Measurement of neutral flow velocity in an ECR plasma using tunable diode laser LIF spectroscopy combined with saturated absorption spectroscopy

M. Aramaki¹, K. Ogiwara², S. Etoh³, S. Yoshimura⁴, and M. Y. Tanaka²

¹Nagoya University, Furo-cho, Chikusa, Nagoya 464-8603, Japan
²Kyushu University, Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
³Central Research Institute of Electric Power Industry, Nagasaka, Yokosuka, Kanagawa 240-0196, Japan
⁴National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan

E-mail: aramaki@nuee.nagoya-u.ac.jp

Abstract. The radial flow of neutral particles in an electron-cyclotron-resonance (ECR) argon plasma has been measured by using a newly developed high resolution laser induced fluorescence (LIF) measurement system. The flow velocity is determined by the Doppler shift of the LIF spectrum. A very high accuracy calibration of an excitation laser has been achieved by installing a saturated absorption spectroscopy unit into the LIF system. We utilized the Lamb dip, which is obtained by the saturated absorption spectroscopy, as a frequency standard for the determination of the flow velocity. The use of Lamb dip is particularly appropriate for the flow velocity measurement, since the position of Lamb dip in the frequency scale is Doppler-shift free and is not disturbed by the motion of reference medium. By utilizing the Lamb dip as the frequency standard, the reliability and stability of the laser frequency calibration is increased. From the radial measurements of LIF spectra of metastable argon atoms at the microwave power of 250 W and 5 kW, it is found that there exists an inward flow of neutral particles in the both plasmas. Both of the radial flow velocity profiles peak around 4 cm from the center, which is comparable with the radius of the boundary of the \( E \times B \) rotation and anti-\( E \times B \) rotation in the 5 kW discharge. The maximum flow velocity increases with the microwave power.

1. Introduction

The kinetic interaction between plasma and neutral particles has been attracting in the recent years an increasing attention. In particular to understand the static structure of neutral particle distribution in highly-ionized low-pressure plasma, the electron static pressure has to be taken into account [1]. A class of vortices, in which ions rotate in the opposite direction to the \( E \times B \) drift, has been observed in our laboratory [2]. This result suggests the existence of a strong force which dominates the electric field. The force acting on ions due to charge exchange collision between the ions and neutrals is considered to play an essential role in generating anti-\( E \times B \) rotation. The momentum transfer between ions and neutral particles may change the dynamic behavior of ions. In addition to the static pressure, the dynamic pressure which is caused by the neutral particle flow should be taken into account to clarify the formation mechanism of the anti- \( E \times B \) vortices.
To study the role of ion-neutral interaction, it is needed to measure the flow velocity field of the neutral particles. LIF Doppler spectroscopy is the most promising method for the direct measurement of the local neutral flow velocity; however, the lowest neutral-flow velocity that is detectable by the LIF system is limited by the accuracy of frequency calibration and the stability of the excitation laser. Up to date, the flow velocity measurement of the neutral particles has been carried out by Engeln et al. for a fast flowing case [3]. However, the LIF Doppler velocimetry for slow neutral particles has not been done so far. The expected neutral flow velocity in our experiment is of the order of 10 m/s or less, and the corresponding Doppler shift is of the order of 10 MHz in visible light range. The newly-developed LIF system utilizes saturated absorption spectroscopy, in which the laser frequency is calibrated by the frequency of a Lamb dip. A set of counter propagating laser beams, which are tuned at same frequency, is used in saturated absorption spectroscopy. The one beam is called a pump beam, and the other beam is called a probe beam. The pump beam is used to pump out the lower state atoms of the absorption transition, and the probe beam is used for absorption spectroscopy. A Doppler absorption spectrum is observed by sweeping the laser frequency. When the pump beam excites the atoms which are travelling at velocity \( v_0 \) along the beam line, the probe beam is absorbed by the atoms which are travelling at \(-v_0\). At the resonance frequency, the both laser beams are absorbed by the same atoms with \( v_0 = 0 \). Since the lower state atoms are pumped out by the pump beam, the amount of absorption of the probe beam decreases at the resonance frequency. The decrease of absorption is called a Lamb dip. The line width of the Lamb dip is the order of natural broadening, and is significantly narrower than the Doppler spectrum. The utilization of the saturation spectroscopy for separating overlapped isotopic transitions has been reported [3]. In the present experiment, we utilized the Lamb dip as a frequency standard for the neutral flow measurements [4]. The use of Lamb dip is particularly appropriate for the flow velocity measurement, since the position of Lamb dip in the frequency scale is Doppler-shift free and is not disturbed by the motion of reference medium. By utilizing the Lamb dip as the frequency standard, the reliability and stability of the laser frequency calibration is increased. In addition, Lamb dip appears at the frequency corresponding to the zero velocity in the laboratory frame, which provides the origin of the velocity space. In this study, we adopt the Lamb dip of the \( 4s[3/2]_2^o(M_J=0) - 4p[1/2]_4(M_J=0) \) transition. The \( M_J = 0 \) to 0 transition is not perturbed by the variation of the magnetic field intensity in the target plasma. This advantage assures long-time stability of the frequency standard without any special requirement for the control of
In the experimental environment. Consequently, the accuracy for frequency calibration is much more improved.

In the following sections, the experimental setup and the new LIF system are explained (Sec. 2). The results of system performance and flow velocity measurement in an ECR plasma are presented in Sec. 3, followed by conclusions.

2. Experiments
The experiments have been carried out using the high density plasma experiment (HYPER-I) device at the National Institute for Fusion Science. The HYPER-I device is a linear plasma device equipped with ten magnetic coils (Figure 1). The sizes of cylindrical vacuum vessel are 30 cm in diameter and 200 cm in axial length. Argon plasma is generated by electron cyclotron resonance (ECR) heating with microwave at 2.45 GHz. The input microwave power and the operation pressure were fixed at 250 W or 5 kW and $0.8 \times 10^{-2}$ Torr, respectively. Optical measurements were performed at the position $z = 95$ cm from the microwave input window. The detailed descriptions of the HYPER-I device have been reported in detail elsewhere [6, 7].

Figure 2 shows the high resolution LIF Doppler spectroscopy system which has been developed for the measurement of neutral flow velocity. The metastable argon atoms populated in the $4s[3/2]_2$ state are excited to the $4p[1/2]_1$ state by an external cavity diode laser (ECDL, Toptica Photonics DL100) tuned at 696.73 nm. Here, we use the Racah (j-l coupling) notation. The output power of the ECDL is 16 mW. The coarse tuning of the frequency of the ECDL is performed using a wavemeter. A Fabry-Perot interferometer (FPI) is used to check the single mode operation of the ECDL, and its fringes are used as frequency markers when scanning the laser frequency. The free spectral range (FSR) of the FPI is 294 MHz. The laser power is modulated by using an electro-optical modulator (EOM, Linos LM 0202). The modulated laser beam is introduced into the plasma along the center chord of the...
Doppler width, the LIF spectrum is proportional to the velocity distribution function. The neutral flow velocity was determined by the Doppler shift of the LIF spectrum. The radial profile of neutral flow velocity is obtained by changing the position of the collection optics on the movable stage. The signal from the PMT is amplified using a current amplifier and then detected by a lock-in amplifier.

The saturated absorption spectroscopy of argon metastable state is carried out simultaneously with the Doppler LIF spectroscopy, where the incident beam of the LIF measurement is utilized as a pump laser. The transmitted beam is attenuated to 0.01% by a neutral density (ND) filter and reflected to re-enter into the plasma along the same path of the pump beam. This backward beam is used as a probe beam of the saturated absorption spectroscopy. The power of the probe beam is weak enough to avoid the saturation of the absorption and the disturbance to the LIF measurement. The absorption signal of the probe beam is detected by a photodiode behind the beam splitter (BS), and finally detected by a lock-in amplifier. The Lamb dip obtained by the saturated absorption spectroscopy is used as a frequency standard.

3. Results and Discussions
Optical emission of plasma is the strong noise source in the LIF measurement. Figure 4 shows the power spectra of optical emission of plasma generated at the microwave power of 250 W and 5 kW. Since the power spectrum of the 5 kW discharge emission has strong high frequency component, it was necessary to increase the operating frequency of the EOM to 100 kHz to obtain the sufficiently
good signal-noise ratio of the LIF signal. The maximum operating frequency of the EOM is limited by the Einstein’s A coefficient of the LIF scheme. Figure 5 shows the set of spectra utilized for high-accuracy neutral-flow detection. The spectra were simultaneously recorded at the microwave power of 250 W. The frequency of the laser beam has been swept around the resonance frequency. Figure 5(a) shows the Doppler LIF spectrum of metastable argon atoms taken at the center of the chamber (x, y = 0 cm, z = 95 cm). The profile of the LIF spectrum is quite well fitted by a Gaussian distribution function. The full width at half maximum (FWHM) of the LIF spectrum is 950 MHz, and the corresponding temperature is 0.033 eV. Figure 5(b) is the saturated absorption spectrum composed of the Doppler-broadened absorption spectrum and the three Lamb dips. It is noted that the line width of the Lamb dip is significantly narrower (~30 MHz) than that of Doppler broadening (~1 GHz), which assures the improvement of accuracy in determining the standard frequency. The splitting of Lamb dips are attributed to the Zeeman splitting of magnetic sublevels of 4s[3/2]o2 and 4p[1/2]1 states. The center dip, which is M[J] = 0 to 0 transition, is used for the calibration of the absolute value of the laser frequency. Figure 5(c) shows the fringes of the FPI. The cavity length of FPI is fixed during the observation. The frequency interval of each fringe is 294 MHz, and is utilized as the frequency scale. By combining the position of Lamb dip and the fringes of interferometer, we have determined the center frequency of the LIF spectrum. The velocity of the neutral flow has been evaluated from the Doppler shift of the distribution function.

The radial flow velocity profile of the metastable argon atoms has been obtained by measuring the set of spectra at different radial positions. Figure 6 shows the radial flow velocity profile of neutrals along the horizontal axis at the microwave power of 250 W and 5 kW. The sign of Doppler shift is positive in positive x-region and negative in negative x-region. This result means that the...
neutral particles flow from right to left in the positive x-region and from left to right in the negative x-region, showing the existence of radial inward flow of neutrals in the plasma. To keep the continuity of particle flux, the neutral particles are ionized and pumped out along the axial magnetic field in the plasma column. The plasma rotates in the $E \times B$ direction at 250 W discharge power. On the other hand, in the 5 kW case, the core plasma rotate in the anti-$E \times B$ direction while the peripheral plasma rotate in the $E \times B$ direction. Both of the radial flow velocity profiles peaks around 4 cm from the center, which is comparable with the radius of the boundary of the $E \times B$ rotation and anti-$E \times B$ rotation. The maximum flow velocity increases with the microwave power. The relation between the increase of the flow velocity and the generation of the anti-$E \times B$ will be reported elsewhere.

4. Conclusion

We have developed a high-resolution LIF system with a narrow line-width tunable diode laser. Utilizing a saturated absorption spectrum to calibrate the laser frequency, we have achieved a high accuracy frequency determination. The radial flow velocity of the metastable argon atoms has been measured in an ECR plasma generated at microwave powers of 250 W and 5 kW. It is found that there exists a radial inward flow in the both plasma. Both of the radial flow velocity profiles peak around the boundary of the $E \times B$ rotation and anti-$E \times B$ rotation in the 5 kW discharge. The maximum flow velocity increases with the microwave power. The detailed results will be reported elsewhere.

Saturated absorption spectroscopy is one of the basic methods in precision laser spectrometry. We have introduced this technique into the LIF Doppler spectroscopy system for plasma physics research, and demonstrated that the minimum detectable velocity is significantly improved. LIF Doppler velocimetry with saturated absorption spectroscopy will become a powerful tool for studying dynamical behavior of plasma interacting with neutral flow, which has not been fully explored yet because of the lack of diagnostic tools.

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