ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 976–979

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Spectroscopic measurement of biasing effect on sheath electric field distribution in front of a metal plate inserted in a plasma flow

K. Takiyama [a,*], T. Oda [b], K. Sato [c]

[a] Department of Applied Physics and Chemistry, Faculty of Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan
[b] Faculty of Engineering, Hiroshima Kokusai Gakuin University, Nakano, Aki-ku, Hiroshima, 739-0321, Japan
[c] National Institute for Fusion Science, Toki, 509-5292, Japan

Abstract

A model type experiment was made to study the biasing effect on localized electric field distribution in front of a negative DC biased metal disk in the He plasma flow from an ECR plasma source using the polarized laser-induced fluorescence (LIF) technique. A nonlinear decrease of the electric field strength was observed in distance from the electrode surface for the biasing voltage from 300 to 650 V. The sheath thickness variation was found to be proportional to the applied bias voltage to the 3/5 power. The experimental results are explained on the basis of a collisional sheath model. The applicability of this LIF technique to measurement of the electric field distribution in a biased divertor plasma is briefly discussed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Plasma sheath; Electric field; Biasing; Laser-induced fluorescence

1. Introduction

The issue of biasing to plasmas has become important quite recently for improvement of plasma confinement in fusion devices [1]. To reveal the biasing effect, a direct measurement of the electric field distribution in front of divertor plate is highly desired. Little detailed experimental study, however, has been made of the electric field distribution in plasmas near the biased electrode region. The main reason is that no suitable method has been developed to directly measure the electric field especially at low pressure and magnetic field. On the other hand, to optimize the quality of plasma processing, a bias voltage is also often applied to the substrate such as in electron cyclotron resonance (ECR) plasmas.

We have developed a sensitive measurement method of the sheath electric field structure in discharge plasmas utilizing the polarized laser-induced fluorescence (LIF) spectroscopy [2]. The first reported direct measurement of a sheath electric field structure has been made in front of a substrate in an ECR plasma flow in a magnetic field using the LIF spectroscopy [3]. A linear decrease of the electric field strength was observed in distance from the electrode surface for the rather low biasing voltage from 10 to 80 V. The sheath thickness variation was found to be proportional to the square root of the bias voltage applied. The experimental result has been explained on the basis of a simple sheath model.

In this article, we report a model type experiment using our LIF technique to measure the sheath electric field distribution in front of the substrate inserted in an ECR plasma flow when a higher negative bias is applied to the substrate. The bias voltage dependence of the sheath electric field structure is discussed on the basis of the sheath theory [4]. A brief discussion is made on the applicability of this LIF technique to direct measurement of the electric field distribution in a biased divertor plasma.

---

[*] Corresponding author. Tel.: +81-824 24 7615; fax: +81-824 24 7192.

E-mail address: takiyam@ipc.hiroshima-u.ac.jp (K. Takiyama).

PII: S0022-3115(00)00544-4

2. Experiments

2.1. Experimental apparatus and procedure

The schematic setup of our LIF experiment is shown in Fig. 1. The He plasma is produced by an NTT-type ECR plasma source (AFTEX PS-501) under the same conditions as in [3]. A brass substrate (diameter: 25 mm, thickness: 5 mm) is inserted perpendicularly to the z-axis. The sheath is formed in front of the substrate, where the electric field is parallel to the z-axis. A DC bias voltage from −140 to −650 V with respect to the ground is applied. Magnetic field of 25–30 G parallels the z-axis in the observation region.

The laser light with wavelength of 504.2 nm (line width: 1 pm, pulse width: 5 ns, power: 0.1 mJ/pulse, cross-section of 0.3×3 mm^2) is introduced to excite the metastable He atoms (2^1S) to the 3^1D states into the chamber along the y-axis [5]. The light is linearly polarized parallel to the x-axis ($\boldsymbol{e}_x$).

We observed the fluorescence emitted in the x-direction. The signal is separated into two mutually orthogonal components linearly polarized parallel to the y- and z-axes (I_y and I_z) by using a sheet polarizer, and is detected by a 25 cm monochromator equipped with a gated photomultiplier tube (HAMAMATSU R3896). The observing volume and solid angle were 5.4×10^{-3} cm^3($\Delta z \Delta y \Delta x = 0.3 \times 6 \times 3$ mm^3) and 2×10^{-2} sr, respectively. The signal is averaged over 500 shots using a digitizing oscilloscope (Tektronix TDS620, 2 Gs/s).

Spatially resolved measurement of LIF is carried out by moving the optical system, which includes the laser injection optics, along the z-axis with a spatial resolution of 0.3 mm. The distance from the substrate is denoted by dz (mm).

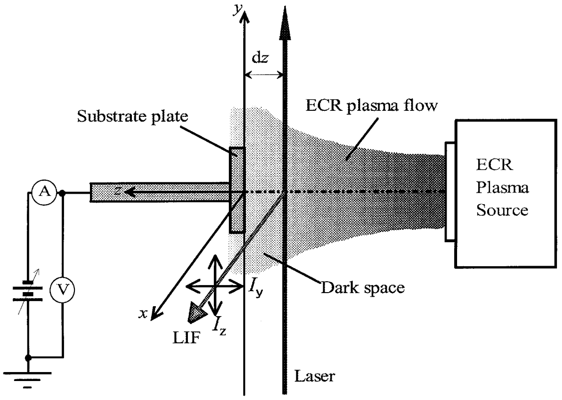

Fig. 1. Partial energy diagram of HeI and relevant transitions among the magnetic sublevels in $\boldsymbol{E}//\boldsymbol{B}$ configuration.

2.2. Forbidden-line excitation of HeI2^{1}S atom for electric field measurement

A partial energy level diagram of HeI and the relevant transitions among the magnetic sublevels are shown in Fig. 2, where the polarization direction of the excitation laser $\boldsymbol{e}_x$ is taken as the x-axis which is perpendicular to the magnetic field $\boldsymbol{B}$ and the electric field $\boldsymbol{E}$ directions. According to the selection rule, the Stark-induced transition, its absorption coefficient being denoted by B^{S}, takes place for the $\Delta m_l = \pm 1$ transition while the QDP transition with corresponding coefficient B^{Q}, which is independent of E, is induced for $\Delta m_l = \pm 2$ [6]. Consequently, both transitions produce the anisotropic population (alignment) between the magnetic sublevels of the upper level (3^1D) by laser excitation. Then the atoms emit polarized radiation depending on E. We denote the sum of π components of LIF (667.8 nm line) by I_z and that of σ components by I_y, as shown in Fig. 1. The polarization of LIF is characterized using longitudinal alignment $\alpha(t)$ defined by [7]

$$\alpha(t) = \frac{I_z(t) - I_y(t)}{I_z(t) + 2I_y(t)}. \qquad (1)$$

The forbidden-line excitation is induced by a short-pulse laser, and the LIF signal is observed as a function of time. Because of the collisions between the excited states and the plasma particles, $\alpha(t)$ decays exponentially with a characteristic time constant τ_{da} (disalignment). The initial value α_0 of $\alpha(t)$ can be determined from $\alpha(t)$ at the onset time of the laser pulse.

Using a similar procedure to that described in [2], the longitudinal alignment α_0 is expressed for the present excitation geometry by

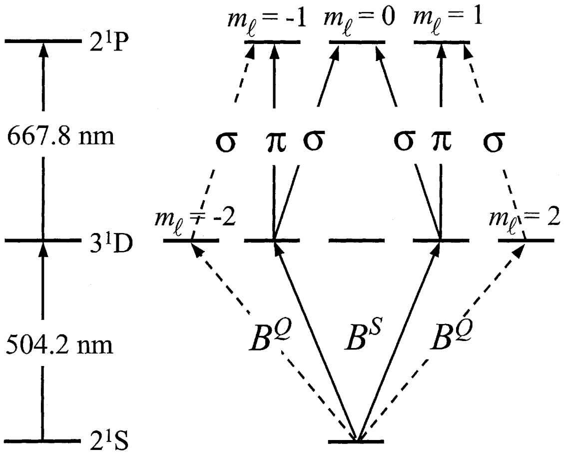

Fig. 2. The geometry of LIF observation. Excitation laser light polarized perpendicular to the z-axis is introduced into the chamber along the y-axis and LIF is observed along the x-axis. Bias voltage (−140 to −650 V) is applied to the metal substrate with the external power supply.

$$\alpha_0 = \frac{B_R - 2}{4B_R + 4}, \tag{2}$$

where $B_R = B^S(E)/B^Q$. When the quadratic Stark effect is valid, B^S is proportional to the square of E, and we obtain $B_R = E^2/C^2$ where the constant C indicates the electric field strength for $B^S(E) = B^Q$, e.g., $C = 1.7$ kV/cm for $n = 3$. Then, E is expressed by

$$E = C\sqrt{\frac{8(2\alpha_0 + 1)}{3(1 - 4\alpha_0)}}, \quad -1/2 \leqslant \alpha_0 < 1/4. \tag{3}$$

The field strength can be directly determined from observed values of α_0.

3. Results and discussion

Fig. 3 shows the temporal variation of the LIF polarization components and $\alpha(t)$ observed (a) at $dz = 6.74$ mm in the plasma region and (b) at $dz = 0.3$ mm in the sheath region. The substrate is biased at −300 V in both cases. The curves of $\alpha(t)$ decay exponentially. From the gradient the disalignment time constant τ_{da} is estimated to be approximately 240 ns, which is much longer than our instrumental response time of 6 ns. The initial longitudinal alignment α_0 is determined at the time of the laser onset, which is defined as the time when the intensity of the I_y component rises to 10% of its maximum in the temporal evolution of the LIF signal. In the plasma region (Fig. 3(a)), the fluorescence is perfectly polarized and then α_0 is obtained to be −0.5, which corresponds to $E = 0$ from Eq. (3). On the other hand, in the sheath region, I_z is obviously observed, as shown in Fig. 3(b). This is due to the π-component of the Stark-induced fluorescence. We obtain $\alpha_0 = -0.39$, from which the value of E is determined to be 0.81_4 kV/cm.

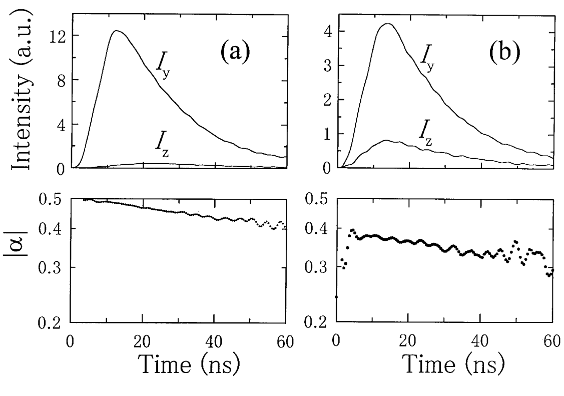

Fig. 3. Temporal variation of each of the polarization components I_z and I_y, and of longitudinal alignment of 667.8 nm LIF observed (a) at $dz = 6.74$ mm in the plasma region and (b) at $dz = 0.3$ mm in the sheath region. The bias voltage is −300 V.

The spatially resolved measurement of LIF was made in the region of $0.3\ \text{mm} \leqslant dz < 11$ mm. The spatial profiles of the electric field were obtained for various bias voltages as shown in Fig. 4, where profiles (a) and (b) are quoted from [3]. It is noted that the E-profile at $V_0 = 140$ V is approximately linear relative to the distance from the substrate surface ($dz = 0$). This means that the net positive charge density is constant in the sheath. The sheath thickness, which is defined as the distance from the substrate surface to the point where $E = 0$, and the sheath potential V_{LIF} determined from the measured electric field distribution are in good agreement with the extrapolated values from the dependencies on $V_0^{1/2}$ and V_0 observed in [3], respectively.

With increasing the bias voltage the sheath thickness, s, and the electric field strength at the substrate surface, E_0, increase in a similar manner as seen in [3]. However, the E-profiles obviously deviate from the linear dependence, especially at the vicinity of the substrate. Such behavior is originated from a non-uniform distribution of He ions in the sheath. The distribution is dominated by the collisions between He ions and atoms. Then the sheath structure is subject to the relative size of the ion mean free path λ_i to the sheath thickness s [4].

In the present case, assuming the He$^+$–He collision, λ_i can be estimated to be 2 mm from He gas pressure according to [8]. Since values of s observed at

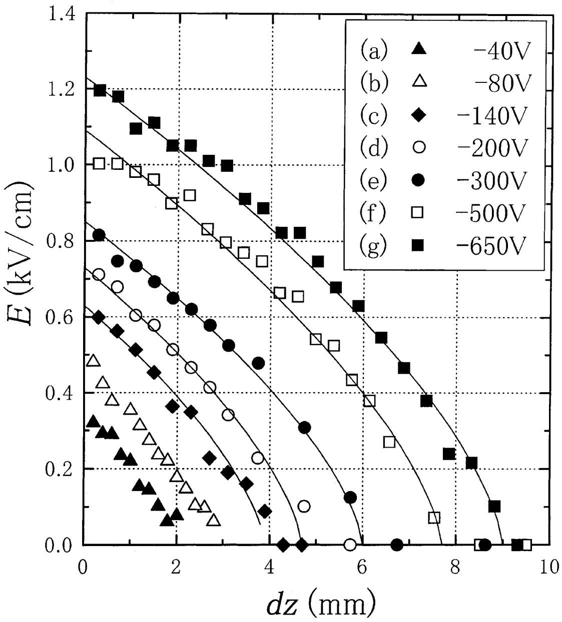

Fig. 4. Spatial distributions of measured electric field along the z-axis for seven different substrate bias voltages, where (a) and (b) are quoted from the previous work [3]. Curves are calculated on the basis of the collisional sheath model.

$V_0 = 140$–650 V are larger than λ_i, it is reasonable to consider that the collisional sheath is generated. In this model, the sheath electric field is proportional to the 2/3 power of distance from the plasma-sheath edge, ξ, in the following:

$$E = \left(\frac{3en_s u_s}{2\varepsilon_0 (2e\lambda_i/\pi M)^{1/2}} \right)^{2/3} \xi^{2/3}, \tag{4}$$

where n_s and u_s are the density and velocity of He^+ at the sheath edge ($\xi = 0$), e and M the charge and mass of the ions, and ϵ_0 is the dielectric constant in vacuum [4]. The potential Φ is then proportional to $\xi^{5/3}$. Since $\Phi = -V_0$ at $\xi = s,\ s \propto V_0^{3/5}$.

To analyze the observed spatial E-profile, the above equation is rewritten using E_0, s and dz in our experimental geometry as follows:

$$E(\mathrm{d}z) = E_0[(s - \mathrm{d}z)/s]^{2/3}. \tag{5}$$

Here, the relation between E_0, s and V_0 is given as

$$V_0 = \frac{3}{5} E_0 s. \tag{6}$$

Using Eq. (5) and taking E_0 and s as fitting parameters, the best-fit curves to respective experimental profiles are obtained as shown in Fig. 4. In the high voltage bias this model reproduces successfully the experimental curves. That is, the E-profiles are obviously proportional to the 2/3 power of ξ. On the other hand, in the case of low bias, e.g., $V_0 = 140$ V, the experimental curves show rather linear variation with respect to ξ. The reason is that the sheath thickness is only comparable to the mean free path of ions, so that the particle collisions do not give large effect on the sheath structure in this case. From the fitting parameters, E_0 and s, and Eq. (6), the potential values V_{LIF} were obtained. V_{LIF} is in good agreement with V_0 and increases linearly with respect to V_0 as shown in Fig. 5(a). Fig. 5(b) shows the thickness s seems to obey the 3/5 power law as theory expects. Thus experimental profiles are well explained by the collisional sheath model.

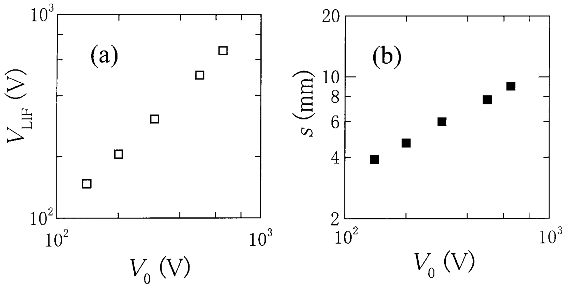

Fig. 5. Measured sheath potential V_{LIF} and thickness s versus bias voltage V_0.

For application of our LIF technique to divertor experiments in magnetic fusion devices, it is essential to make a single laser-shot determination of E possible. For this purpose, sufficient metastable atoms should be injected to the position of interest. The required density is evaluated to be 10^{10} cm^{-3} for the determination under the present experimental conditions. The observation volume required in fusion devices, however, is usually two orders of magnitude larger than in the present experiments. Then the required density in the divertor plasma will be reduced down to 10^8 cm^{-3}.

4. Summary and acknowledgements

A model type experiment was made to measure the sheath electric field distribution in front of a negative DC biased metal disk inserted in the He plasma flow from an ECR plasma source using the polarized LIF technique. Nonlinear decrease of the electric field strength was observed in distance from the electrode surface when a higher biasing voltage was applied to the substrate. The sheath thickness variation was found to be proportional to the applied bias voltage to the 3/5 power. The obtained sheath potential V_{LIF} is in good agreement with the bias voltage V_0. The experimental results are well explained on the basis of a collisional sheath model. This indicates that our LIF measurement is reliable for measurement of the electric field distribution in plasmas such as in the sheath. From the viewpoint of the LIF intensity it is also suggested that the lower limit of the required density of the metastable atoms is 10^8 cm^{-3} for measurement of the electric field distribution in biased divertor plasma.

This work was supported in part by a Grant-in-Aid for Joint Project for Large Helical Device at National Institute for Fusion Science.

References

[1] J.A.C. Cabral, et al., Plasma Phys. Control. Fus. (UK) 40 (1998) 1001.

[2] M. Watanabe, K. Takiyama, T. Oda, Rev. Sci. Instrum. 70 (1999) 903.

[3] M. Watanabe, K. Takiyama, T. Oda, Jpn. J. Appl. Phys. 39 (2000) L116.

[4] M.A. Lieberman, A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, Wiley, New York, 1994, p. 16.

[5] M. Watanabe, K. Takiyama, H. Toyota, T. Oda, Jpn. J. Appl. Phys. 38 (1999) 4380.

[6] R.D. Cowan, The Theory of Atomic Structure and Spectra, University of California, Berkeley, 1981, p. 445.

[7] T. Fujimoto, C. Goto, Y. Uetani, K. Fukuda, Jpn. J. Appl. Phys. 24 (1985) 875.

[8] M.D. Bowden, Y.W. Choi, K. Muraoka, Appl. Phys. Lett. 66 (1995) 1059.