser field. The amplitude of the anisotropy was reduced when the polarization of the laser was changed from p to s polarization. These results show that the observed anisotropy was introduced by the applied laser field and that x-ray polarization spectroscopy is a good tool for diagnosing high-density plasmas created by ultrashort-pulse lasers. [S1063-651X(97)02107-7]

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INTRODUCTION

Recent advances in ultrashort-pulse laser technology have made it possible to create high-density, highly ionized, and nonequilibrium plasmas. They are far from thermal equilibrium so they are expected to be a good medium for x-ray lasers and ultrashort-pulse x-ray sources. In these plasmas, the electrons and ions cannot reach an equilibrium, therefore, the electron temperature, which is normally used for characterizing electron behavior, will be undefined, because the velocity distribution will be non-Maxwellian. To overcome this difficulty, the electron velocity distribution function (EDF) has to be measured directly. In the lower-density plasma that are created using gas targets, it can be measured by the laser Thomson scattering method [1]. However, optical probing of the high-density plasma is difficult due to its large absorbance, refractivity, and fast transit time. A new diagnostic method would be useful because of the interesting physical characteristics of the high-density plasmas produced by the interaction of ultrashort-pulse lasers with solid targets, where the density remains high during the laser pulse because of the limited hydrodynamic expansion.

In these plasmas, the incident laser field causes the electrons inside the plasma to oscillate and drives processes, such as collective plasma waves or thermal conductive flux. Initially, the EDF has a large anisotropy which is determined by the applied laser field. After enough collisions have occurred, this anisotropy may disappear and the plasma will be thermalized. If the applied laser field gives not only energy to the electrons but also anisotropy to them, the anisotropy of the EDF itself can be considered as one of the parameters to denote these plasma behaviors. The driving and relaxation of anisotropy in high-density plasmas is one of the key issues in recent plasma physics studies [2].

The anisotropy of the EDF can be estimated from the polarization of an emission line. It is not necessary to assume an equilibrium model, unlike normal electron temperature measurements. The wavelength of the emission lines can be chosen by tracer ion species, therefore, the soft and hard x-ray signal can be selected for diagnosing the high-density plasma medium. Observation of anisotropy of EDF in laser produced plasma was first achieved by Kieffer *et al.* [3]. A 1 μm wavelength laser interacted with preplasma which was produced by the prepulse of the laser system. The measured density of the plasma was 10^{21} cm^{-3} or less.

To confirm whether the anisotropy of the EDF is a key parameter in a short-life high-density plasma or not, the following two questions had to be answered experimentally. (1) In the higher-density plasma and lower intensity laser field (where the quiver energy is lower than that of the excitation in the target ions), does a significant amount of anisotropy of the EDF occur? (2) If it is observed, is this anisotropy driven by the applied laser field directly? The second question is especially important, because the anisotropy of the EDF can also be driven by the steep density gradient [3].

In this study, it was assumed that the collisions randomize the anisotropy of the EDF. Therefore, the density has to be scaled by the number of collisions which occur during the laser pulse. For this estimate, a 90° deflection time of specific energy electrons by electron-ion collisions was considered.

$$\tau_{90}=\frac{m_e^2 v_e^3}{8\pi n_e Z e^4 \ln\Lambda}.$$

In this formula, e is the electron charge, $\ln\Lambda$ is the Coulomb logarithm, n_e is the electron density, v_e is the electron velocity, m_e is the electron mass, and Z is the ion charge. The dominant velocity of the electrons for the excitation of the ions was dependent on Z, because the rate of excitation and the polarization efficiency are maximum at just above the threshold energy which was dependent on Z^2. The electron density dependence on the laser wavelength can be scaled by the critical density. Therefore, the collisionality of the created plasma was proportional to $\tau_{90}^{-1}\sim n_e v_e{}^{-3} Z \sim\lambda^{-2}Z^{-2}$. For example, in Kieffer's previous experiments, the ratio of the pulse duration and τ_{90} was in the order of unity ($\lambda=1.06$ μm, $Z=13$, $n_e\sim 10^{21}$ cm^{-3}). To simulate a more collisional ''high-density'' plasma, the wavelength of the laser and the Z number of the tracer ions has to be decreased. In our study, a deep ultraviolet KrF ($\lambda = 0.248$ μm) laser was used and F ions ($Z = 9$) were chosen as the tracer. The collisionality was greater by two order of magnitude in comparison with the previous experiment. The created electron density will be a few times 10^{22} cm^{-3} and is as high as only one-tenth of the so-called solid-state density. In other words, the observed anisotropy of EDF simulates that of 2.6 keV electrons in solid density plasma. The intensity where the quiver energy E_{os} is equal to the excitation energy E_{ex} is estimated to be $I = 2 \times 10^{17}$ W/cm^2, all experiments in this study were performed below this intensity.

EXPERIMENTS

The experiments were carried out with a TW KrF laser system [4] at the Institute for Laser Science of the University of Electro-communications. While the maximum output power of this laser is 2 TW/beam with 500 fs pulses, a longer 2 ps duration pulse was used for decreasing the dispersion and nonlinear absorption inside the windows and the focusing lens. The amplified beams were focused on the target with an F/3 aspherical lens and the intensity on the targets was changed from 10^{14} W/cm^2–10^{16} W/cm^2 by changing its position near the best focusing point. Saturable absorber filters of acridine in methanol [5] were introduced between each amplifier. The prepulse energy can be controlled by the concentration of the absorbers. For higher-density plasma creation in this study, the prepulse energy had to be minimized. After careful control of the concentration, the power contrast ratio of the prepulse and main pulse was 10^{-8} on the target. There was no plasma emission and no observable damage on the target without the main pulse.

The polarization of the emissions from the target were measured by a pair of flat KAP crystal spectrometers, which were located at almost the same distance, in the same line of sight, and consisted of the same Bragg crystals and UV-cut filters. The experimental setup is shown in Fig. 1. To compensate for the small difference of each spectrometer, which was mainly caused by the nonunity aspect ratio of the target plasma (expansion length vs plasma width), the intensity of the H-like $L\alpha$ line was used for calibration. This line was considered to be unpolarized [6]. Its opacity effect on these calibrations was small because each spectrometer had the same line of sight which was orthogonal to the incident laser plane. One cleaved surface of the Bragg crystal was aligned to be parallel to the target surface ($I\|$) and the other aligned to the normal ($I\perp$). The Bragg reflection of each crystal was strongly dependent on the polarization. At an incident angle of 40°–50°, the reflectivity ratio of the s and the p-polarized beams was greater than ten. The polarization of the emission was estimated by the ratio of the spectral intensity between each spectrometer signal. In several shots of these studies, a knife edge was introduced between the target plasma and the spectrometer to obtain the spatial profile of the emission. The distance between the peak emission position and the target surface and the length of the emission area were as small as 20 μm, which was the spatial resolution of this measurement.

Because the lower Z fluorine atoms were used as a tracer, CF_2 foil targets were chosen. The laser's angle of incident on the target was 40° for all experiments in this paper. According to our previous experiments [7], the optimum angle of the resonant absorption was 55° at $I = 10^{14}$ W/cm^2 and there were small effects of it within the 40° incident angle condition.

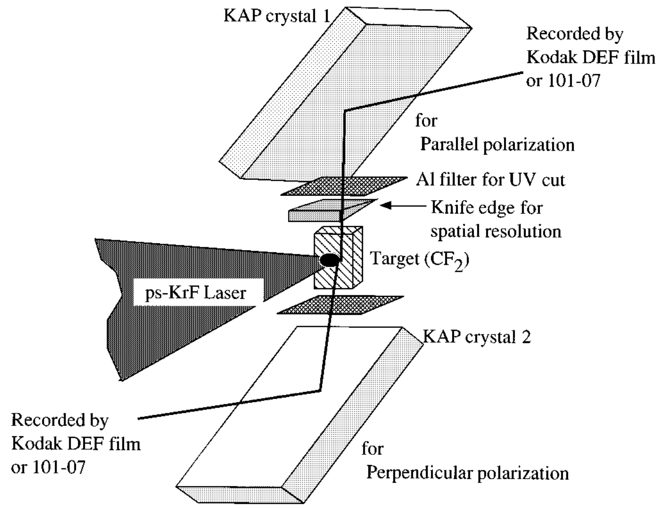

FIG. 1. Experimental setup for measurement of the polarization of the resonant line emission. A pair of crystal spectrometers were located at almost the same distance, in the same line of sight, and consisted of the same Bragg crystals and UV-cut filters. The surfaces of the crystals were aligned orthogonally with each other. A knife edge was set near the plasma for measuring the spatial profile of the line emission.

EXPERIMENTAL RESULTS AND DISCUSSION

Typical spectra from the polarized spectrometers are shown in Fig. 2. A series of He- and H-like F lines were observed. According to the previous paper [3], the degree of the polarization of the Heα line was determined by

$$P = \frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}}.$$

The polarization of Heα in the Fig. 2 spectrum was estimated to be +0.25. If the $P_0 = 0.6$ (the polarization for the monoenergetic electron beam) is assumed [3], this polarization is evidence of a large anisotropy of the EDF ($f_2/f_0 = 2.0$, this means almost beamlike EDF) in this plasma. The electron density of the emitting plasma was estimated by Stark broadening of the Heβ line whilst considering the plasma size and the instrumental broadening effects. The observed electron density was 0.7–1.5 $\times 10^{22}$ cm^{-3}. The ratio of the pulse duration and the collision time was greater than 100. Even in such high-density plasmas, a large beamlike anisotropy of the EDF was observed. In comparing the previous experiments, the sign of polarization was opposite and the absolute value of polarization was large though the electron density was greater than the turning point of the laser field ($n_e > n_c \cos^2\theta$).

To investigate the driving force for the anisotropy, the dependence of the polarization and intensity of the incident laser was measured (Fig. 3). In this figure, the error bars of each data denoted the estimation error of the polarization

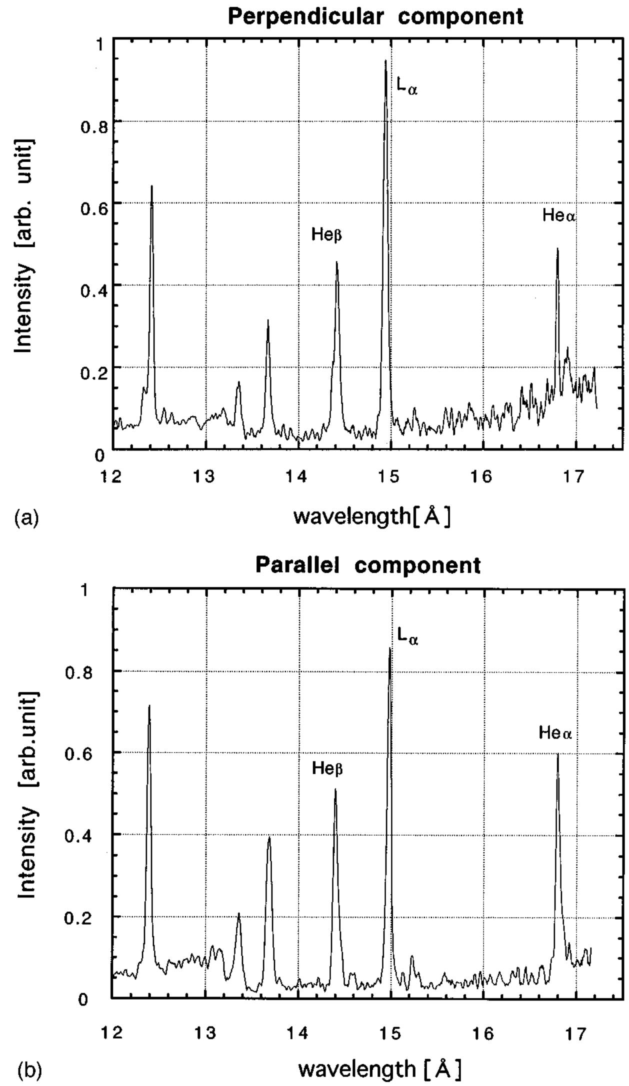

FIG. 2. Typical spectra from the polarization spectrometers. He-like and H-like resonant lines were observed. The ratio of the Heα line and the $L\alpha$ line intensity intensities showed a large difference between the perpendicular (a) and the parallel component (b). The polarization was estimated to be $+0.25$.

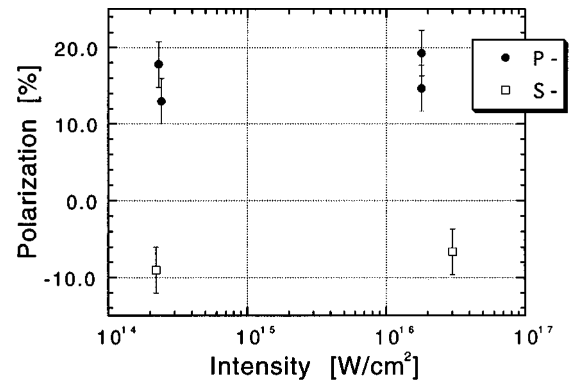

FIG. 3. The dependence of the irradiation intensity and the laser polarization on the emitted x-ray polarization. A large difference was observed with the p-polarized laser condition and the s-polarized one. This is the most reliable evidence for the polarization of the x ray of the resonant line, because the setup and the other conditions were the same except for the laser polarization.

from x-ray spectral intensity. In both 10^{14} W/cm^2 and 10^{16} W/cm^2 irradiance, a strong dependence on laser polarization and a small dependence on laser intensity were observed. The axis of the observation of the beamlike anisotropy was parallel to the laser electric field direction. While a large positive polarization was observed in the p-polarized laser, a small amplitude, negative polarization was observed in s polarization.

It is known that the resonant absorption process and the related wave dumping generate fast nonthermal electrons, in longer pulse experiments. However, in our experiments, the absolute intensity of the He-like and H-like lines was not dependent on the polarization of the lasers. Therefore, resonant absorption was not the main absorption process for exciting the He-like F ions. The incident angle was detuned to the optimum one for the resonant absorption [7]. In addition, the density which was estimated by Stark broadening of the Heβ line was almost the same in both the s-polarized and the p-polarized laser case. These results also highlight the difficulty in explaining the polarization dependence on the anisotropy of the EDF by normal resonant absorption theory.

In a previous paper [3], the anisotropy of the EDF was explained by the short scale length properties. Because the scale length of the created plasma may depend more strongly on the laser intensity than the laser polarization, their model can not explain our experimental results. In addition, they observed a pancakelike EDF($P<0$), while a beamlike EDF($P>0$) was observed in our p-polarized laser shots. If we consider that the small but negative polarization observed in s-polarized laser shots was due to the same mechanism as previous papers [3], then the positive polarization in p-polarized laser shots indicate a new mechanism for driving the anisotropy of the EDF. The obliquely incident laser and small preplasma condition might be responsible for the new results.

Very recently, a few theoretical papers have been published which discuss the anisotropy in high-density plasmas [2]. They estimate the anisotropy of the EDF in the plasma in which the energy of the interaction laser is larger than the thermal electron energy, $E_{os}/E_{th}>1$. In such plasma, the alignment of the electron motion is expected to be with the strong laser field. However, the ratio of the quiver velocity and the ionizing electron's velocity E_{os}/E_{ex} in our experiment was less than 10^{-3} for $I=10^{14}$ W/cm^2. The reason for the large anisotropy still remains undetermined. A new idea such as anisotropy of collisionality due to anisotropy of the EDF [8], or a detailed estimation including the accumulation of anisotropy during the rise time of laser intensity, needs to be introduced.

Although the detailed mechanism of the anisotropy of EDF in our experiments was not determined, it was apparent that this anisotropy was directly driven by the applied laser field. Therefore, this anisotropy may disappear after electron energy has transferred to random thermal energy. Indeed, in much longer pulse duration experiments, there was negligible difference between experiments with the p-polarized and the s-polarized laser. Thus the x-ray polarization spectroscopy has been shown to be a key diagnostic tool for energy transfer process of the electrons in high-density, nonequilibrium plasma produced by ultrashort-pulse lasers.

CONCLUSION

Anisotropy was measured in a high-density plasma which was produced with a KrF laser system, in which the prepulse was well controlled, and lower Z targets. Even though many electron-ion collisions could occur during the laser pulse, a large polarization of the resonant line emission was observed. This positive polarization is evidence that there was beamlike EDF with a p-polarized laser interaction. The laser polarization had a strong influence on this anisotropy. It was difficult to explain the EDF anisotropy with the normal resonant process, because the absorption of laser light had a small dependence on the laser polarization and the electron density was almost the same in both the s-polarized and the p-polarized laser case. Because it was apparent that this anisotropy was driven by the applied laser field directly, x-ray polarized spectroscopy has been shown to be a powerful tool for measuring the relaxation from laser energy to thermal energy in high-density, nonequilibrium plasmas produced by ultrashort-pulse lasers.

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