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Study of The Anisotropy of Electron Energy Distribution of Optical-Field Ionized Oxygen Plasma by Using Polarization Spectroscopy

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The anisotropy of electron energy distribution in oxygen plasmas produced by a high intensity laser was investigated by using polarization spectroscopy. An ultra-short pulsed laser with a pulse duration of 66.5 fs and a power density of 1×10^{17} W/cm^2 was used. At this power density and pulse duration, the plasma was generated predominantly by optical field ionization. The degree of polarization of OVI $1s^2 2p\ ^2P^2$- $1s^2 4d\ ^2D^o$ (J = 1/2-3/2 and 3/2-5/2) transition line at 129.92 Å was measured. O VI $1s^2 2p^2 P^2 - 1s^2 4s^2 S^2$ (J = 1/2-1/2 and 3/2-1/2) transition line at 132.26 Å was used to calibrate the sensitivity of the optical system. The dependencies of the degree of polarization on the initial gas density and on the laser polarization were investigated. When the laser polarization was changed from a linear to a circular polarization, the degree of polarization was decreased. When the initial gas density was increased, the degree of polarization was decreased.

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I. INTRODUCTION

Due to the development of ultra-short pulse high intensity lasers, the optical field ionization(OFI) process in the gaseous media has been widely studied because of its potential applications, including soft x-ray lasers [1–4]. The parameters of an OFI plasma such as temperature and ionization stage can be controlled by laser parameters, such as laser polarization and intensity, so that the conditions for soft x-ray lasers can be realized, and soft x-ray lasing using OFI plasmas have already been demonstrated.

The initial condition of the electron distribution function has been also studied. The OFI theory indicates that the initial electron distribution is highly anisotropic, and the anisotropy can also be controlled by laser polarization [5]. The measurement of the initial electron distribution was reported in Ref. [6], using the recombination continuum. But using this method, it is hard to measure the anisotropy of the electron distribution.

Plasma polarization spectroscopy provides an alternative way to measure the anisotropy of the electron energy distribution [7,8]. The polarization spectroscopy is based on the observation of polarized lights. A polarized light is emitted whenever a population imbalance exists among magnetic sublevels of an excited state in an atomic or ionic system. The imbalance can be produced whenever the excitation processes are spatially anisotropic, such as in the case of excitation by charged particle beams. The polarization also changes with respect to collision energy, because the average direction from which the atom receives the collisional impulse varies. Hence the degree of polarization is closely related to collisional excitation strengths for magnetic sublevels. The collision strength contains the information on the electron energy distribution function(EDF), which can be, therefore, deduced from the measurement of the degree of polarization.

In this work, the plasma polarization spectroscopy was applied to OFI plasmas in the extreme ultra-violet (XUV) wavelength region to measure the anisotropy of the electron distribution function. Li-like oxygen plasmas were investigated under various experimental conditions such as initial gas density and laser polarization.

When an atom orion is in a strong external electric field, the potential barrier of a bound electron is suppressed. By tunnelling process, the bound electron can be ionized through this potential barrier. This process is known as optical field ionization(OFI).

The energy distribution function of electrons optical-field ionized by a linearly polarized laser is given by two-dimensional Maxwellian distributions in directions $\|$ and $\perp$ to the laser electric field $f(\mathbf{p})d^3\mathbf{p} = f(p_{\|})dp_{\|}f(\mathbf{p}_{\perp})d^2\mathbf{p}_{\perp}$ [4] [5] [9], where

$$f(p_{\|}) = \frac{1}{\sqrt{2\pi m T_{\|}}} \exp\left(-\frac{p_{\|}^2}{2mT_{\|}}\right) \qquad (1)$$

$$f(\mathbf{p}_{\perp}) = \frac{1}{2\pi m T_{\perp}} \exp\left(-\frac{\mathbf{p}_{\perp}^2}{2mT_{\perp}}\right),$$

where corresponding temperatures are given as follows.

$$T_{\|} = \frac{3\omega}{2\gamma_z^3} = 4.8(E_i/E_H)^{9/2}\lambda^2/Z^3 \qquad (2)$$

$$T_{\perp} = \frac{\omega}{2\gamma_z} = 0.85(E_i/E_H)^{3/2}/Z.$$

Where ω is the laser frequency in eV, γ_z is the Keldysh parameter calculated at the appearance intensity, λ is the laser wavelength in μm, E_H is the ionization energy of hydrogen, E_i is the ionization potential in eV, and $p_{\|}$ and $p_{\perp}$ mean the momentum parallel and perpendicular to the laser polarization direction. In general, $T_{\|}$ is much higher than $T_{\perp}$. The electron distribution is elongated along the laser polarization direction, looks like an ellipse in velocity space. Hence a linearly polarized laser produces an anisotropic electron distribution.

For the case of a circularly polarized laser, the electron distribution is expected to be isotropic and Maxwellian, and the temperature is given by

$$T_c = 12.8\frac{\lambda^2}{Z^2}\left(\frac{E_z}{E_H}\right)^4. \qquad (3)$$

The initial electron distribution depends on the laser polarization and other reasons, such as nonlocal electron heat flow.

II. EXPERIMENTAL SETUP

To generate an optical field ionized plasma, an ultrashort pulse laser was used. The laser energy per pulse was about 50 - 65mJ. The pulse width was 66.5fs, which was measured using a single-shot autocorrelator.

A gas target was used. The gas density was controlled by the backing pressure. When the backing pressure is 8 bar, the gas density at 500 μm away from the nozzle was measured to be of the order of 1×10^{18} cm^{-3}.

To take extreme ultra violet(XUV) spectra, a flat-field spectrometer equipped with a concave mirror in front of an entrance slit was used. An X-ray CCD camera (Princeton Instrument, SX-TE/CCD-1024SB) was used for data acquisition.

Fig. 1 shows the experimental setup. To obtain the polarization resolved spectra, two spectra were taken. First, the spectrometer was aligned to look at the source (plasma) directly and then was rotated by θ to observe the reflected light off a multi-layer mirror. To ensure that the spectrometer saw the symmetric position of the plasma along a laser incidence axis, the laser incidence direction angle, α, was adjusted as follows.

$$2\alpha + (\pi/2 - \theta) = \pi \qquad (4)$$

Due to the restriction of a vacuum chamber, the spectrometer rotation angle was set to be 4°, and the laser incidence angle was $\alpha = 47°$. Using this experimental geometry, the radiation field intensity along the direct measurement direction (as the z' direction in Fig. 1) can be described

$$\vec{E}_d = (E_{0z}\sin\alpha + E_{0x}\cos\alpha)\hat{x'} + E_{0y}\hat{y'}, \qquad (5)$$

and the field intensity along the mirror measurement direction is

$$\vec{E}_m = (E_{0z}\sin\alpha + E_{0x}\cos\alpha)\hat{x''} + E_{0y}\hat{y''}. \qquad (6)$$

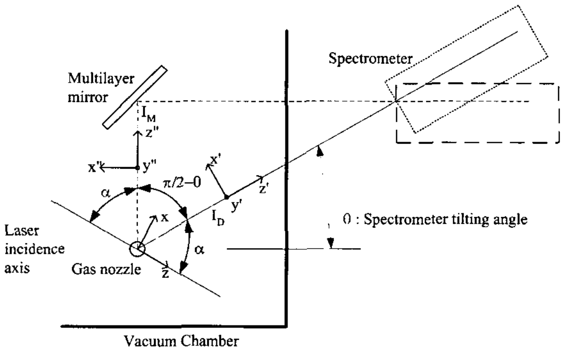

FIG. 1. Experimental layout.

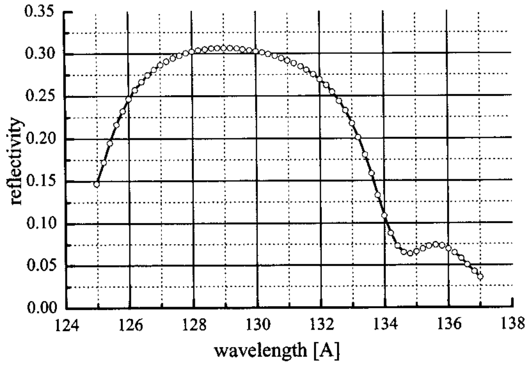

FIG. 2. Mo/Si multi-layer mirror reflectivity as a function of wavelength at t he incidence angle of 45°. The measurement was done at ALS

As in Fig. 1, the symmetry axis is along the laser incidence axis, so the parallel and perpendicular directions are defined relative to the laser incidence axis. Due to the symmetry of the experimental setup, the electric fields along the $\hat{x}$ and $\hat{y}$ directions have then the same magnitude, $E_{0x}^2 = E_{0y}^2 = E_{0\perp}^2$, and the electric field for $\hat{z}$ direction is defined as $E_{0z}^2 = E_{0\|}^2$.

The degree of polarization is then defined by

$$P = \frac{I_\| - I_\perp}{I_\| + I_\perp}. \tag{7}$$

A Mo/Si multi-layer soft x-ray mirror was used; a Mo layer thickness is 3.93 nm, a Si layer thickness 5.805 nm, the number of bilayers 30, the optimized wavelength 13.2 nm, and the incidence angle 45°. The mirror reflectivity was also measured using synchrotron radiation of Advanced Light Source, Berkeley, CA, USA. Fig. 2 shows the measured reflectivity for S-polarization light at the incidence angle 45°. The calculated reflectivity at the incidence angle of 45° for different polarizations shows that the ratio for the S and P polarization is about 23:1 (= $R_s : R_p$).

III. EXPERIMENTAL RESULTS AND DISCUSSION

1. Polarization analysis

As shown in Fig. 1, to measure the degree of polarization of a spectral line, two spectra were taken, one directly and the other in the reflection by a multilayer mirror. The measured spectrum reflected by a multi-layer mirror contains only perpendicularly polarized light, but the directly measured spectrum is composed of polarizations both parallel and perpendicular to the laser incidence axis. To measure the degree of polarization, the parallel component must be estimated from the direct measurement.

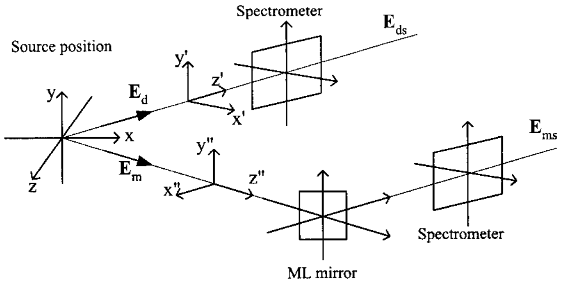

FIG. 3. The polarization state in each optical system.

The polarization state in each optical system position is shown in Fig. 3.

If we denote the sensitivity of the spectrometer for different polarizations by S_p for P polarization and S_s for S polarization, and the multi-layer mirror reflectivity by R_p and R_s, using Eqs. (5) and (6), the electric field after the spectrometer for each direction can be written as Eq. (8):

$$\begin{aligned}\vec{E}_{ds} &= \sqrt{S_p}E_{x'}\hat{x}' + \sqrt{S_s}E_{y'}\hat{y}' \\ &= \sqrt{S_p}(E_{0z}\sin\alpha + E_{0x}\cos\alpha)\hat{x}' + \sqrt{S_s}E_{0y}\hat{y}' \\ \vec{E}_{ms} &= \sqrt{R_pS_p}E_{x''}\hat{x}'' + \sqrt{R_sS_s}E_{y''}\hat{y}'' \\ &= \sqrt{R_pS_p}(E_{0z}\sin\alpha + E_{0x}\cos\alpha)\hat{x}'' + \sqrt{R_sS_s}E_{0y}\hat{y}''.\end{aligned} \tag{8}$$

The measured intensity, which is time average of the magnitude of electric fiel d, is then

$$I_{ds} = S_p(I_z\sin^2\alpha + I_x\cos^2\alpha) + S_sI_y \tag{9}$$

$$I_{ms} = R_pS_p(I_z\sin^2\alpha + I_x\cos^2\alpha) + R_sS_sI_y \tag{10}$$

If a cylindrical symmetry along laser incidence axis is assumed, $I_x = I_y = I_\perp$, where $I_\perp$ is the intensity of the light whose polarization is perpendicular to the laser incidence axis. Since the multi-layer mirror reflectivity for S-polarization is much larger than for the P-polarization ($R_s \gg R_p$) at the incidence angle of 45°,

$$I_{ms} = R_sS_sI_y = R_sS_sI_\perp. \tag{11}$$

Using Eq. (11), from measured intensities I_{ds} and I_{ms}, the intensities of the parallel and perpendicular polarization are written as

$$\begin{aligned}I_\perp &= \frac{I_{ms}}{R_sS_s}, \\ I_\| &= \frac{R_sS_sI_{ds} - (S_p\cos^2\alpha + S_S)I_{ms}}{R_sS_sS_p\sin^2\alpha}.\end{aligned} \tag{12}$$

The intensity ratio is then

$$I_R = \frac{I_\parallel}{I_\perp} = \frac{R_s I_{ds} - (1 + S_r \cos^2\alpha) I_{ms}}{S_r \sin^2\alpha I_{ms}} = \frac{R_s I_{RM} - (1 + S_r \cos^2\alpha)}{S_r \sin^2\alpha} \tag{13}$$

where $S_r \equiv S_p/S_s$ is the sensitivity ratio of the spectrometer and $I_{RM} \equiv I_{ds}/I_{ms}$ is the ratio of the measured intensity. Using this relation, the degree of polarization can be written using the measured intensities.

$$P \equiv \frac{I_R - 1}{I_R + 1} = \frac{(R_s I_{RM} - 1) - S_r}{(R_s I_{RM} - 1) - S_r \cos(2\alpha)} \tag{14}$$

For an unpolarized line, Eq. (14) gives the spectrometer sensitivity ratio.

$$S_r = R_s I^u_{RM} - 1 \tag{15}$$

where I^u_{RM} is the measured intensity ratio of the unpolarized line.

If we measure the direct intensity I_{ds} and reflected intensity I_{ms} for an unpolarized line, the sensitivity ratio S_r can be measured, using Eq. (15). Using this value, and the measured multi-layer mirror reflectivity R_s and the measured polarized line intensity, the degree of polarization can be estimated by Eq. (14).

2. Experimental results

The polarization measurement was done for O VI, $1s^2 2p\,^2P^2$- $1s^2 4d\,^2D^o$, J = 1/2-3/2 and 3/2-5/2 transition line at 129.92 Å. The O VI, $1s^2 2p\,^2P^2 - 1s^2 4s\,^2S^2$, $J = 1/2 - 1/2$ and $3/2 - 1/2$ transit ion line at 132.26 Åwas chosen as a sensitivity calibration line, because the transition line can not be polarized if the upper level of the transition has $J = 1/2$ or $J = 1$.

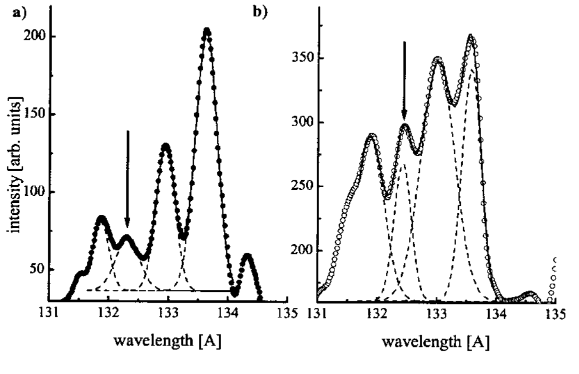

FIG. 4. Spectra for polarization sensitivity calibration. a) was taken using m ulti-layer mirror and b) was directly taken.

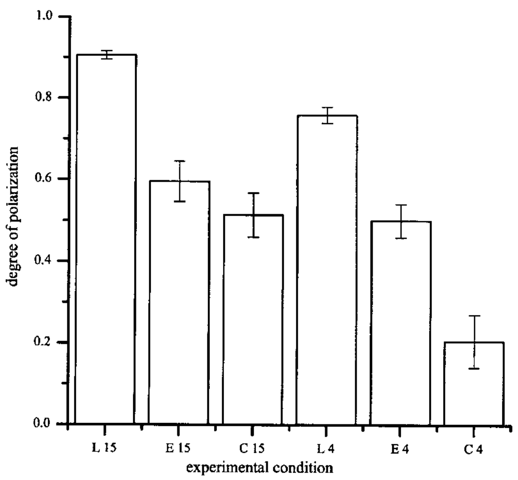

FIG. 5. Measured degree of polarization for different laser polarization and nozzle pressure. The x-axis indicates the experimental condition. The laser polarization is linear, L, elliptical, E, and circular, C. The number after L, E, and C indicate the backing pressure of the valve.

The laser polarization was varied from a linear (horizontal), through an elliptical, to a circular polarization using a waveplate. The gas pressure was changed by controlling the backing pressure: 1.5 Bar, 4 Bar, and 8 Bar. For each pressure, the gas density at the laser focus position, was previously measured to be 2×10^{17}, 4×10^{17}, and 1×10^{18} cm^{-3}, respectively. Fig. 4 shows the spectra of the polarization calibration line. The transition line was blended with the lines from O VI so that the line profile was de-convoluted by using the Gaussian profile to estimate the intensity of the 132.26 Å line, which was then used to measure S_r. The measured value of S_r is 1.50 ± 0.12.

Fig. 5 shows the measured degree of polarization. First of all, the measured degree of polarization is very large, indicating that the energy distribution is highly anisotropic. For the case of a circularly polarized laser beam, Eq. (3), indicates that the electron energy distribution is isotropic in v_x and v_y space. The intensity I_x and I_y is assumed to be the same. But the intensity I_z can be different from either I_y or I_x, because an anisotropy can exist in the v_z and v_y or v_z and v_x phase space. The degree of polarization defined by Eq. (7) with the intensity definition of Eq. (12) indicates that there exists an anisotropy in EDF in the $v_\parallel$ and $v_\perp$ phase space, where $v_\parallel = v_z$ and $v_\perp$ are the velocity parallel to and perpendicular to the laser incidence direction, respectively.

When a linearly polarized laser is used, there initially exists a strong anisotropy parallel to and perpendicular to the laser electric field, as shown in Eq. (1) . For this case, the assumption of the cylindrical symmetry may not be applied; all I_x, I_y, and I_z may be different from each other. If the difference between

I_x and I_y is denoted by $\Delta I \equiv I_x - I_y$, the intensity of direct measurement is changed to

$$\begin{aligned} I_{ds} &= S_p(I_z \sin^2\alpha + I_x \cos^2\alpha) + S_s I_y \qquad (16) \\ &= S_p(I_{\|} \sin^2\alpha + I_{\perp}\cos^2\alpha) + S_s I_{\perp} + S_p \Delta I \cos^2\alpha. \end{aligned}$$

Using this equation, the intensity ratio can be written as

$$\begin{aligned} I_R^r &= \frac{R_s I_{RM} - (1 + S_r\cos^2\alpha)}{S_r \sin^2\alpha} - \frac{\Delta I}{I_y}\cot^2\alpha \qquad (17) \\ &= I_R - \Delta I_R, \end{aligned}$$

where $\Delta I_R \equiv \{(I_x - I_y)/I_y\}\cot^2\alpha$. The first term in the righthand side comes from the different intensities of I_z and I_y, and the second term comes from the difference between the intensities I_x and I_y. The degree of polarization is modified to

$$P = \frac{I_R^m - 1}{I_R^m + 1} = \frac{I_R^r + \Delta I_R - 1}{I_R^r + \Delta I_R + 1}. \qquad (18)$$

This may lead to different numbers for the degree of polarization, but since the observed degree of polarization is very large, this does not affect the fact that the electron energy distribution is highly anisotropic.

When the laser polarization was changed from a linear to a circular polarization, or the initial gas density increased, the degree of polarization decreased.

For the case of linear laser polarization, high polarization may come from the initial anisotropy of the electron distribution function. But the laser polarization is changed to the circular, the initial anisotropy decreased. The measured polarization dependence on the laser polarization can be understood qualitatively in this way.

If the particle density increases, the collision frequency also increases. The electron collision frequency is given by

$$\nu_e = 2.91 \times 10^{-6}\frac{n_e \ln\Lambda}{T_e^{3/2}}, \qquad (19)$$

where $\ln\Lambda$ is the Coulomb logarithm [10], n_e is the electron density in cm^{-3}, and T_e is the electron temperature in eV. If the electron density increases, the collision frequency increases. The anisotropy in the electron distribution disappears more rapidly in a higher electron density which explain the density dependence of the degree of polarization.

IV. CONCLUSION

Using an ultra-short pulsed laser with a pulse duration of 66.5 fs and a power density of 1×10^{17} W/cm^{-3}, oxygen plasmas were generated. The degree of polarization was measured for O VI $1s^22p\ ^2P^2$- $1s^24d\ ^2D^o$ (J = 1/2-3/2 and 3/2-5/2) transition at 129.92 Å. O VI $1s^22p^2P^2 - 1s^24s^2S^2$ (J = 1/2-1/2 and 3/2-1/2) transition at 132.26 Å was used to calibrate the sensitivity of the optical system. The observed degree of polarization is very large, indicating the highly anisotropic energy distribution of electrons. When the laser polarization was changed from a linear to a circular polarization, the degree of polarization was decreased. When the initial gas density was increased, the degree of polarization was decreased.

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