Observation of Axial Neutral-Gas Flow Reversal in an ECR Plasma

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Axial neutral gas transport has been experimentally investigated in a partially ionized cylindrical plasma. The high-accuracy laser induced fluorescence spectroscopy is embraced to evaluate the absolute flow velocity of ions and neutral particles, and the axial flow velocity associated with the mass transport parallel to the magnetic field has been measured by changing the filling gas pressure. It has been found that the neutral gas flow is spatially non-uniform, and the axial flow reversal takes place under a certain circumstance. The experimental results indicate that non-uniformity of neutral gas flow field is generated as a consequence of the plasma-neutral coupling and the axial neutral transport plays an important role in the plasma structure formation.

Keywords: ECR plasma, laser induced fluorescence spectroscopy, neutral gas flow, plasma-neutral coupling, axial flow reversal

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Partially ionized plasma can be ubiquitously found in nature, laboratories, and the edge region of magnetically confined plasmas [1,2], and the neutral gas in plasma plays an important role in the physical processes and the organization of plasma discharges. A plasma fluid is coupled with a neutral fluid via collision and radiation processes, and hence, understanding the characteristics of neutral gas transport is important. Neutral particles in plasma, however, have been frequently treated by simplification or insufficient modeling, and little attention has been given to dynamical behavior of the neutral gas flow in the direction parallel to the magnetic field line.

In this rapid communication, we report the non-uniformity of neutral gas flow measured with the laser induced fluorescence (LIF) spectroscopy. The axial flow reversal of neutral gas has been observed in an electron cyclotron resonance (ECR) plasma for the first time, and the neutral gas transport in partially ionized plasma immersed into a magnetic field is discussed.

Experiments have been carried out with the HYPER-II device at Kyushu Univ. [3], which is shown in Fig. 1. The HYPER-II device consists of the plasma production chamber (0.3 m in diameter and 0.95 m in axial length) and the diffusion chamber (0.76 m in diameter and 1.2 m in axial length). A high density argon plasma is produced by ECR heating with a 2.45 GHz microwave, and the input microwave power is 6 kW in this experiment. The plasma diameter is approximately the same as the device diameter. A diverging magnetic field is applied by eight magnetic coils set around the production chamber, and the ECR point is placed in the plasma production chamber (z = 0.41 m). The typical electron density and temperature at z = 1.155 m in the plasma center are 7×10^{16} - 3×10^{18} m^{-3} and 1.3 - 8.0 eV, respectively. The detailed description of experimental apparatus is given in Ref. [3].

In order to directly measure the velocity distribution function of both the ions and neutral particles, we have utilized a LIF spectroscopy method [4]. A tunable diode laser tuned at 668.61 nm (vac.) and a TiS laser tuned at 696.73 nm (vac.) are used for the measurements of metastable ions and metastable neutral particles, respectively. The LIF signal is collected by a set of collecting optics installed in the vacuum chamber [3] (z = 0.75 m and 1.155 m) and a photo-multiplier tube, in which the emission lines of 443 nm (vac.) for ions and 826 nm (vac.) for neutrals were lock-in detected. Since the band width of those lasers is much narrower than the thermal broadening of distribution function, we can precisely trace the velocity distribution function of target particles by scanning the laser wavelength. The laser beam is injected from the end

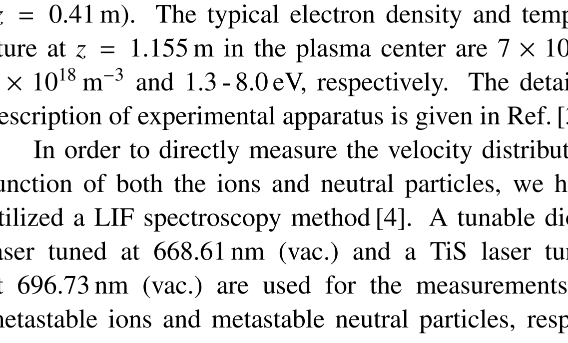

Fig. 1 Schematic diagram of the HYPER-II device. In the experiment, a gas feeding port located at either z = 0.133 m or z = 1.555 m is used.

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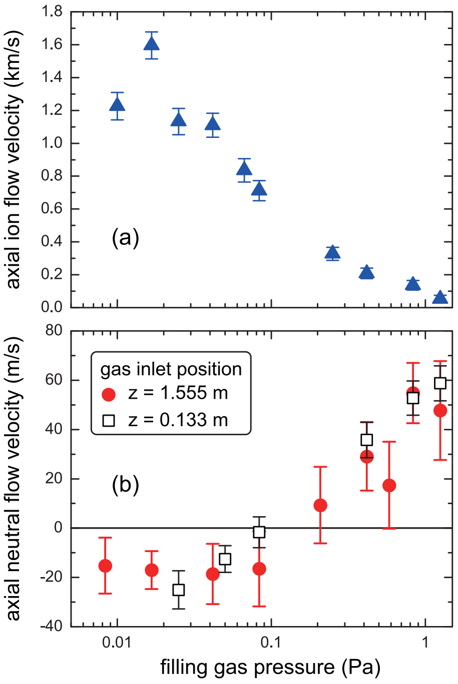

Fig. 2 Filling gas pressure dependences of (a) axial ion flow velocity and (b) axial neutral flow velocity at z = 1.155 m.

of device shown in Fig. 1, and the axial flow velocity has been measured with the laser beam propagating on the z-axis. Details on the precise LIF measurement system are given in Ref. [4].

In the present experiment, we have assumed that the velocity distribution function of metastable neutral particles coincides with that of ground-state particles and confirmed the validity of this assumption from the following reasons: Firstly, the dominant emission lines between visible to near-IR wavelength range are related to the energy levels with 11 - 13 eV, which are located the lower excited levels near the ground state. Secondly, we have calculated the population of these energy levels by calculating a collisional-radiative (CR) model [5, 6] in our previous study [7], in which the experimental conditions including the device parameters are almost the same. Regarding the ion flow measurement, we have confirmed the reliability of LIF measurement system by using a directional Langmuir probe.

Figure 2 shows the axial flow velocity at z = 1.155 m on the axis as a function of filling gas pressure; (a): ion flow and (b): neutral gas flow. The error bars are attributable to the reproducibility of discharge and are evaluated by standard deviation in several discharges (typically five shots). The axial ion flow from the plasma production region to the weaker magnetic field region has been found in all conditions, and the flow velocity decreases with increasing the gas pressure. The mean free path of the charge exchange collision becomes short compared to the device length above the pressure of 0.01 Pa in this experiment, and hence, it is considered that the decrease in ion flow velocity is attributable to momentum loss due to the ion-neutral collision.

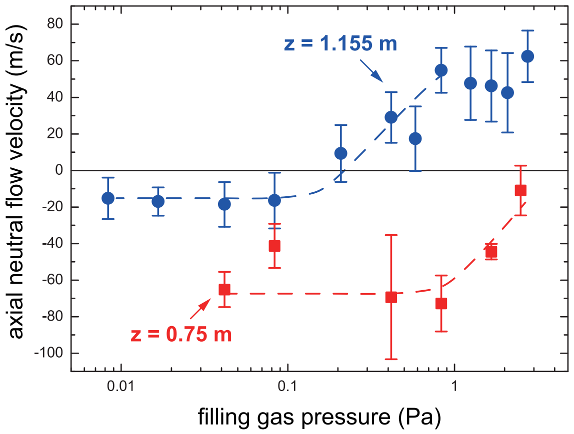

Fig. 3 Axial neutral flow velocity as a function of filling gas pressure at z = 0.75 m (closed rectangles) and z = 1.155 m (closed circles).

An interesting characteristic in terms of neutral flow can be seen in Fig. 2 (b). The sign of axial neutral flow velocity changes around the filling pressure of 0.1 Pa; negative axial flow has been observed in the lower pressure conditions, and positive axial flow in the higher pressure conditions, respectively. It is worth pointing out here that the flow structure does not depend on the gas inlet position, which indicates that the neutral transport is organized by the presence of plasma and is not affected by the change in external conditions.

Furthermore, the magnitude of axial ion flux (positive) is almost the same as that of axial neutral flux in the low pressure conditions (< 0.1 Pa), where the absolute neutral density is evaluated from the filling gas pressure, and the temperature of neutral particle is assumed to be the room temperature, because the ionization degree in the low pressure condition is much less than unity. Total mass conservation is sustained in the axial direction, and hence, axial transport of neutral gas is important in practical circumstance.

On the other hand, in the high pressure conditions (> 0.1 Pa), the total mass flux is clearly positive, and the neutral flux is much larger than that of the ion flux, where the neutral density is estimated by using the density at the filling gas pressure. This implies that inhomogeneity of neutral flux in the axial direction is necessary to sustain a steady state discharge.

To study the spatial structure of neutral gas flow, we have also measured the axial neutral gas flow in the plasma production chamber (z = 0.75 m). Figure 3 shows the filling gas pressure dependence of axial neutral flow velocity, where the data at z = 1.155 m (circles) are the same with that in Fig. 2 (b). As we expected, the neutral flow velocity is non-uniform in the axial direction. It is worth pointing out that the axial neutral-gas flow reversal takes place in the pressure conditions of 0.2 - 1 Pa. In this experiment, the inhomogeneity is generated by the electron-neutral ionization and the ion-neutral collision processes. The ionization process makes a density gradient of neutrals so as to recover the neutral gas and is predominant in the ECR layer. The neutral particles gain the positive axial momentum from the ions, since the axial ion flow velocity is positive as shown in Fig. 2. The result associated with the flow reversal suggests the existence of inward radial flow. For a better understanding of the plasma structure formation, there is now a strong need for more detailed spatially resolved and radial flow velocity measurements.

We have measured the neutral flow field in an ECR plasma and reported the first observation of axial neutral-gas flow reversal generating in the central region of the plasma. The neutral gas transport in the axial direction takes place as a result of plasma-neutral coupling and is important as well as that in the radial direction. It is worth pointing out that the inhomogeneity of neutral flow induces the non-uniformity of collision rate, which may induce the velocity shear of ions. To understand physics of structure formation in plasmas, a viewpoint that plasma and neutral particle strongly couple each other and consist of a multi-fluid system, is of crucial importance.

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