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Low-energetic He-atom beam as a diagnostic probe for electric field measurement in the plasma edges

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Abstract

Two types of low-energetic He-atom beam sources were constructed for direct measurement of electric field distribution in tokamak plasma edge region with aid of laser-induced fluorescence (LIF) technique. One is a continuous plasma flow extracted from an electron cyclotron resonance (ECR) plasma source. The plasma parameters were measured by Langmuir probes, while density profiles and velocity of metastable He atoms (2^1S) in the plasma flow were measured by LIF method. It was found that extremely high density metastable atoms of $\sim 10^{11}$ cm^{-3} were created at 7 cm apart from the outlet of the source. Formation mechanism of such high density 2^1S atoms was briefly discussed on the basis of atomic processes. Another is a pulsed free jet having a pair of discharge electrodes to produce the 2^1S atoms in the jet. High density 2^1S atoms ($\sim 10^{10}$ cm^{-3}) were found to be created in the discharged jet by means of the optical absorption method.

Keywords: JFT-2M; SOL plasma; Boundary plasma; Radial electric field; Atomic physics

1. Introduction

It has been recognized that weak electric field generated in the plasma edges plays an important role for the plasma confinement in the magnetic fusion device [1]. No direct measurement of such electric fields, however, has been made in the torus-plasma edge region. Forbidden lines due to the Stark effect of atoms or molecules have been used to directly measure the electric field in plasmas [2–6]. By using the laser-induced fluorescence (LIF) technique, these lines can be observed with high sensitivity and high spatial resolution [3–6].

In fusion device experiments, LIF has to be combined with a neutral beam probe having suitable energy levels for the electric field measurement [3,4,7]. The beam, however, should be slow enough in velocity to minimize the motional Stark effect due to the strong magnetic field in the fusion devices and also be high enough in density at the edge region [8]. Helium atoms have a potentiality for satisfying the above requirements. The singlet metastable state will make it possible to measure electric fields by the visible LIF technique [5,7]. The ground state has the largest ionization potential among atoms, which gives us relatively large penetration depth of the metastable states into the edge plasma even when the beam is in thermal velocity, because the loss of metastable atoms due to ionization are compensated by the electron impact excitation of the ground states at the higher electron density region [8,9].

We have developed a high-sensitive method utilizing polarization of LIF due to the forbidden excitation of the He metastable atom (2^1S–n^1D) which is caused by the Stark mixing of n^1P to n^1D in the electric field E and also by the electric quadrupole moment (QDP), as shown in Fig. 1 [10,11]. Most of the excited atoms subsequently decay with intense allowed fluorescence (n^1D–2^1P). The intensity I_F is written as a function of E as follows:

$$I_F \propto n_{2s}\,\rho_L[B_S(E)+B_Q], \qquad (1)$$

where ρ_L is a laser power density, n_{2s} is the density of the

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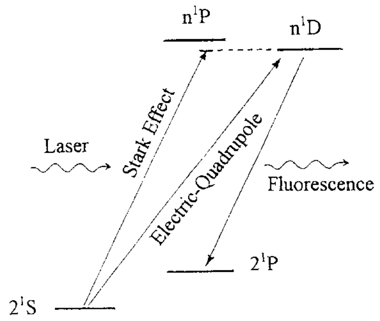

Fig. 1. Partial energy diagram of HeI and forbidden transitions inducing the fluorescence. Both the Stark effect and electric quadrupole transitions are involved.

metastable atoms, $B_s(E)$ is the absorption coefficient as a function of E for the Stark transition, and B_Q is the absorption coefficient for the QDP transition. When the quadratic Stark effect is valid, that is, for not so high electric field, $B_s(E)$ is proportional to the square of E. The fluorescence I_F is generally polarized. The polarization of fluorescence due to the Stark excitation is quite different from that due to the QDP excitation [10]. Considering the alignment of atoms achieved with the polarized laser excitation, the coefficient $B_s(E)$ is simply described in a given configuration for measuring the LIF as a function of the polarization degree P of LIF in the following:

$$B_s(E) = f(P) B_Q. \tag{2}$$

Then, $B_s(E)$ can be determined if B_Q and $f(P)$ are known and the electric field strength is obtained. Here, B_Q can be quantum-mechanically calculated. The sensitivity of this method for $n = 5$ is high enough to measure the weak electric field of a few tens V/cm [10]. An expected relative error is ~ 30% in this measurement.

To apply this method to the weak electric field generated in the fusion plasma edges, it is essential to construct the slow He atom beam including a lot of metastable atoms. In a previous paper, we proposed a pulsed supersonic He beam for direct measurement of electric field in the plasma edges [9]. On the basis of a collisional–radiative model, we made a numerical study of LIF associated with a forbidden transition due to the Stark effect when the beam is injected into a medium-size tokamak, JFT-2M. The required metastable atom density was estimated to be more than 10^8 cm^{-3}.

In this paper, first, we report the construction of two types of low-energetic He-beam sources including the metastable atoms i.e. an electron cyclotron resonance (ECR) plasma source with divergent magnetic field from which the dense He plasma will be continuously extracted and a pulsed free jet. Second, we make a detailed observation of the ECR plasma flow and then discuss qualitatively the formation mechanism of the metastable atom in the plasma flow. Finally, we show experimentally a possibility for introducing high density metastable atoms into the pulsed free jet of He(1^1S) by a discharge.

2. Experimental setup

2.1. ECR plasma source

Fig. 2 shows a top view and a side view of an experimental apparatus including a cylindrical vacuum chamber (20 cm ∅) with a compact NTT type ECR plasma source and a plasma measuring system, where z-axis is taken along a central axis of the chamber and x- and y-axes are also horizontal and vertical ones perpendicular to the z-axis, respectively, passing through windows for spectroscopic observation. A helium plasma was produced in a plasma chamber, whose diameter was 4 cm and outlet was 5 cm apart from an origin of z-axis ($z = -5$ cm), under the optimum conditions for the metastable atom creation i.e. the microwave power is 260 W and the He gas pressure 2.5×10^{-2} Torr. The plasma was extracted with the divergent magnetic field in the z-direction. Axial (z-direction) and radial (y-direction) profiles of plasma parameters, plasma potential ϕ, electron density n_e and temperature T_e, were obtained by Langmuir probes 1 and 2, respectively.

Metastable atom density and its spatial profiles were measured by the LIF method [12]. The excitation of the metastable helium atoms (2^1S) to the 3^1P level was made

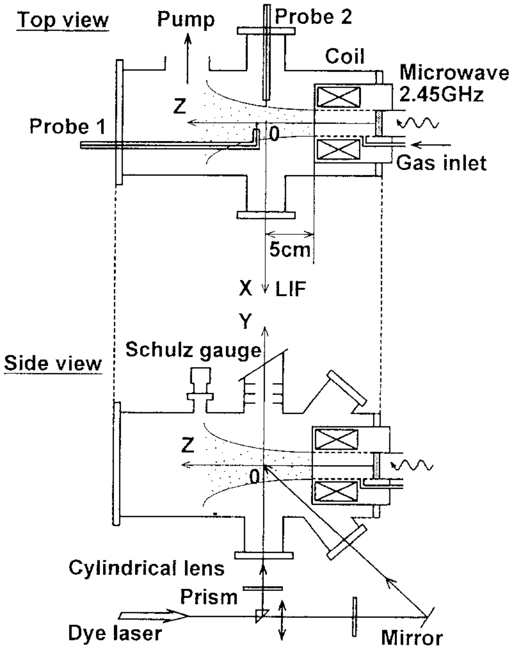

Fig. 2. Experimental apparatus for production of the ECR plasma flow and observation geometry for LIF.

by a YAG-laser-excited dye laser at the wavelength of 501.6 nm with a pulse width of 3 ns and a spectral width of ~ 1 pm. The peak power was strong enough to satisfy the saturation condition between 2^1S and 3^1P levels. The laser light, polarized linearly parallel to the z-axis, was injected into the plasma along the y-axis. The cross section was 10 mm (x-direction) × 0.4 mm(z-direction) at $y = 0$.

The time evolutions of the $z(\pi)$- and $y(\sigma)$-components in the resonance fluorescence of 501.6 nm (3^1P–2^1S) were observed separately by a sheet polarizer along the x-axis. The sensitivity of the whole detection system was calibrated for light with polarization parallel and perpendicular to the z-axis by using a standard tungsten ribbon-filament lamp, respectively.

Spatial distribution of fluorescence was measured by moving a stage, on which optical elements for injecting laser beam and for detecting LIF are set, from -2.5 to $+2.5$ cm along the z-axis (axial) or y-axis (radial).

To measure the Doppler shift the laser light was incident at an angle of 45° to the z-axis in the yz-plane. To avoid the laser stray light we observed the 667.8 nm fluorescence (3^1D–2^1P) induced by the forbidden excitation (504.2 nm) of the metastable atoms to the 3^1D state due to the electric quadrupole transition [10]. The incident laser power was weak enough to ensure the proportionality of the excitation with respect to the power. The excitation spectrum (Doppler profile) was obtained by scanning the laser wavelength with a step of 0.5 pm. The wavelength was calibrated by the optogalvanic signal from a commercial hollow cathode He lamp.

2.2. Pulsed free jet source

Fig. 3 shows a schematic diagram of the apparatus for free jet experiments. A beam production chamber with a diameter of 13 cm has an electromagnetic pulsed nozzle with a diameter of 0.8 mm (GV9-659-900) and a couple of discharge electrodes (Al) i.e. a ring anode and a cylindrical cathode with inner diameters of 2 cm and a separation of 4 mm, to collimate the gas jet from the nozzle and to introduce metastable He atoms in the beam by a discharge. A pulsed discharge using a capacitor of 1 μF with charging voltage of 2.2 kV was operated on the atom beam. A beam observation chamber has a fast ionization gauge (FIG) to measure temporal evolution of injected gas density and has a window and three pairs of windows located in order to look at positions of 5 cm (position 1), 14 cm (position 2), 18.5 cm (position 3) and 23 cm (position 4) apart from the nozzle on the z-axis for spectroscopic measurements.

Emission lines from the discharged beam were measured by a detection system with a lens, a monochromator, a photomultiplier with a load registor of 100 kΩ and a digital storage oscilloscope. Transient optical absorption of HeI 501.6 nm line from the hollow cathode lamp due to the metastable atoms in the beam was also observed with the detection system.

3. Results and discussion

3.1. Metastable atom (2^1S) density distribution in the ECR plasma flow

Axial profiles of the plasma potential, electron density and electron temperature obtained from the probe measurements are presented in Fig. 4. The parameters n_e and ϕ decreased gradually toward a down stream of the plasma flow, while T_e was almost constant. The radial profiles

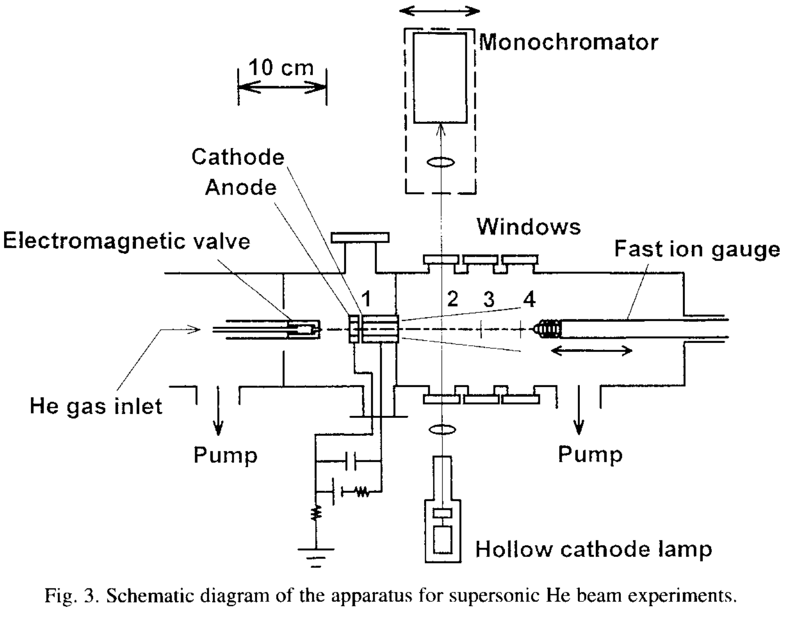

Fig. 3. Schematic diagram of the apparatus for supersonic He beam experiments.

were also measured by scanning the probe between −2.5 and +2.5 cm perpendicularly to the central axis at the distance of 5 cm from the outlet of the plasma source. In this case every parameters seem to be almost flat and symmetric, unlike the axial one. Gradual decrease of n_e at the both sides suggests that the diameter of the plasma is almost 8 cm. It is noted that the obtained ion density from the saturated ion current assuming the ion velocity is several eV is in the same order of magnitude as n_e at each position.

Axial distribution of metastable atom was obtained by the LIF method, whose density was estimated from the intensity of the resonance fluorescence according to a procedure written in Ref. [12]. The density was extremely high ($\sim 1 \times 10^{11}$ cm^{-3}) and was almost constant at least in the observed region, although n_e decreased to the down stream. On the other hand the radial profile was almost the same as those of the other parameters.

Two possible mechanisms are considered for the production of the metastable atoms. One is a recombination of the He$^+$ ions with electrons, in which the ions are produced in the ECR plasma source and then extracted from the source by the divergent magnetic field. These ions are accelerated and have an energy of several eV. If these ions convert to metastable atoms due to the recombination with electrons, the metastable atoms will move with a velocity of several eV. Another mechanism is an excitation of the He ground state atoms, which flows out from the plasma chamber without being ionized, to the 2^1S due to electron impact ($T_e \sim 3$ eV). In this case the metastable atoms will move toward the down stream with a thermal speed.

To measure the velocity of the metastable atoms we observed an excitation spectrum of the 667.8 nm fluorescence due to the forbidden excitation, as shown in Fig. 5.

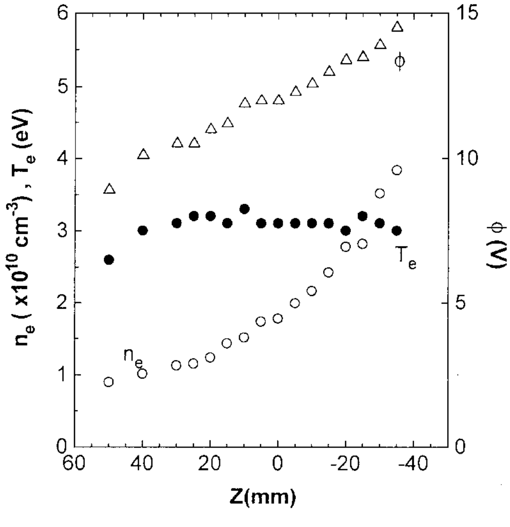

Fig. 4. Axial profiles of the plasma potential ϕ, electron density n_e, electron temperature T_e.

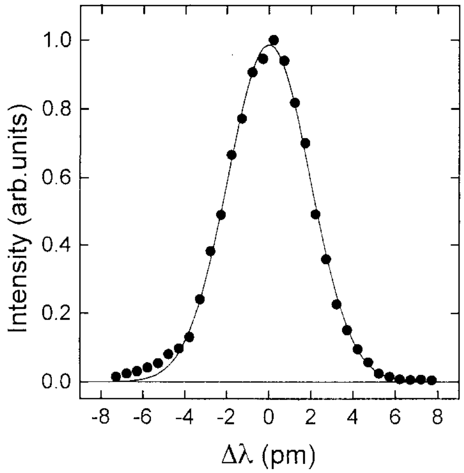

Fig. 5. Excitation spectrum of the 667.8 nm fluorescence due to the forbidden excitation (2^1S–3^1D) obtained by scanning the laser wavelength. The laser light was incident at an angle of 45° to the z-axis in the yz-plane.

The horizontal axis of wavelength difference $\Delta\lambda$ was calibrated by using the optogalvanic signal of the hollow cathode He lamp as a wavelength standard. Any remarkable shift was not observed within the experimental ambiguity of ~ 1 pm in wavelength. This ambiguity corresponds to the thermal velocity in this configuration. This rules out obviously the possibility for the metastable atom creation due to the recombination of fast ions with electrons.

The extraordinary effective production of the metastable atoms can be qualitatively explained on the basis of the collisional-radiative model. The 2^1S atoms are created through various channels by the electron impact excitation of the ground state atoms. Most of the metastable atoms would be subsequently excited to the 2^1P states by the electron impact whose rate is much higher than the creation rate from the ground state atoms at $T_e = 3$ eV. Then, these atoms would decay radiatively to the ground states through the resonance transition (2^1P–1^1S). In the present case, however, this plasma was optically thick for the resonance transitions (3^1P–1^1S) from the fact that the lifetime of the 3^1P state was very close to the inverse of the radiative transition probability for 3^1P–2^1S. Then the 2^1P atoms return back radiatively to the metastable states, not to the ground states.

3.2. Observation of the free jet

3.2.1. Temporal evolution of HeI emission line from the discharged free jet

The pressure of the He atom beam was measured by using the FIG to show that the particle beam intensity was about 10^{20} He-atoms cm^{-2} s^{-1} at a distance of 7 cm from the nozzle when the He gas was filled into the reservoir to a pressure of 2.5 bar. This indicates that the He-atom beam density can be as high as 10^{12} cm^{-3} at a further distance of 100 cm where the beam is assumed to reach the plasma edge region.

The beam was electrically broken down to produce the metastable atoms in the beam at a pair of electrodes between which the high voltage of 2.2 kV was applied. Fig. 6 shows the emitted HeI 501.6 nm line from the discharged He beam observed through four side windows. Only a fast intense emission, whose onset corresponds to the beginning of the discharge, was observed at the position 1. At the down stream another component was observed, whose front is delayed remarkably with increasing distance from the nozzle. From the time of flight the velocity was estimated to be $\sim 1 \times 10^5$ cm/s whose value was in good agreement with that of gas pressure measured by the FIG.

3.2.2. Optical absorption due to the metastable atoms in the discharged free jet

We also observed absorption of the HeI 501.6 nm line, which passed vertically through the beam, from a hollow cathode He lamp whose gas temperature was much higher than 300 K. Fig. 7 shows temporal change in the transmitted light intensity, $\Delta I/I_0$, obtained at a distance of 14 cm from the nozzle. A sharp peak at 0.3 ms is a false signal, that is, the emitted line originated from the discharge and/or the discharged beam. A dip with a depth of 0.014 at 0.8 ms means obviously the absorption of the 501.6 nm line due to the metastable atoms in the beam. The time behavior of the absorption, however, seems to be considerably distorted in the region from 0.9 ms to 1.3 ms because of superimpose of the emission from the beam as shown in Fig. 6. It should be noted that the absorption was observed at the earlier stage than the emission from the beam. This cause is not clear at present. The produced metastable atom density can be derived from the transmittance of resonance fluorescence [12,13]. Assuming that the metastable atoms are distributed uniformly in the beam with a diameter of 2 cm which corresponds to the inner diameter of the cylindrical cathode and the gas temperature is 300 K, the density is estimated to be higher than $\sim 1 \times 10^{10}$ cm^{-3} in order of magnitude from $\Delta I/I_0 = 0.014$ measured at 0.8 ms. To produce a high quality supersonic He beam, an experiment with suitable skimmer inserted in front of the nozzle is in progress. Then the He beam would have quite feasibility to directly measure electric field distribution in plasma edge region.

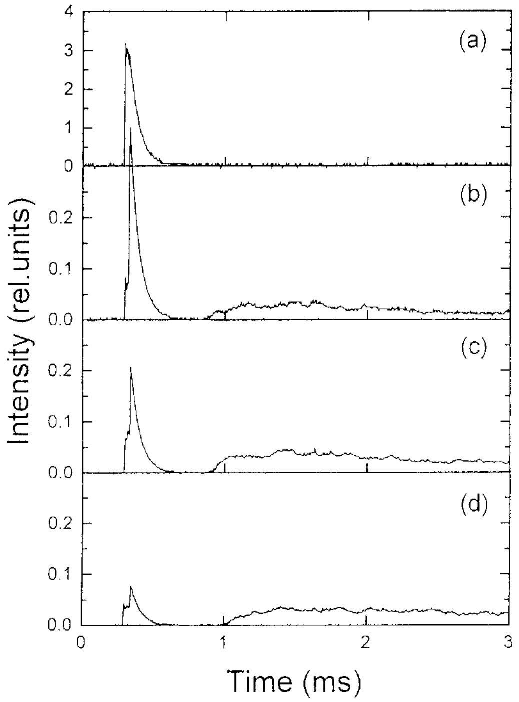

Fig. 6. Time evolution of HeI 501.6 nm line at (a) position 1, (b) position 2, (c) position 3 and (d) position 4.

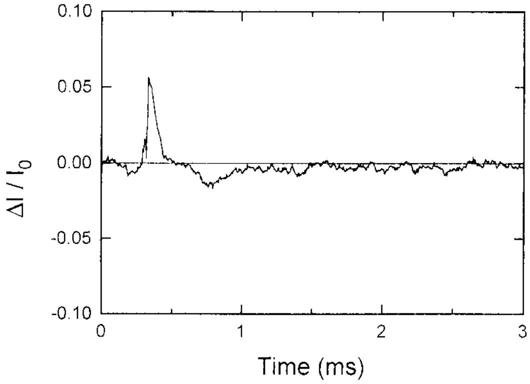

Fig. 7. Temporal change in the transmitted light intensity, $\Delta I/I_0$ at the position 2.

4. Summary

We have measured the density of metastable atoms included in two types of the He plasma flows i.e. a continuous ECR plasma flow and a discharged pulse free jet. The obtained densities were large enough to apply the LIF method for the electric field measurement in plasmas e.g. JFT-2M. In the ECR plasma flow the metastable atoms are created not due to the recombination of He ions with electrons but due to the electron impact excitation of the He ground atoms flowing with a thermal speed. The efficient production is possibly achieved in the plasmas which is optically thick for the resonance transition (e.g. 2^1P-1^1S). To make clear the formation mechanism in the free jet more detailed experiments are required.

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