Observation of Interference between Stark and Electric Quadrupole Transitions in LIF from He Atoms in Plasmas

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Interference between Stark-induced dipole and electric quadrupole amplitudes was observed in a He hollow cathode plasma with axial magnetic field perpendicular to the sheath electric field E by laser-induced fluorescence (LIF) method. Circularly polarized LIF signals were observed in the sheath region. Spatial profile of the degree of polarization P_C showed characteristic features of the interference. Using theoretically calculated P_C-E relationship, E-profile was successfully obtained from the measured P_C.

1. Introduction

The importance of measuring the electric field E induced in plasma edges which plays an essential roll in plasma confinement and plasma processing has been well recognised. Laser-induced fluorescence (LIF) methods utilizing the Stark effect have been extensively developed to directly measure electric field distributions because of their high sensitivity and high spatial resolution [1-3]. There have been, however, few methods applicable to plasmas in a magnetic field B. We have developed a sensitive method to directly measure the electric field in plasmas by using LIF of helium atoms [2]. In this technique the electric field can be determined from the linear polarization of LIF (He I: $n^1D \rightarrow 2^1P$) subsequent to the excitation of forbidden transitions (He I: $2^1S \rightarrow n^1D$). This method has been extended for the plasma in a magnetic field, such as ECR plasma, by considering the influence of the magnetic field on the LIF observation [4, 5]. In $E \perp B$ geometry, as in Fig. 1, the applicability has been demonstrated by previous experiments using a cylindrical hollow cathode plasma in the axial B [6].

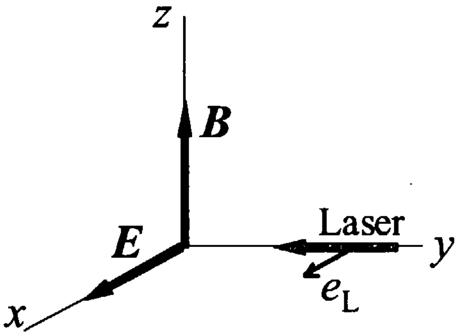

Fig. 1 Geometry for laser-induced fluorescence. e_L: laser polarization

When E is perpendicular to B (Fig. 1), the atomic interference can take place between the Stark-induced electric dipole and the electric quadrupole (QDP) transition amplitudes [6, 7], as shown in Fig. 2. This makes possible a new higher-sensitive LIF measurement. The laser excitation generates anisotropic populations among magnetic sublevels with opposite sign, e.g. $m=+1$ and -1. The anisotropy can be observed as the circular dichroism of LIF along the magnetic field, which is expected to be an order of magnitude higher than the linear one in sensitivity with respect to the electric field.

The aim of this work is to show the existence of the interference in the laser absorption process and the possibility of higher sensitive electric field measurements by a model-type experiment using a cylindrical hollow cathode discharge with the magnetic field applied perpendicularly to the radial electric field in the plasma sheath.

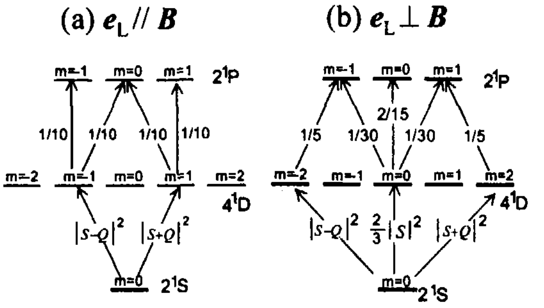

Fig. 2 Relative excitation and fluorescence transition probabilities for the various magnetic sublevels of He I when $E \perp B$. S and Q represent the Stark and quadrupole amplitudes.

2. Experimental

The structure of the cylindrical hollow cathode is depicted in Fig. 3 (a). The He plasma was produced in a cylindrical hollow cathode (inner diameter of 30 mm and length of 60 mm) made of aluminium, with a discharge current of 20 mA at a He gas pressure of 0.53 Torr. A magnetic field of 55 G was applied to the plasma by setting a permanent magnet disk on the central axis (z-axis) of the hollow cathode. The cathode-fall potential was observed by an electric probe to be 220 V. The cathode has two rectangular slits (28x0.8 mm^2) to introduce a laser beam into the cylinder and then LIF can be observed in a region between −14mm and +14mm along x-axis.

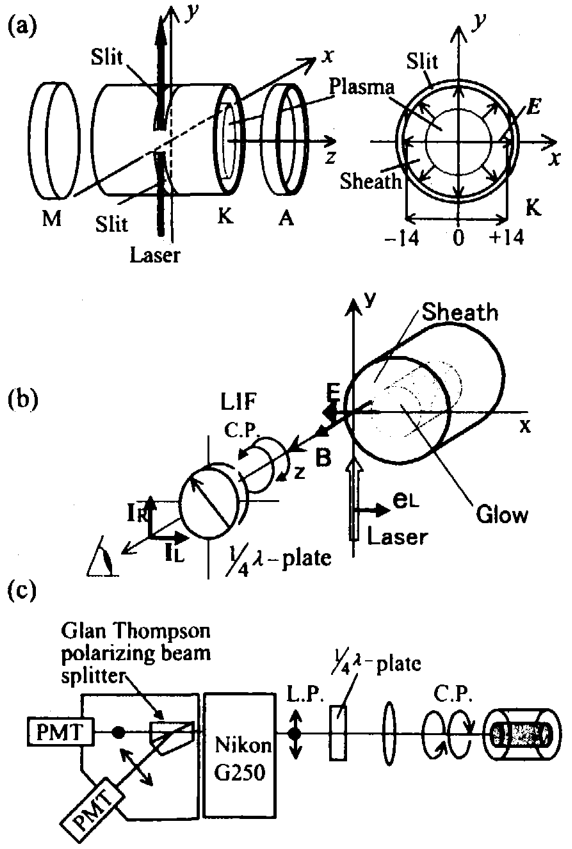

Fig. 3 (a) Schematic view of cylindrical hollow cathode. (b) Geometry for LIF observation. (c) Detection system of circular polarisation.

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The excitation of forbidden transition (2^1S-4^1D, 397.2 nm) was made by a YAG pumped dye laser (397.2 nm) with pulse width of 5 ns. The polarization direction of laser $\boldsymbol{e}_\mathrm{L}$ was chosen to be parallel $\boldsymbol{e}_z$ or perpendicular $\boldsymbol{e}_x$ to z ($\boldsymbol{B}$). The intensities of circularly polarized LIF (4^1D-2^1P, 492.2 nm) were observed in the z-direction, as in Fig. 3 (b). The σ-light was separated into left hand I_L and right hand I_R circular polarization components by a 1/4λ plate and a Glan Thompson polarizing beam splitter (Fig. 3 (c)). Sensitivity of the detection system for both polarization components was *in situ* calibrated by using circularly unpolarized LIF. The degree of circular polarization P_C is defined as follows;

$$P_C = \frac{I_L - I_R}{I_L + I_R}. \qquad (1)$$

The spatial distribution was measured by scanning the plasma vessel in the x direction.

3. Results and Discussion

Figure 4 shows temporal circular polarization components of LIF, I_L and I_R, observed with an axial magnetic field (B=55G) for $\boldsymbol{e}_x$-excitation at the negative glow (x=+6 mm). The observed σ-light was unpolarized in the negative glow, where only the QDP transition was excited, since the electric field is negligibly small.

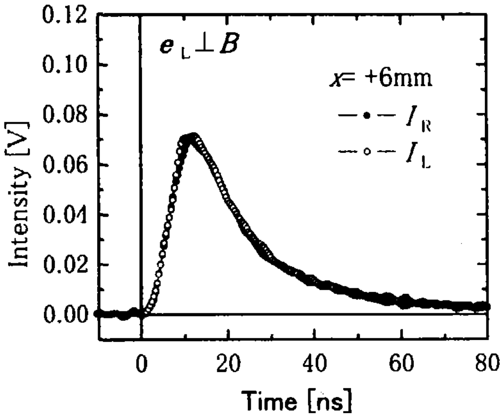

Fig. 4 Time evolutions of polarization components, I_L and I_R of 492.2 nm fluorescence excited by laser polarized in the x direction, observed in the negative glow.

On the other hand strongly polarized LIF was observed in the sheath (x=+12 mm) for (a) $\boldsymbol{e}_x$-excitation and (b) $\boldsymbol{e}_z$-excitation, as in Fig. 5. I_L is much stronger than I_R. This clearly shows a difference in population among the magnetic sublevels with opposite sign in the final state of the laser absorption transition, 4^1D. This is due to the Stark-QDP interference. The pulse shapes also differ from each other. For I_R pulse the width is broader and the peak is delayed with respect to I_L pulse. The value of P_C is very close to unity at the onset of the pulse and then rapidly decreases toward zero with time. The decay of polarization is caused by collision of the excited atoms with plasma particles, mainly He ground state atoms in this plasma: I_R predominantly originates from the population created due to the collisional transfer from m=+1 for (a) and m=+2 for (b). The intensity of LIF observed for $\boldsymbol{e}_x$-excitation is strong compared with that for $\boldsymbol{e}_z$-excitation. This is reasonably explained to be mainly due to the difference in the excitation rate by laser as shown in Fig. 2. There is a difference in the decay profile of P_C. The decay in case (b) seems to begin with a time delay compared with case (a). In case (b) laser excitation creates the population in a sublevel with +2 in 4^1D to emit I_L. Subsequent collisional transfer from m=+2 to m=0, -1 or -2 causes depolarisation. The collisional transfer m=+2 to 0 might take longer time than the transfer +1 to 0 in case (a).

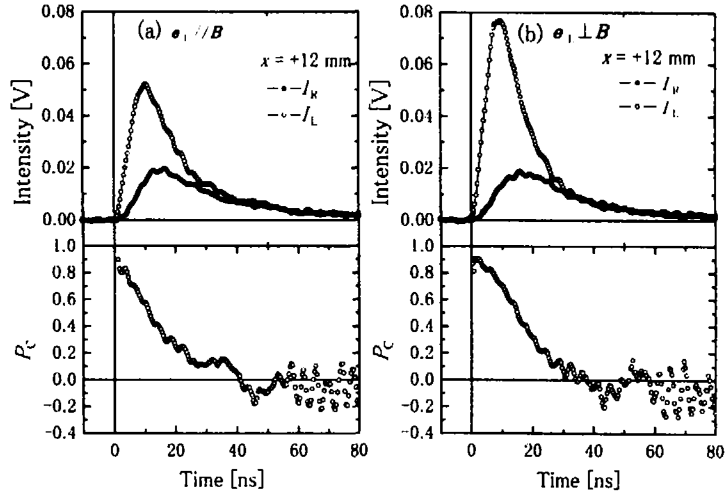

Fig. 5 Time evolutions of polarization components, I_L and I_R, and of polarization degree of LIF (492.2 nm) observed in the sheath for (a) e_z-excitation and (b) e_x-excitation.

The spatial distribution of P_C is represented in Fig. 6. Values of P_C are almost 0 in the negative glow region between x = -9 and +9 mm, where the macroscopic electric field can be considered to be zero. On the other hand in the sheath region P_C shows an increase for $x>0$ and oppositely a decrease for $x<0$ towards the cathode surface. It is noted that the P_C-profile has a positive peak for $x>0$ and a negative peak for $x<0$ in the middle of the sheath where the electric field increases linearly.

The observed P_C-profile can be explained by the following theoretical consideration on the basis of the atomic interference mentioned in Sect. 1. In the case of e_z-excitation, for example, using the relative amplitudes of the transitions described in Fig. 2, the relative intensities of polarization components are given as,

$$I_L = |S+Q|^2, \qquad (2)$$

$$I_R = |S-Q|^2, \qquad (3)$$

Substituting eqs (2-3) into eq. (1), P_C is written as a function of S/Q,

$$P_C = \frac{2S/Q}{[1+(S/Q)^2]}. \qquad (4)$$

In a similar way P_C in the case of e_x-excitation can be obtained as follows,

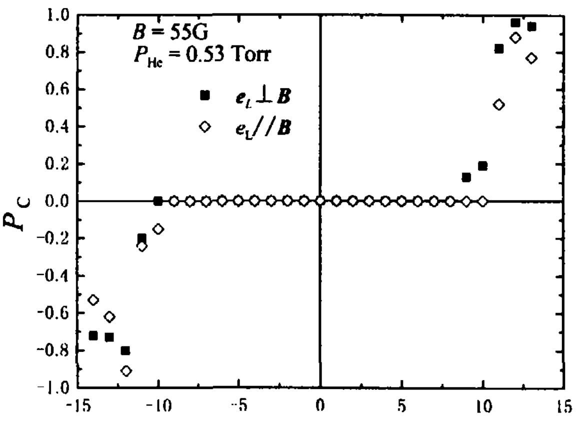

Fig. 6 Radial distribution of degree of polarization of LIF. The cathode surface is situated at $x = \pm 15$ mm.

$$P_C = \frac{2S/Q}{\left[1+\frac{10}{9}(S/Q)^2\right]} . \qquad (4')$$

Here, S is the Stark-induced electric dipole transition (2^1S - 4^1D) amplitude, which involves a matrix element of the Stark mixing between 4^1P and 4^1D. Since the matrix element has a linear dependence on E, the signs of numerators, S/Q, in equations (4) and (4') are changed when the electric field vector is reversed. Then, P_C becomes positive (negative) when $x > 0$ ($x < 0$).

The ratio S/Q can be related to E as follows,

$$S/Q = \sqrt{\frac{3}{4C^2}} \cdot E \,, \quad \cdots (5)$$

where C=0.24 kV/cm for n=4 [6]. Putting eq. (5) into eqs. (4) and (4'), the degree of circular polarization, P_C, is obtained as a function of E. Values of P_C calculated for e_x- and e_z-excitation are plotted versus E in the upper part of Fig. 7. A peak in each P_C curve is situated at an electric field where S/Q approximately equals 1. Similarly, it can be considered that peaks in P_C-profiles shown in Fig. 6 correspond to the positions where $|S/Q| \approx 1$. P_C has high sensitivity and wide dynamic range compared with the case of linear polarization method as shown in the lower part of Fig. 7 [6]. Circular polarization method is higher in sensitivity by one order of magnitude. In the present case of n=4 it will be possible to measure very weak electric fields of the order of 10 V/cm.

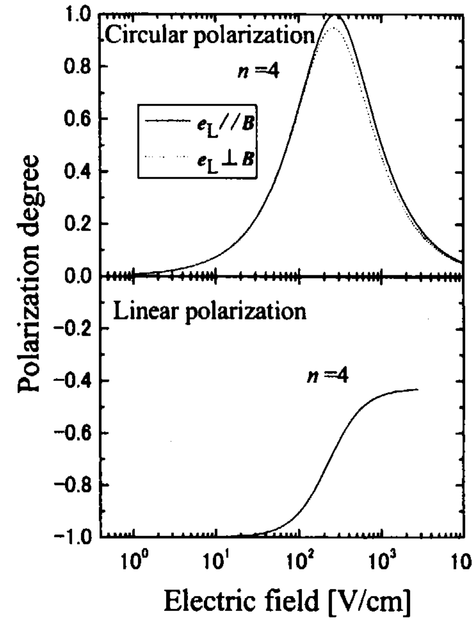

Fig. 7 Calculated sensitivity of circular polarization.

Figure 8 shows the radial distribution of E obtained from the observed P_C profile using the theoretically calculated P_C–E relationship (Fig. 7). Here, values obtained from P_C observed at x<0 are also plotted. In the sheath region the distribution shows a linear dependence against x. By extrapolating E the cathode-fall potential and the sheath thickness were estimated to be 200±20 V and 4 mm, respectively. The obtained potential agrees

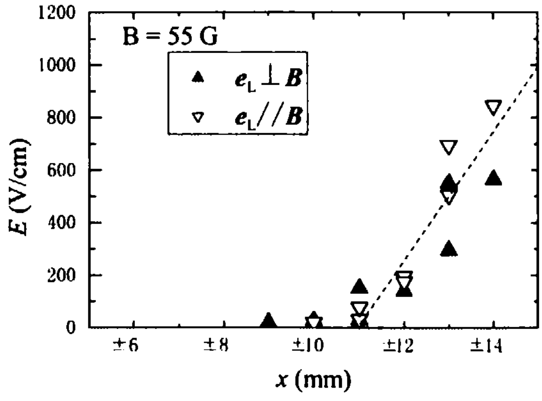

Fig. 8 Radial distribution of electric field

with that obtained by a cylindrical electric probe within the experimental errors.

4. Concluding remarks

The interference effect between the Stark-induced electric dipole and the electric quadrupole amplitudes involved in laser absorption processes has been observed for the first time in a cylindrical hollow cathode He plasma with the magnetic field applied perpendicularly to the sheath electric field ($E \perp B$). In the middle of the sheath the LIF observed in the direction of magnetic field was strongly polarized, which was obviously due to anisotropic population created by laser excitation between magnetic sublevels with different sign, ±1 for e_Z-excitation or ±2 for e_X-excitation. The observed radial profile of the degree of circular polarization P_C also showed characteristic features of the interference. A positive and a negative peak in the P_C profile were observed in the sheaths located in $x>0$ and $x<0$, respectively. The theoretical consideration showed that the peaks corresponded to the boundary between $S<Q$ and $S>Q$ and the sign of P_C means the direction of electric fields. The radial profile of E was obtained from the observed P_C using the theoretical P_C-E relationship calculated according to our model. Sheath potential estimated from the resulting profile of E was in good agreement with probe measurements.

It was demonstrated that our new LIF technique using interference of atomic transition amplitudes had high sensitivity to measure the weak electric field of the order of 10 V/cm for $n=4$ and a wide dynamic range of 3 orders of magnitude. It should be noted that the new technique enables us to measure the direction of the electric field vector in plasmas. In plasmas with higher particle density (electrons, ions and atoms), however, the decay of polarization becomes faster and the LIF waveform is considerably modified by the frequent collisions of n^1D atoms with the plasma particles. In such cases it will become difficult to estimate E straightforwardly from the experimental P_C. To evaluate E accurately, we will need to simulate the temporal evolution of polarized LIF by using a rate-equation model involving the depolarisation process of oriented atoms

Acknowledgments

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