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Polarized laser-induced fluorescence technique to measure localized electric field induced perpendicularly to magnetic field in the plasma-edge

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Abstract

To develop a direct measurement of the weak electric field induced in a magnetically confined edge plasma, the crossed magnetic- and electric-field effect was investigated on the linear polarization of laser-induced fluorescence. The fluorescence was induced by laser excitation of metastable He atoms 2^1S to 4^1D state due to Stark-induced electric dipole and electric quadrupole moments. In a model-type experiment carried out in a cylindrical hollow cathode plasma column, the radial distribution of the polarization of fluorescence was analyzed to determine the electric field dependence. The measured degree of polarization agreed with estimates from a theoretical model based on the selection rules of the spontaneous radiative transition. The minimum detectable electric field is estimated to be a few tens of V/cm in our scheme. We briefly discuss techniques to increase our measurement sensitivity by the interference between both the forbidden transitions in the laser excitation.

Keywords: Boundary plasma; Plasma edge; Radial electric field; Laser-induced fluorescence

1. Introduction

We have proposed a sensitive method to directly measure the electric field in the edge plasma by using a laser-induced fluorescence (LIF) of a supersonic helium atom beam. A design study has been carried out to install the beam and spectroscopic measurement system on a medium size tokamak [1–3]. In this LIF technique the electric field **E** can be measured by observing only the linear polarization of the allowed fluorescence (e.g. $4^1D \rightarrow 2^1P$) subsequent to the forbidden excitation (e.g. $2^1S \rightarrow 4^1D$) of metastable atoms, which is created in the atom beam by the electron impact, due to the Stark effect and the electric quadrupole (QDP). There is no need to calibrate the absolute intensity of LIF and tunable laser used.

We have also pointed out that LIF signals observed due to QDP excitation are affected when the magnetic field **B** is applied parallel to **E** [1]. The polarization is strongly dependent upon the geometric configuration of the laser polarization vector and the observation direction with respect to the quantization axis of excited atoms, whose direction is mostly determined by the magnetic field. In the recent tokamak experiments, the weak but significant electric field induced in the plasma edge region is almost perpendicular to the toroidal magnetic field (**E**⊥**B**) [4]. In this case the magnetic field effect should also be considered on LIF signals due to the Stark excitation, because atoms are quantized by the magnetic field, instead of the electric field. Then metastable atoms are excited through the Stark transition according to the different selection rules from that in the case of **B**||**E** or $B=0$. The corresponding relative excitation and fluorescence transition probabilities for the various magnetic sublevels are represented in Fig. 1 where S and Q represent the Stark-induced electric dipole and quadrupole amplitudes of electromagnetic transition matrix elements [5].

To study the fundamental behavior of linearly polarized LIF signals in the **E**⊥**B** configuration, a model-type

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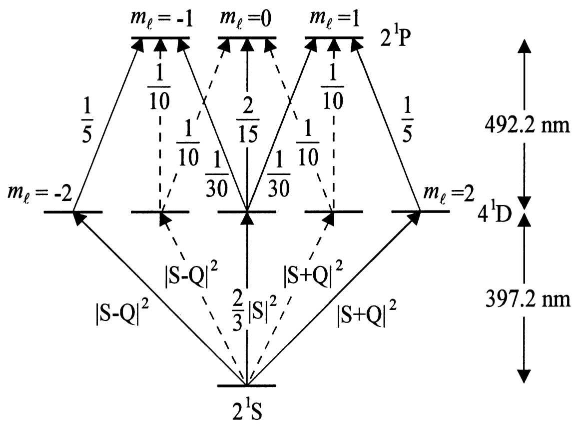

Fig. 1. Relative excitation and fluorescence transition probabilities for the various magnetic sublevels of HeI in crossed magnetic and electric fields. *S* and *Q* represent the Stark and quadrupole amplitudes. Solid (dashed) lines represent the transitions corresponding to a pump laser polarized along $\boldsymbol{x}(\boldsymbol{z})$.

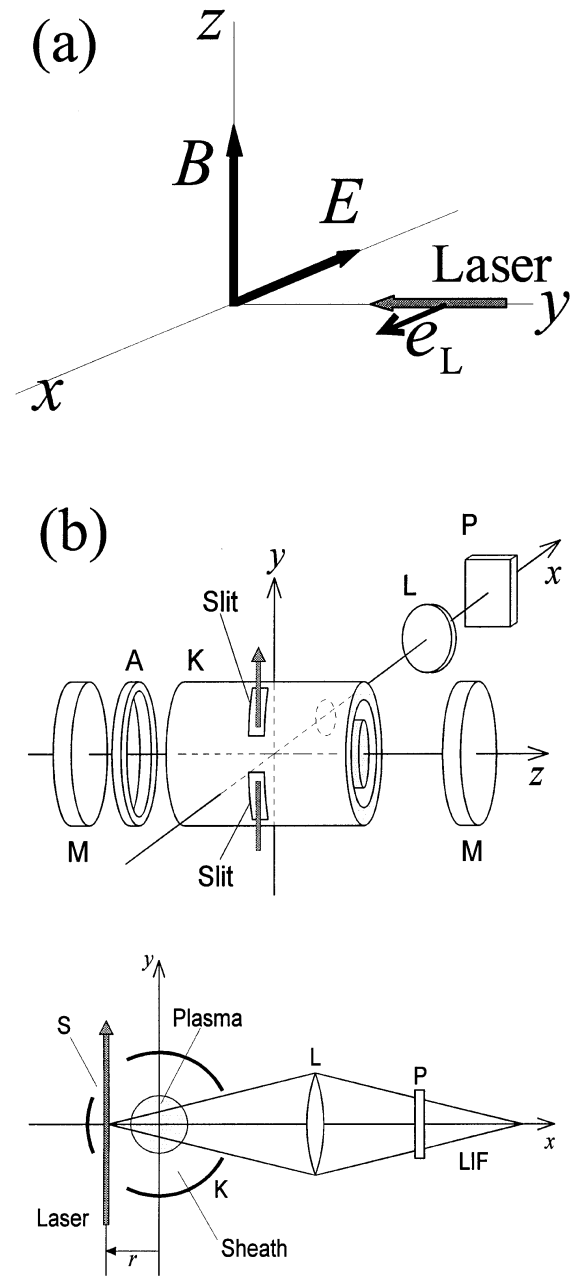

Fig. 2. (a) Observation geometry for LIF. (b) Schematic view and x–y cross section of cylindrical hollow cathode discharge lamp; K: hollow cathode, A: anode, M: magnet, L: lens and P: polarizer.

experiment was performed with a cylindrical hollow cathode discharge with the magnetic field applied perpendicularly to the electric field in the cathode dark space. In this study the applied magnetic field is very weak compared to those expected in magnetic fusion devices such as tokamaks, i.e. 5.5×10^{-3} T compared to 3 T. As mentioned above, the polarization strongly depends on the direction of the quantization axis which is fixed at considerably weak magnetic field. Results obtained here will make a large contribution to a design study to apply this spectroscopic method for fusion devices.

2. Experimental setup

Fig. 2(a) shows the transverse observation geometry where x-, y-, and z-axes are taken along **E**, propagation direction of laser light linearly polarized along $\mathbf{e}_L$, and **B**, respectively. The polarization direction of laser $\mathbf{e}_L$ is chosen to be parallel $\mathbf{e}_z$ or perpendicular $\mathbf{e}_x$ to $\boldsymbol{z}$.

The experimental arrangement and structure of the cylindrical hollow cathode lamp are depicted in Fig. 2(b). The He plasma was produced in a cylindrical hollow cathode (inner diameter of 20 mm ϕ and length of 50 mm) made of aluminum with discharge current of 20 mA at a He gas pressure of 0.4 Torr. The cathode-fall potential V_K and sheath thickness d_S were estimated to be 140 V and 3.6 mm, respectively, when no magnetic field was applied, from the spatial distribution of LIF polarization under the $\mathbf{e}_x$ excitation in a similar way of Ref. [6], where electric field linearly increased toward the cathode surface.

A magnetic field of 55 G was applied to the plasma by setting a pair of permanent magnet disks facing each other on the central axis (z-axis) of the hollow cathode, i.e. perpendicular to the electric field in the sheath. The cathode has a viewing aperture (3 mm ϕ) to observe LIF and two rectangular slits (0.5×6.5 mm^2 onto x–z plane) to introduce a laser beam into the cylinder.

The excitation of forbidden transition (2^1S–4^1D, 397.2 nm) was made by a YAG pumped dye laser with pulse width of 5 ns. Intensities of LIF (4^1D–2^1P, 492.2 nm) linearly polarized along $\boldsymbol{z}$ and $\boldsymbol{y}$, I_z and I_y, were observed separately by a sheet polarizer along $\boldsymbol{x}$. The degree of polarization is defined as follows;

$$P = \frac{I_z - I_y}{I_z + I_y}. \quad (1)$$

The spatial distribution was measured as a function of the distance r from the center by scanning the plasma vessel along $\boldsymbol{x}$.

3. Results and discussion

3.1. LIF polarization under the magnetic field crossed to the sheath electric field

Fig. 3(a) shows temporal polarization components of 492.2 nm fluorescence, I_z and I_y, and the degree of polarization P (open squares) were observed without magnetic field ($B = 0$) under excitation by laser polarized along x-direction ($\mathbf{e}_x$) at the negative glow ($r = 4.5$ mm), where only the QDP transition was excited, since the electric field is negligibly small. The polarization decays rapidly by collision of the excited atoms with plasma particles, mainly He ground state atoms, and, hereafter, we take values of P at the earlier period from the onset of signals (5 ns) when the depolarization effect is smaller. Obtained polarization is ~−0.85 very close to unity, reflecting a feature of polarized LIF due to the QDP excitation. Since the quantization axis for QDP excitation is perpendicular to the polarization plane of the laser without magnetic field, the preferred direction is the z-axis and the atoms are selectively excited to the magnetic sublevels $m_\ell = \pm 2$ in 4^1D [7]. The excited atoms subsequently decay down to the 2^1P state with σ-fluorescence of 492.2 nm whose y component is emitted to the x-direction; $I_y \gg I_z$.

Fig. 3(b) shows temporal variation of I_z, I_y and P observed at the sheath ($r = 8.2$ mm) where both Stark and QDP transitions are simultaneously excited by a polarized laser. The quantization axis of excited atoms through the Stark transition can be taken to the direction of electric field (//$\boldsymbol{x}$). The subsequent fluorescence is unpolarized ($P = 0$) in this excitation geometry. On the other hand fluorescence due to QDP excitation should be almost perfectly polarized ($P \sim -1$), because the corresponding axis is taken to be the z-direction. An observed small negative value of P at the early stage (~5 ns) indicates that the Stark component included in LIF is much larger than the QDP one. In other words, most of the excited atoms are populated in the sublevel $m_\ell = 0$ in 4^1D.

Fig. 4 shows temporal LIF signals and P observed under the magnetic field of 55 G (a) in the negative glow ($r = 4.5$ mm) and (b) in the sheath ($r = 8.2$ mm). The observed LIF signal in Fig. 4(a) is almost the same as in the case of $B = 0$, because the quantization axis of the QDP coincides with the magnetic field direction. On the other hand, LIF polarization ($P \sim -0.5$) shown in Fig. 4(b) is less than that shown in Fig. 3(b), which means the Stark component is polarized differently from that shown in Fig. 3(b). The difference comes from the fact that the atoms being excited through the Stark transition prefer the direction of magnetic field as the quantization axis rather than the electric field direction. According to the diagram in Fig. 1 and selection rules for allowed fluorescence, the atoms emit the π light to the x-direction as well as the linearly polarized y component of σ light whose intensity is always stronger than that of the π light; $I_y > I_z$. This results in a negative value for P.

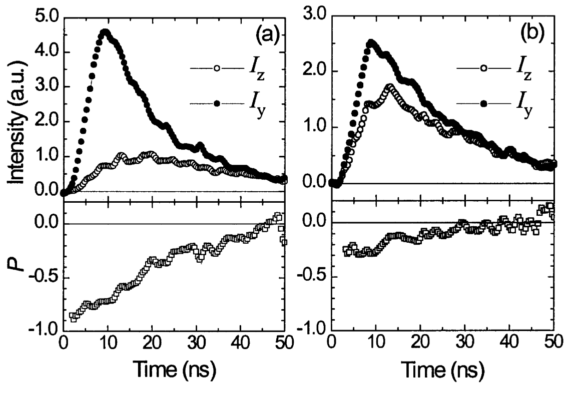

Fig. 3. Time evolutions of each polarization components, I_z (open circles) and I_y (closed circles), and of polarization degree (open squares) of 492.2 nm fluorescence excited by laser polarized along $\boldsymbol{x}$ observed in (a) negative glow and (b) sheath without magnetic field.

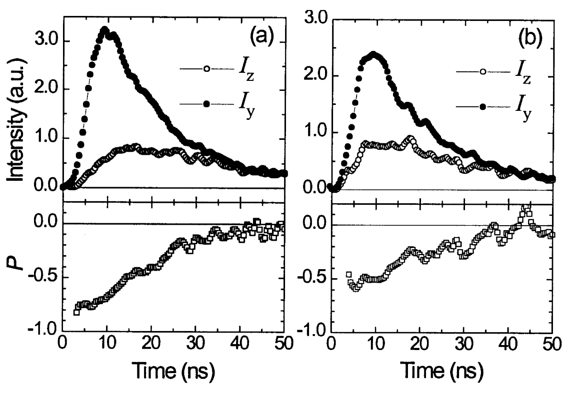

Fig. 4. Time evolutions of each polarization components, I_z (open circles) and I_y (closed circles), and of polarization degree (open squares) of 492.2 nm fluorescence excited by laser polarized along $\boldsymbol{x}$ observed in (a) negative glow and (b) sheath with magnetic field ($B = 55$ G).

In the case of $\mathbf{e}_z$ excitation LIF signals without magnetic field were expected to be unpolarized over the whole region considering the selection rules on the basis of spontaneous emission and the observation geometry. However, the LIF signal obtained in the sheath shows a different feature from that in the negative glow. This is responsible for the coherent interference between two σ-emissions induced by the Stark excitation, whose details will be described in a forthcoming paper. When the magnetic field was applied, LIF shows a finite polarization in the negative glow. No change in polarization, however, was found in the sheath region. We obtained that P was approximately 1/3 over the whole range, from negative glow to sheath.

3.2. Spatial distribution of LIF polarization under crossed magnetic and electric fields

Spatial distribution of P whose values are obtained at 5 ns from the onset of LIF signals are represented in Fig. 5, where (a) is for $\mathbf{e}_z$ excitation and (b) for $\mathbf{e}_x$ excitation. Polarization in (a) shows no spatial dependence even in the sheath, as understood from the energy diagram in Fig. 1. In this case Stark excitation component can not be extracted from LIF signals by a linear polarization method. On the other hand, the spatial distribution of P in (b) indicates the dependence on the sheath electric field E.

Using the similar procedure based on quantum mechanical considerations as described in Ref. [6], the theoretical relationship between P and E can be obtained for the forbidden excitation and fluorescence transitions shown in Fig. 1. When both transitions are simultaneously excited by laser with low power density, the fluorescent intensity I^S due to Stark excitation (I^Q due to QDP excitation) in LIF intensity is proportional to the corresponding absorption coefficients $B_S(E)$ (B_Q). In the present case, as both quantization axes of the Stark-induced electric dipole moment and QDP point to the z-axis, I^S and I^Q are described by each z- and y-polarized components as follows,

$$I^S = I_z^S + 2I_y^S, \quad I^Q = I_z^Q + 2I_y^Q, \tag{2}$$

where the ratio of z- to y-components for each transition are calculated according to the selection rules and are denoted by r^S and r^Q, respectively, i.e. $I_z^S = r^S I_y^S$ and $I_z^Q = r^Q I_y^Q$. These components are also connected to the observed polarization intensity I_z and I_y by the following,

$$I_z = I_z^S + I_z^Q, \quad I_y = I_y^S + I_y^Q. \tag{3}$$

Taking into consideration that the intensity ratio of I^S to I^Q involved in LIF is considered to be the ratio of $B_S(E)$ to B_Q, the degree of polarization defined in Eq. (1) can be rewritten as,

$$P = \frac{B_R(r^S - 1)(r^Q + 2) + (r^Q - 1)(r^S + 2)}{B_R(r^S + 1)(r^Q + 2) + (r^Q + 1)(r^S + 2)}. \tag{4}$$

Here, $B_R = B^S(E)/B^Q$ whose values are quantum-mechanically calculated [6]. When the quadratic Stark effect is valid, $B^S(E)$ is proportional to the square of E. Then we obtain $B_R = (1/C^2)E^2$ where the constant C means the electric field strength for $B^S(E) = B^Q$; e.g. $C = 0.24$ kV/cm for $n = 4$.

In the case of $\mathbf{e}_z$ excitation, r^S and r^Q equal 2 from the selection rules, the square of 3j-symbol, for the allowed fluorescence transition in Fig. 1 and the observation geometry in Fig. 2(a). Then P shows a constant value of 1/3 independent of the electric fields, which agrees well with the experimental P in Fig. 5(a).

On the other hand, in the case of $\mathbf{e}_y$ excitation, since both constants r^S and r^Q are 0.4 and 0, respectively, P varies from -1 to $-3/7$ when E changes from 0 to infinity. In plasmas, however, the depolarization effect should be considered, as described before, which brings about the decrease in P and either the increase or the decrease in $r^{S,Q}$. Using Eq. (4) and assuming that V_K and d_S does not change due to the magnetic field of 55 G [8] and therefore the electric field is increasing linearly toward the cathode surface in the sheath, the experimental P profile shown in Fig. 5(b) was analyzed by using r_S and r_Q as fitting parameters. A best-fit curve was obtained as shown by a solid curve in Fig. 5(b), where the

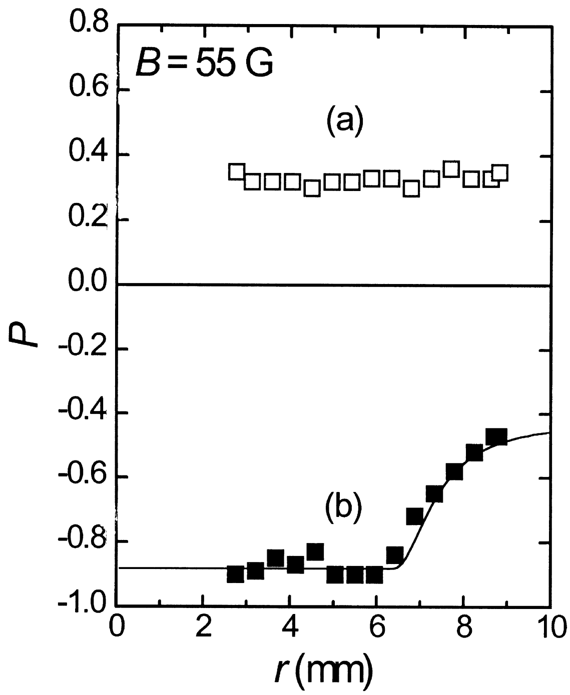

Fig. 5. Radial distributions (a) and (b) of polarization degree of LIF with magnetic field ($B = 55$ G) obtained under excitation by laser polarized along $\boldsymbol{z}$ and $\boldsymbol{x}$, respectively. Calculated distribution is drawn by a solid curve. Cathode surface is situated at $r = 10$ mm.

parameters of r_S and r_Q were 0.42 and 0.055, respectively. The obtained values were very close to the theoretical ones. Thus, it was successfully demonstrated that our model for linear polarization of LIF from the plasma sheath also held under crossed magnetic and electric fields

4. Concluding remarks

It was shown that the LIF polarization spectroscopy was applicable to measure the spatial distribution of the electric field perpendicular to the magnetic field in plasmas. The measurable field strength with high sensitivity was around 240 V/cm which is the corresponding electric field strength when $B_S(E) \sim B_Q$. Using the higher n level excitation can increase the sensitivity of this method. At $n = 5$, the electric field of a few tens of V/cm can be measured.

The crossed magnetic field to electric field can induce the interference between the Stark-induced electric dipole and QDP amplitudes, S and Q, as shown in Fig. 1 [5]. Forbidden excitation induces anisotropic population between magnetic sublevels with opposite sign of quantum number, e.g. $m_\ell = +1$ and -1. The anisotropy appears as the dichroism in circular polarization components of LIF which is very sensitive to the electric field in plasmas. According to our model shown in Fig. 1, the sensitivity of circular polarization is increased by an order of magnitude compared to that of linear polarization. Even in $n = 4$ case it will be possible to measure weak electric field of the order of 10 V/cm.

Strong magnetic fields such as those in fusion devices bring about the very large Zeeman splitting of atomic states. In such a case the metastable atoms will selectively be excited to a given sublevel in n^1D due to the forbidden excitation by a usual laser. To determine the electric field, we should excite two transitions simultaneously, one of them is Stark transition and another is QDP, by using an adequate laser system.

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