Neutral Flow Measurement Using a Tunable Diode Laser

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A vortex with anti-$\mathbf{E}\times\mathbf{B}$ flow has been observed in an argon cylindrical plasma. It is considered that the anti-$\mathbf{E}\times\mathbf{B}$ flow is generated by interaction between the background neutral flow and the ion fluid. To confirm the new mechanism of vortex formation, we have developed the high resolution laser induced fluorescence (LIF) spectroscopy system for measuring the neutral flow. The wavelength resolution of this LIF system is 14 fm, which corresponds to a velocity of 6 m/sec. The high wavelength resolution is attained by using a tunable external cavity diode laser (ECDL), whose spectral width is typically 5 fm. Preliminary results on neutral flow velocity measurements using newly developed LIF system are presented.

Keywords: anti-$\mathbf{E}\times\mathbf{B}$, neutral flow, Laser Induced Fluorescence, diode laser

1. Introduction

In understanding dynamical behavior of plasma, the effect of neutrals on the motion of ion fluid is usually neglected (collisionless). Even when it is considered, the contribution of neutrals is included as a small dissipation term, which slightly modifies the motion of ion fluid. In these circumstances, large-scale flow structure in a plasma is primarily determined by $\mathbf{E}\times\mathbf{B}$ drift [1, 2]. In a case of cylindrical geometry with axial magnetic field, azimuthal rotation takes place due to the radial electric field, forming a vortical flow structure.

Recently, it is experimentally found that there exists a class of vortices [3], which rotate to the opposite direction of $\mathbf{E}\times\mathbf{B}$ drift (referred to as anti-$\mathbf{E}\times\mathbf{B}$ vortex). One typical example is tripolar vortex, and is shown in Fig. 1. This result suggests that there is a force acting on ion fluid and it does exceed the electric field. The problem is then the generation mechanism of this force.

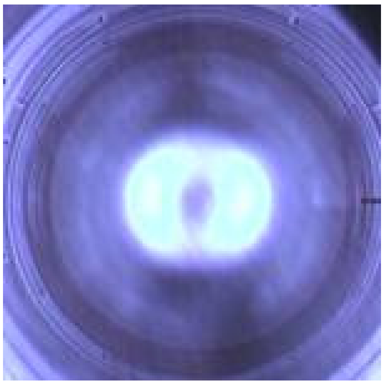

Fig. 1 CCD image of tripolar vortex. Three vortices, center and two satellites, respectively rotate to the anti-$\mathbf{E}\times\mathbf{B}$ direction.

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The anti-$\mathbf{E}\times\mathbf{B}$ vortices are considered to be driven by the strong interaction between neutrals and ions [3, 4]. As shown in later section, anti-$\mathbf{E}\times\mathbf{B}$ vortices always accompany deep density depletion in the background neutrals (see Fig. 2) [5]. In the case of monopolar vortex, steep gradient of the neutral density causes a flow of the neutrals, which directs to the center of vortex. When the momentum of neutral flow (inward) is transported to the ions through charge exchange collisions, an inward force arises, and the anti-$\mathbf{E}\times\mathbf{B}$ drift occurs when this force exceeds the electric field (outward). To understand the effect of neutrals on the behavior of ion dynamics, visualization of neutral flow field is of primary importance. However, method for measuring neutral flow velocity with high accuracy has not been established yet. The reason is that flow velocity of neutrals is expected to be two-order slower than ion flow velocity, and consequently high resolution laser induced fluorescence (LIF) Doppler spectroscopy system is needed.

We have been developing a high precision LIF system using a tunable external cavity diode laser. A narrow bandwidth laser is essential for high resolution measurement of the neutral velocity distribution function and Doppler shift [6, 7]. The system is capable of determining Doppler shift of about 9 MHz (14 fm), which corresponds to a velocity of about 6 m/sec. In this paper, a newly developed LIF system is described as well as the preliminary results on neutral flow velocity measurement.

2. Measurement of Neutral Flow

The experiments have been performed in the high density plasma experiment (HYPER-I) device at National Institute for Fusion Science, (Fig. 3). The vacuum vessel is 0.3 m in diameter and 2 m in axial length. Plasmas are generated and sustained by electron cyclotron resonance

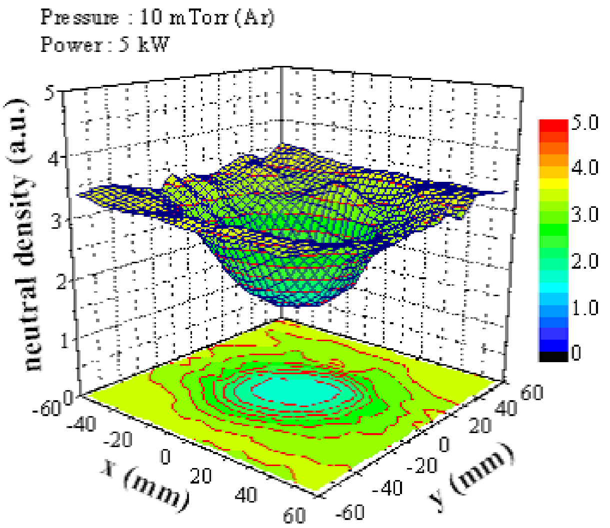

Fig. 2 Density profile of background neutrals in the region of a monopolar vortex. This is obtained from emissions with 480.6 nm ($\propto n_p^2$), and 420.1 nm ($\propto n_p n_n$).

(ECR) heating of argon with the pressure of 10 mTorr. The frequency of microwave is 2.45 GHz, and the input power (Pw) is changed from 40 W (low power operation) to 5 kW (high power operation). The LIF system (laser and collection optics) has been first developed with the plasma in low power operations, in which the LIF signal is easy to observe. The anti-$\mathbf{E} \times \mathbf{B}$ vortex appears in the high power operations.

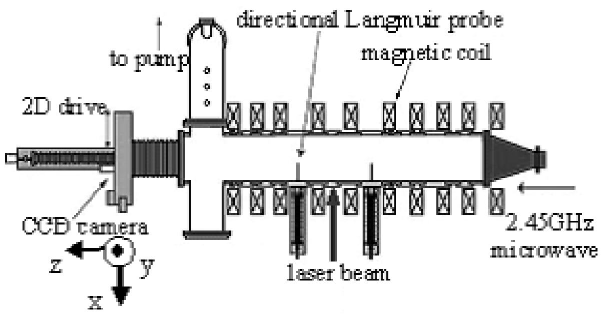

Fig. 3 HYPER-I (High Density Plasma Experiment) device. A laser beam is introduced along x axis.

The schematic diagram of LIF spectroscopy system is shown in Fig. 4. A tunable diode laser (external cavity diode laser), whose bandwidth is 5 fm (3 MHz) and output power is 15 mW, is tuned at a wavelength 696.7352 nm (430281.8 GHz) and is introduced into the plasma. Metastable argon atoms are excited to an upper energy level ($3s^2 3p^5 (^2P^o_{3/2}) 4s \rightarrow 3s^2 3p^5 (^2P^o_{1/2}) 4p$), and then de-excited by $3s^2 3p^5 (^2P^o_{1/2}) 4p \rightarrow 3s^2 3p^5 (^2P^o_{1/2}) 4s$ transition, emitting fluorescence photons of 826.6794 nm (362646.6 GHz). A photomultiplier tube (PMT) with collection optics is installed on the top viewing port of the vacuum vessel, and receives the fluorescence light collected by a lens. The laser beam is modulated by an optical modulator, and the PMT signal is detected by a lock-in amplifier to improve the signal to noise (S/N) ratio. The focal length of the collecting lens is 250 mm, and the effective diameter of the lens is 45 mm. The solid angle of collection optics is 0.012 sr (the latest version of the collection optics is 0.065 sr).

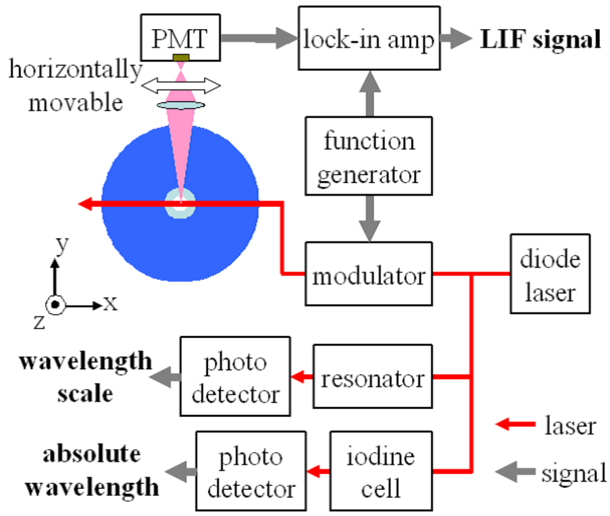

Fig. 4 Schematic diagram of LIF spectroscopy system.

The laser beam is split into two parts, and the sub beam is fed into two optional units; one consists of Fabry Perot resonator, which functions as a wavelength scale, and the other is an iodine gas cell, which gives absolute wavelength reference (Fig. 5). The free spectral range of the resonator is 476 fm, and the absorption lines of iodine located at 696.7428 nm and 696.7337 nm (430277.1 GHz, 430282.7 GHz, respectively) are used as the wavelength references [8].

Sweeping the laser wavelength (16 pm), we have obtained the LIF spectrum, which is proportional to the neutral distribution function. Moving the collection optics along the horizontal axis, the distribution functions at radially different positions can be obtained. The flow velocity of neutrals is determined by the Doppler shift of distribution functions.

3. Experimental Results

To confirm the existence of metastable atoms, we carried out absorption spectroscopy experiment. The maximum absorption was 34 % in the low power operation (P_w = 40 W), while 8 % in the high power operation (P_w = 5 kW). This result means that the number of metastable atoms decreases in the high power operation due to collisional deexcitation process.

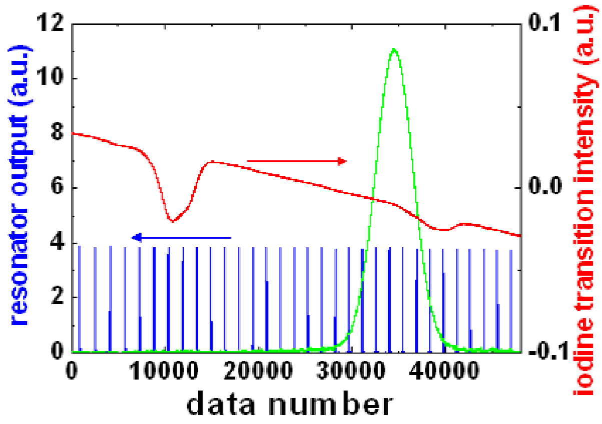

Fig. 5 Wavelength calibration sub-system is composed of resonator and iodine gas cell. A left vally of the iodine transition spectrum is used for calibration. Wavelength of the absorption line is 696.7428 nm.

After confirming the presence of metastable atoms, we measured the LIF spectrum at P_w = 40 W, which is shown in Fig. 6. The observed spectrum is quite well fit by a Gaussian distribution, and the temperature of metastables is 0.034 eV. Measuring the LIF spectra and determining the Doppler shift at different points along the horizontal axis, we have obtained the radial flow velocity profile. An inward flow with the maximum velocity 12 m/sec has been observed.

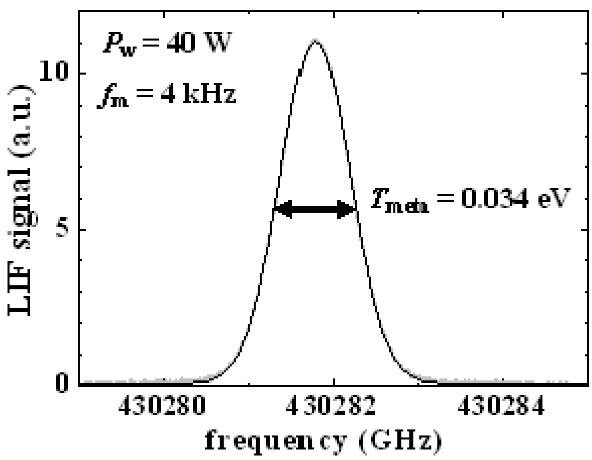

Fig. 6 LIF spectrum for a low power case (P_w = 40 W, f_m = 4 kHz). The neutral velocity distribution function is in well agreement with a Gaussian distribution.

In the high power operations, the level of background light at 825 nm ($\Delta\lambda$ = 10 nm) increases by 20 times higher than the low power case (see Fig. 7), which causes further reduction in S/N ratio in addition to the decrease in metastable atoms. The LIF spectrum obtained with the same LIF system as in the low power case gives unphysical result. This means that S/N ratio is not sufficient for this case. The reasons for the result are already mentioned above, i.e., depletion of metastable atoms and increase of background light.

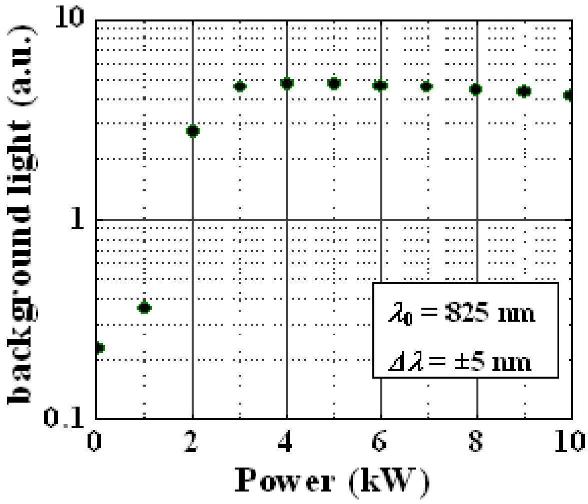

Fig. 7 Background light with wavelength 825 ± 5 nm, emitted from plasma, as a function of input microwave power.

In order to overcome the reduction of S/N ratio, we have improved the collection optics so as to receive more LIF signal. The solid angle is increased to 0.065 sr, and the modulation frequency f_m is raised up to 100 kHz. As shown in Fig. 8, the output signal which originates from the background light decreases with increasing the modulation frequency, and becomes minimum in the frequency range between f_m = 70 kHz and 600 kHz.

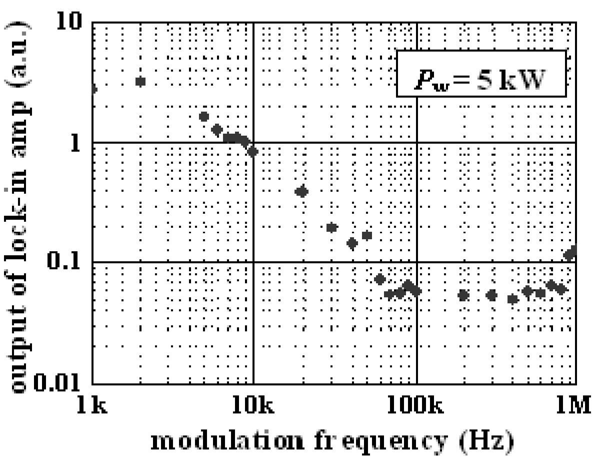

Fig. 8 Plasma background light detected by a lock-in amplifier. Detected background light is reduced logarighmically till f_m = 70 kHz.

When the modulation frequency of lock-in amplifier is set at 100 kHz, several ten times of increase in S/N ratio is expected compared with that of 4 kHz modulation. We have modified the LIF spectroscopy system by introducing an electro-optical modulator, and carried out high frequency lock-in detection. The result is shown in Fig. 9. As seen in the figure, the expected LIF spectrum is clearly recovered. The temperature of metastables in this case is 0.11 eV.

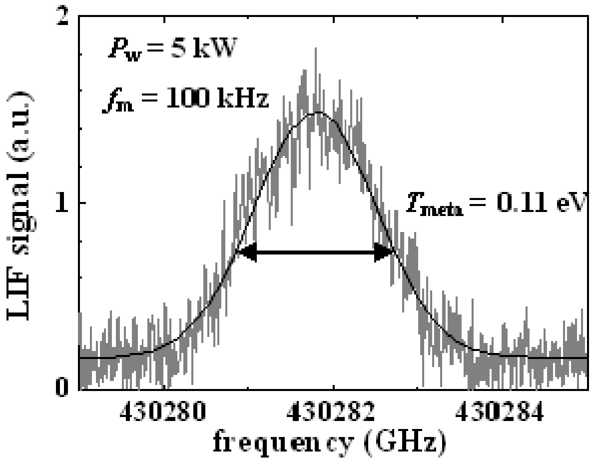

Fig. 9 LIF spectrum for a high power case. (P_w = 5 kW, f_m = 100 kHz). By increasing modulation frequency f_m, LIF spectrum comes to be observable. A smooth solid line is a Gaussian fits to the experimental data.

Measuring the distribution functions of neutrals at different points on the horizontal axis, we have found that there exists an inward flow with the maximum velocity 70 m/sec. The distribution functions except for that of vortex core are slightly asymmetric. This result suggests that the distribution function of the neutrals consists of slow bulk and fast component, which respectively comes from the wall and is produced through charge exchange process with fast ions. In the present experiments, the spatial resolution (radial) of collection optics is 5 mm in order to collect a lot of LIF photons. Further improvement in spatial resolution is needed for detailed experiments on this problem, which is left for future work.

4. Conclusion

A high resolution LIF spectroscopy system for neutral flow velocity measurements is described. The preliminary experiments show that this system is capable of measuring slow velocity field of 10 m/sec. To extend this performance into velocities of the order of m/sec, there remain a few problems to be solved. Wavelength stabilization (long term and short term) is the most important. The present limit of wavelength resolution is close to the stability limit of the laser system (ECDL). By introducing an additional external feedback circuit, the stability problem will be overcome.

The improvement of S/N ratio is still left for future work. It will be raised to a certain extent by increasing the laser power because the LIF signal does not saturate at the present power level (15 mW).

In addition to radial flow velocity, azimuthal flow velocity measurement is of interest from the viewpoint of ion-neutral interaction. The distribution function consists of neutrals from the wall and those from the ions through charge exchange collisions, the latter of which constitute fast rotating component. Therefore, measuring the azimuthal distribution will give us important information of the degree of ion-neutral interaction.

Our system can be applied to ion flow velocity measurements with an appropriate ECDL, which is tuned to a certain energy level of ion. Comparison of the ion flow velocity profiles obtained by LIF spectroscopy and that with a directional Langmuir probe [9] provides a systematic and *in-situ* calibration of probes (directional probe or Mach probe), which is still under discussion in case of supersonic regime.

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