

Measurement of Azimuthal Flow Velocity Using Laser-Induced Fluorescence Spectroscopy in a HYPER-I Plasma

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A laser-induced fluorescence (LIF) spectroscopy has been applied to an electron cyclotron resonance plasma. The absolute azimuthal flow velocity has been determined by the Doppler-shifted LIF spectrum and compared with that measured with a directional Langmuir probe (DLP) and the $E \times B$ drift velocity, respectively. The velocity profiles obtained with the three different methods show good agreement. The validity of LIF spectroscopy as a tool of local and absolute flow velocity measurement has been confirmed.

Keywords:

laser-induced fluorescence, Doppler shift spectroscopy, tunable dye laser, $E \times B$ drift rotation, absolute velocity measurement, directional Langmuir probe

Recently, a variety of vortical flow structures have been observed in an electron cyclotron resonance plasma [1,2], and are attracting much attention with respect to self-organization and transport. To study vortices in a plasma, which are identified by a vorticity distribution, we have to have velocity field data to construct the vorticity distribution on a plane under consideration. Usually, a directional Langmuir probe (DLP) [3], because it is easy-to-use, is used to acquire the velocity field data. However, there is an ambiguity in determining the absolute value, which is still a subject under dispute. The common understanding on flow velocity measurements is that the probe method is reliable in the sense of relative measurement. We proposed a calibration method of DLP in which the probe data are compared with the $E \times B$ drift determined by the potential measurements [3]. However, the applicability of this method is limited in cases in which the flow mechanism is not dominated by $E \times B$ drift. An example is the tripolar vortex observed in the high-density plasma experiment (HYPER-I) device, where each component vortex is driven by the effective force due to neutral density gradient [2], and, thus, the *in situ* calibration of DLP is impossible. Accordingly, a direct method of absolute velocity measurement, which also has spatial resolution, is needed. Doppler-shifted fluorescence induced by a tunable laser (LIF) has the advantages of both spatial resolution and absolute measurement [4]. In this paper, the LIF Doppler spectroscopy developed for the absolute velocity measurement in the HYPER-I device is described. The azimuthal flow velocity determined by the LIF spectroscopy is compared with that measured with a DLP and with the $E \times B$ drift velocity, and the validity of LIF spectroscopy as a tool of local and absolute velocity measurement is shown.

LIF technique is widely used for detecting abundance of minor species in plasmas and their spatial profile. Using a narrowband tunable laser, we can excite the portion of ions that satisfy the Doppler-shifted resonance condition, and by scanning the laser wavelength, we can obtain the information of velocity distribution function of ions in the local volume at the intersection of the laser beam and the viewing chord. In the present experiment, the laser wavelength is tuned to 611.5 nm, which excites an ArII metastable state ($3d^2G_{9/2} - 4p^2F_{7/2}$). We observe de-excited spontaneous emission of wavelength, 461.0 nm ($4s^2D_{5/2} - 4p^2F_{7/2}$). The experiments were performed in the HYPER-I device at the National Institute for Fusion Science [5]. A schematic drawing of the experimental setup is shown in Fig. 1. A tunable dye laser excited by a Nd:YAG laser produces 30 laser pulses per second, which are transferred with mirror optics and injected

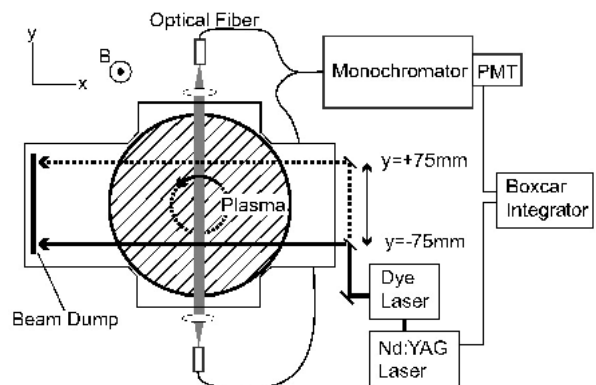


Fig. 1 Schematic drawing of experimental setup.

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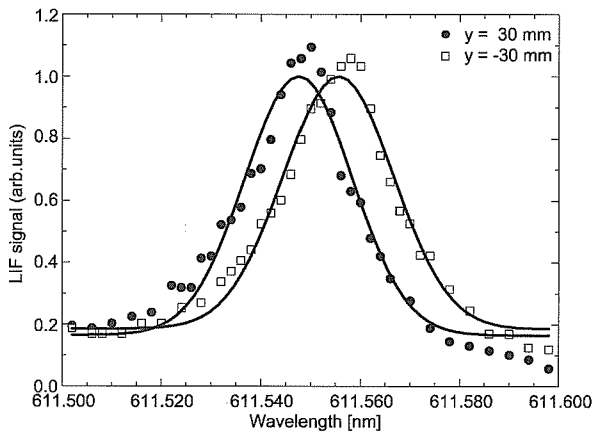


Fig. 2 Output of boxcar integrator as a function of dye laser wavelength. The solid lines indicate Gaussian fitting curves for each case.

into the plasma from a side viewing port. The chord of the laser beam is changed by the position of the side mirror, and its movable range is vertically ± 75 mm. Because the laser energy is sufficiently high (60 mJ/pulse), the scattered light may cause undesired fluorescence and decrease the spatial resolution. To suppress the scattered light of the primary laser beam, baffle plates are located along the beam path, and a knife-edged beam dump is installed on the side opposite the laser injection port.

The laser-induced fluorescence from argon ion is observed from counter-directed fiber optics with collimator lenses, and is detected using a monochromator equipped with a photomultiplier tube. The output signal of the photomultiplier tube is integrated with a boxcar integrator synchronized with the laser pulse. By changing the vertical position of the laser beam, we measured the rotation (azimuthal) velocity of an argon plasma. The output of the boxcar integrator is shown in Fig. 2 as a function of dye laser wavelength. We note that the horizontal scale in Fig. 2, which is the value indicated in the dye laser controller, is shifted about 0.06 nm from the wavelength in the air. Although the line profiles include Zeeman effect due to the external magnetic field (~ 0.09 T), the effect is too small to be distinguished in the present experiment. The solid lines are the Gaussian fitting curves for each case ($y = \pm 30$ mm). The peak positions of the two profiles relatively shift by 0.008 nm, which corresponds to a velocity difference of 4 km/s. The LIF spectrum, which blue-shifts for the $y = 30$ mm case and red-shifts for the $y = -30$ mm case, means that the ions rotate counterclockwise (see Fig. 1).

The LIF Doppler spectrum was measured at five radial points, and the velocities were determined by the shift of the central wavelength of the line profile from that obtained at

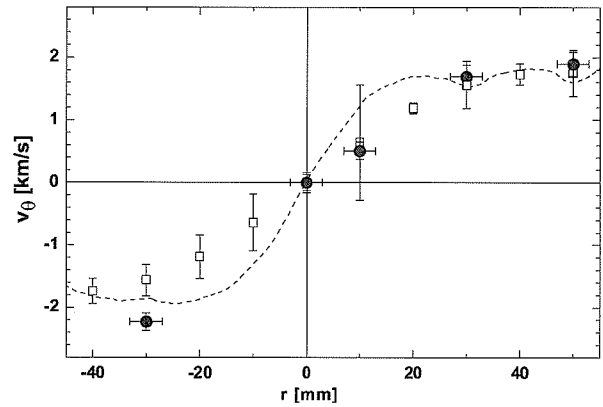


Fig. 3 Azimuthal velocity profile determined by three different methods. The filled circle indicates the velocity determined by LIF spectroscopy, the open square by $\mathbf{E} \times \mathbf{B}$ drift, and the dashed line by DLP.

$r = 0$. The obtained velocities are plotted in Fig. 3. The $\mathbf{E} \times \mathbf{B}$ drift velocities determined by the potential measurement are also shown in the figure. There is quite good agreement between the two. It is worth noting that these methods are completely independent, and therefore the consistency of the two results, as seen in Fig. 3, is very satisfactory. In addition, the ambiguity of the DLP method in determining absolute velocity is removed by using LIF spectroscopy as a calibration standard. The dashed line in Fig. 3 is the DLP result with a calibration constant 1.1 ($1/2\alpha$ in Ref. [3] eq. (2.6)). The profile measured with DLP also agrees with that measured by LIF spectroscopy.

These results show that LIF spectroscopy is a promising tool for local and absolute measurement of flow velocity. They may also suggest that a combined system of DLP and LIF spectroscopy as a calibration standard resolves the ambiguity of absolute value in the DLP method and improves reliability, particularly in the supersonic region.

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