High resolution laser induced fluorescence Doppler velocimetry utilizing saturated absorption spectroscopy

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A high resolution laser induced fluorescence (LIF) system has been developed to measure the flow velocity field of neutral particles in an electron-cyclotron-resonance argon plasma. The flow velocity has been determined by the Doppler shift of the LIF spectrum, which is proportional to the velocity distribution function. Very high accuracy in velocity determination has been achieved by installing a saturated absorption spectroscopy unit into the LIF system, where the absolute value and scale of laser wavelength are determined by using the Lamb dip and the fringes of a Fabry–Pérot interferometer. The minimum detectable flow velocity of a newly developed LIF system is ±2 m/s, and this performance remains unchanged in a long-time experiment. From the radial measurements of LIF spectra of argon metastable atoms, it is found that there exists an inward flow of neutral particles associated with neutral depletion. © 2009 American Institute of Physics.

I. INTRODUCTION

Effect of neutral particles on the dynamical behavior of a plasma has been attracting much attention in many research fields. In plasma application field, neutral depletion and associated transport change in an rf plasma have been discussed to control the plasma parameters and profile.¹,² In a laboratory plasma, a class of vortices, which rotates in the opposite direction to the $E \times B$ drift, has recently been observed. A force acting on ions due to charge exchange interaction between the ions and neutrals is considered to play an essential role in generating anti-$E \times B$ rotation.³,⁴ In boundary plasmas of magnetic confinement devices, it is proposed that the interaction between neutral wind and plasma drives blobs transport.⁵,⁶ Interaction of neutral particles with plasma also play an important role in nature such as dynamical coupling between lower ionosphere (E, F layer) and upper atmosphere.⁷ The problems of interest in those research fields are commonly focused on the momentum transport between ions and neutral particles, which may wholly change the dynamical behavior of ions.

To study the role of ion-neutral interaction in laboratory plasmas, it is needed to measure the flow velocity field of neutral particles. Laser induced fluorescence (LIF) Doppler spectroscopy⁸,⁹ is the most promising method to directly measure the local neutral flow velocity; however, there is a problem originated with slowness of neutral flow. The expected neutral flow velocity in our experiment is of the order of 10 m/s or less, and then the corresponding Doppler shift is of the order of 10 MHz in visible range, which requires the frequency resolution of the order of 0.1 ppm. In addition, the stability of system performance should be long enough, for example, for more than a few hours for the practical use in experiments. Flow velocity measurement of neutral particles has first been carried out by Engeln et al.¹⁰ for a fast flowing case. LIF Doppler velocimetry for slow neutral particles has not been done so far.

Spectral bandwidth of extended cavity diode laser (ECDL) is narrow enough for our requirements; however, there is a difficulty to realize a high resolution LIF spectroscopy system using an ECDL. The key issue is the absolute frequency determination of the ECDL. An absorption line of iodine is often used as the reference frequency, and then the velocity resolution of LIF system is limited by the accuracy of reference frequency, which is usually subjected to Doppler-broadening (typically ~1 GHz). It is much more suitable to use Doppler-free spectrum in the frequency calibration procedure, which has not been utilized in LIF Doppler spectroscopy yet.

We propose a high resolution LIF system installed with a saturated-absorption spectroscopy unit, in which so-called Lamb dip is utilized as the frequency standard.¹¹,¹² The advantage of this method is that Lamb dip exhibits a very sharp profile with a spectral width of the order of natural broadening, and is significantly narrow compared with the Doppler-broadened absorption spectrum. The second advantage is based on the fact that the position of Lamb dip is located at the frequency corresponding to the zero velocity in the laboratory frame, which provides the origin of velocity axis (when the atomic species of reference medium is the same as that of plasma under investigation) and is independent of experimental circumstances such as the temperature of reference medium. This advantage assures long-time stability of the frequency standard without any special requirement for
the control of experimental environment. Consequently, the accuracy of frequency calibration is much more improved.

We have developed a high resolution LIF Doppler spectroscopy system. The velocity resolution of the newly developed LIF system is \( \pm 2 \) m/s. Using the LIF system, we have measured a slow neutral flow velocity in an electron-cyclotron-resonance (ECR) argon plasma and also confirmed that the system performance is stable enough for more than 5 h. The flow velocity measurements using this system revealed that there exists a neutral depletion and the resultant radially inward flow in the plasma even in weak microwave input cases with a few hundred watts.

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

II. EXPERIMENT

The experiments have been carried out using the high density plasma experiment (HYPER-I) device at National Institute for Fusion Science. The HYPER-I device is a linear plasma device with external magnetic fields. The sizes of cylindrical vacuum vessel are 30 cm in diameter and 200 cm in axial length. An argon plasma is generated by ECR heating in a magnetic beach configuration. The frequency of microwave is 2.45 GHz. The detailed description of the HYPER-I device and its performance have been reported elsewhere.\(^{13,14}\) In the experiments presented below, the input microwave power and the operation pressure were fixed at 250 W and \( 0.8 \times 10^{-2} \) Torr, respectively. The duration of discharge was set to 40 s, during which the measurements were made in the interval between 10 and 30 s after the onset of discharge. When the spectral bandwidth of laser is much narrower than the width of Doppler broadening due to thermal motion, the LIF spectrum is proportional to the distribution function. The neutral flow velocity was determined by Doppler shift of the LIF spectrum (distribution function) obtained by tuning the laser frequency.

The argon metastable atoms populated in the \( 4s[3/2]_{2}^{p} \) state are excited to the \( 4p[1/2]_{1} \) state by an ECDL (Toptica Photonics DL100) tuned at 696.73 nm (vacuum). Here, we used the Racah \( (j-l) \) coupling notation.\(^{15}\) The \( 4s[3/2]_{2}^{p} \rightarrow 4p[1/2]_{1} \) transition is split into the \( \pi \) and two \( \sigma \) components by Zeeman effect (Fig. 1). The \( \pi \) components of the \( 4s[3/2]_{2}^{p} \rightarrow 4p[1/2]_{1} \) transition are excited in the present experiment. The Doppler LIF spectrum of argon metastable atoms has been obtained by sweeping the laser frequency around the resonance center of the \( \pi \) component. The LIF photons of 826.68 nm (vacuum) emitted by the \( 4p[1/2]_{1} \rightarrow 4s[1/2]_{1} \) transition have been observed using a photomultiplier tube (PMT) (Hamamatsu R3896).

The lowest velocity detectable by the LIF system is limited by the accuracy of frequency calibration and the stability of the excitation laser. Since the flow velocity of neutral argon atoms is expected to be of the order of \( 10^3 \) m/s, the corresponding Doppler shift in frequency is of the order of 10 MHz. Thus, the accuracy of calibration and the stability should be both within a few MHz. The newly developed LIF system utilizes argon saturated absorption spectroscopy, in which the laser frequency is calibrated by the frequency of so-called Lamb dip generated by the excitation laser. The use of Lamb dip as the frequency standard is particularly appropriate for the flow velocity measurement, because 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 laser frequency calibration is increased. In addition, Lamb dip appears at the frequency corresponding to the zero velocity in the laboratory frame, which automatically provides the origin of velocity space and thus saves procedures of finding the origin of velocity axis.

In this study, we adopt the Lamb dip of the \( 4s[3/2]_{2}^{p}(M_{J}=0) \rightarrow 4p[1/2]_{1}(M_{J}=0) \) transition of argon atom. The \( M_{J}=0 \) to 0 transition is not perturbed by the variation of magnetic field intensity in the target plasma.

Figure 2 shows the schematic diagram of the optics system. The output power of the ECDL is 16 mW. An optical isolator (Linos DLI 3) is installed in front of the ECDL to avoid the frequency fluctuation caused by backscattered laser light from the optical components. The coarse tuning of the frequency of the ECDL is performed using a wavemeter. A Fabry–Pérot interferometer (FPI) is used to check the single mode operation of the ECDL and is also used as the frequency markers when scanning the laser frequency. The free spectral range (FSR) of the Fabry–Pérot interferometer is

\[
\begin{align*}
M_{J} & = +1 \\
& \vdots \\
& -1 \\
\pi & \sigma \\
\sigma & \pi
\end{align*}
\]

FIG. 1. Zeeman splitting of the \( 4s[3/2]_{2}^{p} \rightarrow 4p[1/2]_{1} \) transition of argon.

FIG. 2. Schematic diagram of the optical measurement system.
294 MHz. The laser power is modulated by using an electro-
optical modulator (Linos LM 0202) operated at 100 kHz.
The modulated laser beam is introduced into the plasma
along the center chord of the vacuum chamber. (In the fol-
lowing, we adopt a coordinate system located at the center of
the chamber, and then the laser beam is injected toward the
negative x-axis.) The polarization of the pump laser is
aligned parallel to the magnetic field. The PMT with col-
cction optics is installed on a horizontally movable stage
placed on the top viewing port of the vacuum vessel. The
LIF photons are focused on a slit placed in front of the PMT
by a lens. An interference bandpass filter (825 ± 5 nm) is set
between the PMT and the slit to eliminate the lights from the
plasma emitted in the irrelevant ranges of wavelength. The
spatial resolution of the collection optics is 7.5 mm in radial
direction. The radial profile of neutral flow velocity is ob-
tained 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 am-
plifier. The saturated absorption spectroscopy of argon meta-
stable state is carried out simultaneously with the Doppler
LIF spectroscopy, where the incident beam of LIF measure-
ment is utilized as the pump laser. The transmitted beam is
attenuated to 0.01% by a neutral density (ND) filter and re-
lected to re-enter into the plasma along the same path of the
pump beam. This backward beam is used as the 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 pho-
diode behind the beam splitter (denoted by BS in Fig. 2), and
finally amplified by a lock-in amplifier.

III. RESULTS AND DISCUSSIONS

Figure 3 shows the LIF Doppler spectrum, the satu-
rated absorption spectrum and the fringes of Fabry–Pérot interfer-
ometer simultaneously recorded during the same discharge
period. The frequency of the laser beam has been swept
±4 GHz (0.0065 nm) around the resonance frequency. Fig-
ure 3(a) shows the Doppler LIF spectrum taken at the center of
the chamber (x,y=0 cm). As is expected, the profile of the
LIF spectrum is quite well fitted by a Gaussian distribu-
tion function. The full width at half maximum of the LIF
spectrum is 950 MHz, and the corresponding temperature is
0.033 eV (380 K). Figure 3(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
(∼20 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 attrib-
uted to the Zeeman splitting of magnetic sublevels of
4s[3/2]s and 4p[1/2]t states. The center dip, which is Mj
=0 to 0 transition, is used for the calibration of the absolute
value of the laser frequency. Figure 3(c) shows the fringes of the
Fabry–Pérot interferometer. The frequency interval of
each fringe is 294 MHz, and is utilized as the frequency
scale. By combining the position of Lam dip (reference point
of frequency scale and also origin of velocity scale) and the
fringes of interferometer (scale of frequency axis), we have
determined the position of LIF spectrum on the frequency
axis when scanning the laser frequency. The velocity of neu-
tral flow has been evaluated from the peak shift (Doppler
shift) of the distribution function.

To confirm the long-time stability of the whole system,
we have repeated under the same discharge condition, the
LIF measurements for 5 h and observed the dispersion of the
position of LIF Doppler spectrum. Figure 4 shows the peak
positions of the LIF Doppler spectra as a function of time,
where the open circles indicate the peak position. As seen in
the figure, the deviation of peak position is within a range of
±3 MHz. The corresponding dispersion in velocity is ±2
m/s, which gives the maximum velocity resolution of the
present system. It is emphasized that the deviation of peak

\[ \text{FIG. 3. (a) LIF spectrum, (b) saturated absorption spectrum, and (c) output fringes of Fabry–Pérot interferometer.} \]

\[ \text{FIG. 4. Long-time drift of the peak of LIF Doppler spectrum.} \]
position becomes much larger when we use an iodine cell for frequency calibration, which is also shown in Fig. 4.

The radial flow velocity profile of the metastable argon has been obtained by measuring the LIF spectra at radially different positions. Figure 5 shows the Doppler LIF spectra observed at $x = \pm 2$ cm. As we will show later, the largest Doppler shift in the LIF spectrum has been observed at these points. The profiles of two spectra are almost identical except the peak shift, which can be clearly seen by magnifying the spectra. In this case, the frequency shift is approximately 40 MHz, corresponding to the relative speed of 28 m/s.

Carrying out successive measurements at different positions, we have obtained the radial flow velocity profile of neutral particles, which is depicted in Fig. 6. At each position, the measurements have been made ten times. The dispersion of data points from the each average value is indicated by an error bar. The temperature of neutral particles is radially constant and is 0.033 ± 0.001 eV. 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 left to right in the negative $x$-region, showing the existence of radially inward flow of neutrals in the plasma.

By performing Langumuir probe measurements, we have confirmed that the plasma density profile is flat in the region $|x| < 6$ cm, and the electron temperature is almost constant in the whole plasma ($\sim 4$ eV). We have observed that the LIF intensity at $x = 0$ cm decreases to one-half of that in peripheral region. These results show that a neutral depletion takes place in the central region of the plasma, which has been also observed by O’Connell et al. The inward flow of neutral particle is probably attributable to the concave structure of the neutral density profile. It is interesting to study the relation between neutral flow and neutral depletion.

IV. CONCLUSION

We have developed a high-resolution LIF system with a narrow linewidth tunable diode laser. Utilizing a saturated absorption spectrum as a means of laser frequency calibration, we have achieved the accuracy of frequency determination within ±3 MHz, which corresponds to velocity resolution ±2 m/s. The experiments with an ECR argon plasma revealed that this high performance of the system is maintained for at least 5 h. The radial flow velocity of metastable argon atoms has been measured in an ECR plasma. It is found that there exists a radially inward flow of the order of 10 m/s, which is probably driven by neutral depletion in the central region of the plasma. The detailed results will be reported elsewhere.

Saturated absorption spectroscopy is one of the basic methods in accurate laser spectrometry. We have introduced this technique into the LIF Doppler spectroscopy system for the basic plasma physics research, and demonstrated that the minimum detectable velocity becomes two orders of magnitude down to the existing experiment. 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 lack of diagnostic tool.

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