Experimental study on flow structure formation associated with ion stream line detachment in a diverging magnetic field

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1. Introduction

It has been well known that the plasma acceleration takes place in a diverging magnetic field region, and a supersonic plasma flow and a super-Alfvénic plasma flow have been frequently observed in nature. Magnetized plasma is accelerated by both the hydrodynamic effect and the electric field along the magnetic field line. When the electron temperature is much higher than the ion temperature, the effect of electrostatic acceleration is dominant. In contrast, when the ion temperature is much higher than the electron temperature, the effect of hydrodynamic acceleration (magnetic nozzle acceleration [1]) is dominant. Under the magnetized conditions, the flow structure is essentially characterized by the magnetic field configuration.

Magnetized plasma eventually flows toward the weak field side, and the non-uniformity of the magnetic field becomes important for the gyro-motion of charged particle. In this region, the non-adiabaticity parameter of ions becomes order unity, and it is anticipated that the non-adiabatic detachment (ion stream line detachment) from the magnetic field line takes place [2]. The electrons are still magnetized, and move along the magnetic field line. The difference in motion between the magnetized electrons and the detached ions induces an electric field rotate the plasma. Thus, the flow structure in the detachment region may become different from that in the magnetized region, which has not been fully understood, so far.

Recently, the non-adiabatic detachment of ions was observed in an electron cyclotron resonance (ECR) plasma [3]. The onset of plasma rotation was found in the detachment region. We have experimentally studied the flow structure in a diverging magnetic field using a high-accuracy ion flow velocity measurement system.

2. Experimental Setup

The experiments were performed in the high-density plasma experiment-I (HYPER-I) device at the National Institute for Fusion Science [4]. A schematic diagram of the HYPER-I device is shown in Fig. 1(a). The HYPER-I device consists of a cylindrical vacuum chamber with 2.0 m in axial length and 0.3 m in inner diameter. A steady-state plasma was produced by electron cyclotron resonance (ECR) heating with a 2.45 GHz microwave. An argon gas was used with the gas pressure of 0.1 mTorr.

The magnetic field was produced by ten magnetic coils, and we adopted two different configurations in this experiment [see Fig. 1(b)]. The results of diverging configuration shown by a solid line are mainly presented in this paper. The characteristic scale length of the magnetic field variation ($L_B = |\nabla B/B|^{-1}$) is $0.2 - 15$ m in experimented region ($z \geq 1.175$ m). To examine the flow structure in the diverging magnetic field region, we also used a converging magnetic field configuration shown by a dashed line. The value of L_B between these configurations is different in the plasma acceleration region ($z = 1.2 - 1.4$ m), but almost the same in the diverging-field region ($z \geq 1.5$ m).

The ion Mach number was measured with a directional Langmuir probe (DLP [4]). The DLP has a tungsten electrode with a diameter of 1.5 mm and an insulating tube with an inner diameter of 1.6 mm and an outer diameter of 3.0 mm. The insulating tube covers the electrode, and has an ion collection hole with a diameter of 1.0 mm. The ion Mach number ($M_\mathrm{i} = V_\mathrm{i}/C_\mathrm{s}$) is evaluated from the ion saturation current [$I_\mathrm{is}(\theta_\mathrm{p})$] using the following equation

$$M_\mathrm{i} = \frac{V_\mathrm{i}}{C_\mathrm{s}} = \frac{1}{\alpha}\frac{I_\mathrm{is}(\theta_\mathrm{p}+\pi) - I_\mathrm{is}(\theta_\mathrm{p})}{I_\mathrm{is}(\theta_\mathrm{p}+\pi) + I_\mathrm{is}(\theta_\mathrm{p})}, \tag{1}$$

where θ_p shows an angle between the magnetic field and the normal vector of probe surface. The radially movable DLPs were introduced from the radial ports at $z = 1.175$, 1.400, 1.555, and 1.828 m. We also used an axially movable DLP inserted from the end port of the device. The axially movable DLP, which has independent two ion collection holes, was calibrated by the reference probes (radially movable DLPs). To clarify the flow structure formation, it is important to know the absolute ion flow velocity (V_i). We have experimentally determined calibration

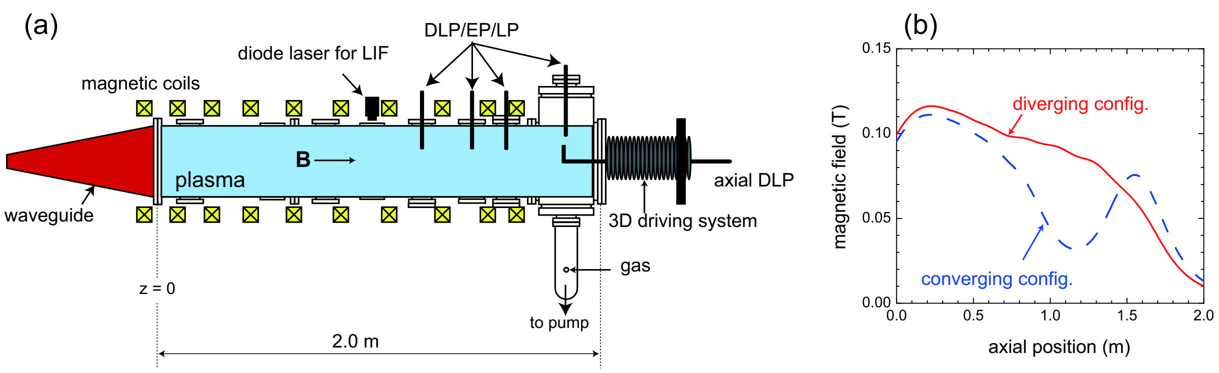

Figure 1: (a) A schematic of the HYPER-I device. (b) Axial profile of the magnetic field strength.

factor as $\alpha = 1.0 \pm 0.1$ with a laser induced fluorescence Doppler spectroscopy system [5, 6].

A Langmuir probe and an emissive probe were used to measure the electron density (n), the electron temperature (T_e), and the plasma potential (ϕ). These probes were inserted from the radial ports at $z = 1.400$ m and 1.555 m. The typical electron density, electron temperature, and ion temperature are $n = 10^{17}$ m^{-3}, $T_e = 7.5$ eV, and $T_i = 1.2$ eV, respectively.

3. Experimental Results

Figure 2 shows the relation between the normalized electron density $[\ln(n/n_0)]$ and the normalized electrostatic potential $[e\phi/(k_B T_e)]$ for the cases of the diverging configuration (circles) and the converging configuration (boxes), where the reference density (n_0) and the reference potential ($\phi = 0$) were taken at $z = 1.500$ m. When the ion is magnetized, these normalized parameters are written by the Boltzmann relation

$$\ln\left(\frac{n}{n_0}\right) = \frac{e\phi}{k_B T_e}, \qquad (2)$$

where e and k_B denote the elementary charge and the Boltzmann's constant, respectively. In the case of the diverging configuration, the data in the diverging magnetic field region ($z \geq 1.5$ m) well agree with the Boltzmann relation. From the DLP measurements, the ion flow velocity in the region $z = 1.555$-1.828 m is found to be smaller than 3.0 km/s, and the non-adiabaticity parameter $|f_{ci}L_B/V_{iz}|$ is larger than 10. In the case of the diverging configuration, on the other hand, the Boltzmann relation is not satisfied in the region $z \geq 1.5$ m, and the non-adiabaticity parameter becomes order unity. This result implies that the electrostatic potential in the diverging magnetic field region varies by whether the non-adiabatic detachment takes place or not.

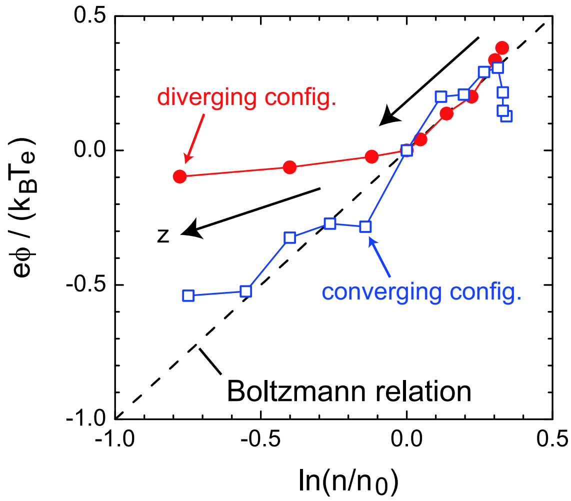

Figure 2: The relation between the normalized electron density $[\ln(n/n_0)]$ and the normalized potential $[e\phi/(k_B T_e)]$ in the cases of the diverging configuration (circles) and the converging configuration (boxes). A dashed line shows the Boltzmann relation.

Figure 3(a) shows the ion flow field (arrows) and the magnetic field line (solid lines) on the r-z plane in the case of the diverging configuration [7]. In the region $z < 1.5$ m, the ions flow lying along the magnetic field lines. On the other hand, the ion stream line detachment takes place in the region $z > 1.5$ m. It is interesting to note that the azimuthal rotation is initiated as the ion detachment takes place. Figure 3(b) shows the axial profile of the azimuthal rotation velocity ($V_{i\theta}$) normalized by the ion sound speed ($C_s = 4.6$ km/s) at $r = 50$ mm. In the detachment region

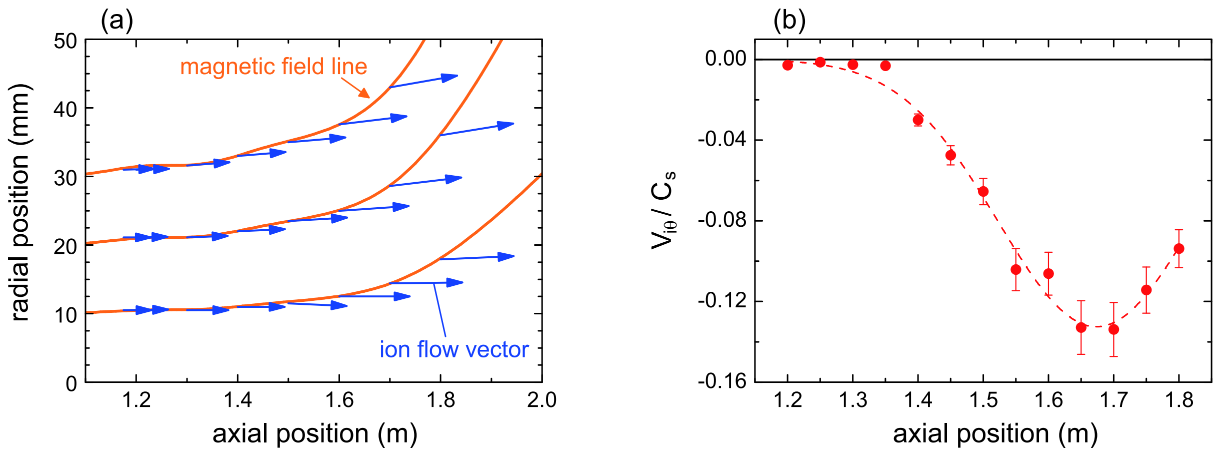

Figure 3: (a) The ion flow vector field (arrows) and the magnetic field line (solid lines) on the *r*-*z* plane, and (b) axial profile of the azimuthal ion flow velocity normalized by the ion sound speed [7].

$z > 1.4$ m, the ions start rotating in the ion diamagnetic direction ($V_{i\theta} < 0$). From the radial plasma potential measurement with emissive probe, this rotation is explained by the $\boldsymbol{E} \times \boldsymbol{B}$ drift due to radial electric field, which may be generated by the difference in motion between the magnetized electrons and the detached ions.

4. Summary

We have observed the ion stream line detachment from the magnetic field line and the associated plasma rotation in a steady-state ECR plasma. The rectilinear propagation of ion flow appears, when the plasma rotation starts. These results suggest that the flow structure formation in the detachment region should be considered with the conservation of angular momentum.

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