Experimental studies on ion acceleration and stream line detachment in a diverging magnetic field

K. Terasaka,¹ S. Yoshimura,² K. Ogiwara,¹ M. Aramaki,³ and M. Y. Tanaka¹

¹Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

²National Institute for Fusion Science, Toki, Gifu 509-5292, Japan

³Department of Electrical Engineering and Computer Science, Nagoya, Aichi 464-8603, Japan

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The flow structure of ions in a diverging magnetic field has been experimentally studied in an electron cyclotron resonance plasma. The flow velocity field of ions has been measured with directional Langmuir probes calibrated with the laser induced fluorescence spectroscopy. For low ion-temperature plasmas, it is concluded that the ion acceleration due to the axial electric field is important compared with that of gas dynamic effect. It has also been found that the detachment of ion stream line from the magnetic field line takes place when the parameter $|f_{ci}L_B/V_i|$ becomes order unity, where f_{ci} , L_B , and V_i are the ion cyclotron frequency, the characteristic scale length of magnetic field inhomogeneity, and the ion flow velocity, respectively. In the detachment region, a radial electric field is generated in the plasma and the ions move straight with the $\mathbf{E} \times \mathbf{B}$ rotation driven by the radial electric field. © 2010 American Institute of Physics. [doi:10.1063/1.3457139]

I. INTRODUCTION

Plasma flow in an inhomogeneous magnetic field plays an important role in various phenomena. A plasma jet ejected from a protostar affects the angular momentum transport in star formation,^{1,2} and the tearing of vortices by a zonal flow³ enhances the confinement performance of fusion oriented devices. In plasma applications, a directed ion flux is used to obtain an efficient momentum exhaust for electric propulsion, e.g., variable specific impulse magnetoplasma rocket,⁴ and to achieve high aspect ratios in material processing (plasma etching).⁵⁻⁷

Diverging magnetic field configurations are often used to obtain a unidirectional flow,⁸⁻¹³ where we may anticipate that the magnetization of ions breaks down in the low magnetic field region. For realizing and controlling the plasma flow, it is important to have the knowledge on flow structure in the low magnetic field region, in which the detachment of ion stream line from the magnetic field line takes place.^{14,15}

There are two effects on ion motion in a diverging magnetic field: the magnetic nozzle effect (Laval nozzle)^{16,17} and the electrostatic acceleration.¹⁸ The magnetic nozzle effect is analogous to the gas dynamic effect of ordinary fluid, and has been discussed in the conventional acceleration experiments.^{8,16} On the other hand, the effect of electrostatic field, which is present in an inhomogeneous plasma,^{17,19-21} has not been fully understood so far, because of the difficulty of experiments.

We have measured the flow velocity field of ions in an inhomogeneous electron cyclotron resonance (ECR) plasma and experimentally confirmed that the electrostatic acceleration is important compared with the gas dynamic effect. The flow velocity vector has been measured with directional Langmuir probes (DLPs),²² which have been carefully calibrated with the laser induced fluorescence (LIF) spectroscopy. It has been experimentally found that the detachment

of ion stream line from the magnetic field line takes place when the characteristic period of field inhomogeneity experienced by the flowing ions L_B/V_i becomes the same order of ion cyclotron period, where L_B is the characteristic scale length of the magnetic field inhomogeneity, and V_i the ion flow velocity. It is also found that the radial electric field is generated in the plasma and the ions flow straight with the $\mathbf{E} \times \mathbf{B}$ rotation induced by the electric field, where $\mathbf{E}$ and $\mathbf{B}$ are the electric field and the magnetic field, respectively.

In the following, the experimental setup is described in Sec. II and the experimental results are given in Sec. III followed by conclusions.

FIG. 1. (a) Schematic of the HYPER-I device and (b) axial profile of the magnetic field intensity.

FIG. 2. (a) Axial profile of the normalized electron density. The solid line indicates the normalized magnetic field strength. (b) Axial profile of the normalized potential. The absolute electron density at $z=1.555$ m is $1.2 \times 10^{17} \text{ m}^{-3}$.

II. EXPERIMENTAL SETUP

The experiments have been performed in the high density plasma experiment-I device (HYPER-I) (Ref. 23) at National Institute for Fusion Science, which is shown in Fig. 1(a). The HYPER-I device consists of a cylindrical vacuum chamber (0.3 m in diameter and 2.0 m in axial length) and water-cooled 10 magnetic coils for producing a steady and weakly diverging magnetic field. The plasmas are produced and sustained by ECR heating with a microwave of frequency 2.45 GHz, which is launched from an open end of the vacuum chamber. The field intensity for a 2.45 GHz microwave ECR is 0.0875 T, the position of which is located at $z=1.16$ m [see Fig. 1(b)]. The microwave excites an electron cyclotron wave (right-hand polarized wave) in the plasma and is fully absorbed before the ECR point. An argon gas was used in the experiment with an operation pressure of 0.1 mTorr. The typical electron density and temperature were $n=10^{17} \text{ m}^{-3}$ and $T_e=7.5 \text{ eV}$, respectively, and the ionization degree was about 10% (maximum).

We have measured the ion Mach number using the radially movable DLPs and the axially movable DLP [see Fig. 1(a)]. The radial DLP is made of a tungsten rod covered with

FIG. 3. Axial profile of ion Mach number (open circles). The theoretical predictions from the Bernoulli's law with the reference point as the initial value are also shown for two cases: the solid line is obtained including the all terms in Eq. (A4), and the dashed line is obtained without the axial electric field (only the gas dynamic effect is included).

an Al_2O_3 insulating tube (3.0 mm in diameter), and is calibrated and used as the reference probe. The axial DLP is made of two tungsten rods covered with an insulating tube (3.0 mm in diameter) of two-hole tubular structure. Two types of axial DLP have been used to measure the perpendicular flow velocity and the axial flow velocity. To prevent the probe tip from entering into the shadow of the probe structure along the magnetic field line, we have adopted an L-shaped structure for the axial DLP. Since the difference of collecting electrode area of the axial DLP makes an error in the flow velocity measurement, the axial DLP has been calibrated with the reference radial DLP to give the same result when measured at the same position.

The method of DLP (Ref. 24) is based on the symmetry property of the ion current to the probe as a function of probe angle, and the effect of magnetic field on the DLP output can be eliminated by taking a ratio of $I_{is}(\theta_p + \pi) - I_{is}(\theta_p)$ to $I_{is}(\theta_p + \pi) + I_{is}(\theta_p)$, where $I_{is}(\theta_p)$ is the ion saturation current of DLP at an angle θ_p . The flow velocity component at an angle θ_p is given by

$$\frac{V_i}{C_s} \cos(\theta_p - \theta_f) = \frac{I_{is}(\theta_p + \pi) - I_{is}(\theta_p)}{I_{is}(\theta_p + \pi) + I_{is}(\theta_p)}, \quad (1)$$

where θ_f is the direction of ion flow with respect to the magnetic field. The quantity α is the calibration factor to be specified with other diagnostic methods. In this experiment, the calibration factor of the reference DLP is determined by LIF Doppler velocimetry,²⁵ and is found to be 1.1 ± 0.1 .²⁶ The potential profile has been measured with an emissive probe, which is made of a 2%-thoriated tungsten filament (0.23 mm in diameter).

FIG. 4. (Color online) Contour maps of (a) radial flow, (b) azimuthal flow, and (c) axial flow velocity on a r - z plane. Figures 4(b), 4(d), and 4(f) indicate the cross sectional views of the flow velocity.

III. EXPERIMENTAL RESULTS

Figure 2(a) shows the axial profile of electron density normalized by that of reference point ($z=1.2$ m and $r=0$ mm). The electron density at the reference point is $1.7 \times 10^{17} \text{ m}^{-3}$. The local density is determined by averaging the ion saturation currents at $\theta_p=0$ and π radian (the electron temperature is 7.5 eV and constant along the axial direction). The solid line indicates the axial profile of normalized magnetic field obtained with the magnetic field intensity at the reference point ($B=0.0856$ T). As seen in this figure, the density monotonically decreases in the axial direction, and its behavior is the same as that of normalized magnetic field. This result indicates that the axial decrease in density is attributable to the spatial expansion of the magnetic field line. The mean free paths of ion-neutral collisions are ~ 1.0 m for momentum transfer and ~ 1.9 m for charge exchange. The effect of neutral particle is negligible, and the plasma is considered as collisionless.

Figure 2(b) shows the axial profile of floating potential (ϕ) normalized by the electron temperature. As seen in the figure, the normalized potential monotonically decreases in the axial direction, and the Boltzmann relation $n(z)/n(z_0) = \exp[e\phi(z)/(k_B T_e)]$ is well satisfied in the upstream region

($z < 1.6$ m), where z_0 is the reference point and we take $\phi(z_0)=0$ V. The quantities e and k_B are the electric charge and the Boltzmann's constant, respectively.

In the downstream region ($z > 1.6$ m), on the other hand, the potential decrease is less than that in density, and the axial electric field diminishes its value. The electron Larmor radius in this region is much smaller than the size of the plasma and the characteristic scale length of the magnetic field inhomogeneity (L_B), and the electrons are considered to be still magnetized and move along the magnetic field. However, the ion Larmor radius becomes of the order of one tenths of L_B , and the effect of field inhomogeneity is not negligible in the ion motion. The difference between the normalized density and potential seen in Fig. 2(b) may be attributable to the difference in relative motion between ions and electrons. The experimental result indicates that the ion fluid does not move along the magnetic field as the electron fluid.

We have measured the axial variation of ion Mach number (axial component) and compared it with the theoretical prediction, in which the effect of axial electric field is included. As seen in Fig. 3, the ion Mach number monotonically increases from $M=0.47$ ($V_i=2.2$ km/s) at $z=1.2$ m to $M=0.91$ ($V_i=4.2$ km/s) at $z=1.6$ m and saturates to a con-

FIG. 5. (Color online) Flow vector field of ions measured with the DLPs. The magnetic field line is shown by the solid line. The detachment of stream line from the magnetic field takes place in the region $z > 1.5$ – 1.6 m

stant value $M=0.9$ in the region $z \geq 1.6$ m, where M is the ion Mach number. The Bernoulli's law for a steady-state ion fluid in a magnetic field is given by (Appendix)

$$\frac{M^2}{2} + \kappa \ln(n) + (1 - \kappa)\Phi = \text{const}, \quad (2)$$

where Φ is the normalized electrostatic potential [$e\phi/(k_B T_e)$], and a nondimensional parameter $\kappa = T_i/(T_e + T_i)$ is introduced in the equation. The solid line in the figure shows the theoretical prediction obtained with the reference point as the initial value, showing a good agreement in the upstream region. The dashed line is the theoretical prediction without the effect of electrostatic acceleration ($E_z = 0$ V/m is assumed and only the gas dynamic effect is included). The experimental results clearly indicate that the electrostatic acceleration is not negligible compared with the gas dynamic effect.

To obtain the detailed information on the flow structure in the diverging magnetic field, we have measured the flow velocity vectors on a r - z plane containing the chamber axis. Figures 4(a), 4(c), and 4(e) show the contour maps of the each velocity component (ion Mach number), and Figs. 4(b), 4(d), and 4(f) depict the cross sectional views of the flow velocity profile, respectively.

As seen in this figure, the radial and azimuthal components of the flow velocity are small in the region $z < 1.5$ m, and the flow field structure is almost one-dimensional. In the region $z > 1.5$ m, however, the outward radial flow is formed, and at the same time the plasma exhibits a rigid-bodylike rotation. The axial flow velocity is radially uniform, and saturates in the region $z \geq 1.6$ m.

The flow velocity vectors are reconstructed on the same magnetic field line, and are shown in Fig. 5. The solid lines in the figure indicate the magnetic field lines. In the upstream region, it is noted that the flow velocity vectors are parallel to the magnetic field line. However, in the region $z > 1.5$ – 1.6 m, the direction of flow velocity vectors are

FIG. 6. (Color online) Axial profile of the characteristic time of field inhomogeneity experienced by the ions. The quantity is normalized by the ion cyclotron period.

clearly different from that of the magnetic field line, and the ions move straight compared with the magnetic field line. Detachment of ion stream line from the magnetic field line takes place in this region. The azimuthally rotating ions are likely to move straight to conserve the angular momentum and stay longer in the central part of the plasma compared with the electrons flowing along the magnetic field. This may cause the formation of radial electric field.

The onset of ion flow detachment from the magnetic field may be estimated by comparing the transit time of field inhomogeneity experienced by the ions to the cyclotron period $|f_{ci} L_B / V_i|$, where $f_{ci} = eB/m_i$ and $L_B^{-1} = (1/B_z)(dB_z/dz)$. Figure 6 shows the axial profile of this quantity, and indicates that the ion detachment takes place when the parameter $|f_{ci} L_B / V_i|$ becomes order unity. The azimuthal rotation of ions in the detachment region is explained by the $\mathbf{E} \times \mathbf{B}$ drift induced by the radial electric field

$$V_{i\theta} \approx -\frac{E_r B_z}{B_z^2}. \quad (3)$$

It is noted from Eq. (3) that the radial potential profile is obtained by integrating the observed azimuthal velocity with respect to radius r . Figure 7 shows the radial profile of the potential measured with the emissive probe (closed circles). The solid line in the figure indicates the potential profile obtained by numerically integrating the observed $\mathbf{E} \times \mathbf{B}$ drift profile, where the integration constant is determined to fit the experimental data. There is a good agreement between the expected potential profile and the observed one. We can conclude that the azimuthal rotation is induced by the radial electric field.

It is worth pointing out that the quasineutrality constraint and stream line detachment can coexist in the plasma. Density distribution is determined by satisfying the Poisson's equation, and stream line detachment is governed by the continuity equation. The stream line detachment can coexist

FIG. 7. (Color online) Radial profile of the plasma potential measured with the emissive probe (closed circles). The solid line is obtained by integrating the azimuthal flow velocity with respect to radius r .

with the quasineutrality constraint by adjusting the velocity vector. The electrons are magnetized in the whole plasma region, and thus the density scales with the magnetic field as seen in Fig. 2. The present experiment shows that the ion stream line detachment takes place when the ion magnetization condition breaks down.

IV. CONCLUSIONS

We have studied the ion flow velocity field of an ECR plasma in a diverging magnetic field, where the electrons are magnetized in the whole plasma region while the ions are marginally magnetized in the downstream region. The flow velocity field has been obtained with the calibrated DLPs and the detachment of ion stream line from the magnetic field line is experimentally measured for the first time. It is concluded that the ion detachment takes place when the parameter $|f_{ci}L_B/V_i|$ becomes order unity.

The experimental result has been compared with the generalized Bernoulli's law. When both the ions and electrons are magnetized (upstream region), the axial electric field is generated to satisfy the Boltzmann relation and the ions are accelerated by this electric field. The present experiment shows that in a low ion temperature plasma ($T_i \ll T_e$), the electrostatic acceleration is important compared with the gas dynamic effect. In the downstream region, the radial electric field is generated, and the ions flow straight with $E \times B$ rotation induced by the electric field.

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APPENDIX: BERNOULLI'S RELATION FOR IONS IN THE PRESENCE OF ELECTRIC FIELD

When the electron inertia is neglected in the axial motion, the Boltzmann relation $n = n_0 \exp[e\phi/(k_B T_e)]$ is obtained, where n and T_e are the electron density and the temperature, respectively. The quantity ϕ is the electrostatic potential, and we take $\phi = 0$ at $z = z_0$. The axial motion of ions in an inhomogeneous magnetic field (z -direction) is described by

$$m_i n_i V_i \frac{dV_i}{dz} = -k_B T_i \frac{dn_i}{dz} - en_i \frac{d\phi}{dz}, \quad (\text{A1})$$

where m_i , n_i ($\approx n$), V_i , and T_i are the ion mass, the density, the flow velocity, and the temperature, respectively. We assume here an isothermal process for simplicity ($\gamma_i = 1$, where γ_i is the specific heat ratio of the ion). Introducing the ion Mach number, we obtain the following equation:

$$M \frac{dM}{dz} = -\kappa \frac{dn}{dz} - (1 - \kappa) \frac{d\Phi}{dz}, \quad (\text{A2})$$

where the ion Mach number defined by $M = V_i/C_s$ ($C_s = \sqrt{k_B(T_e + T_i/m_i)}$), $\kappa = T_i/(T_e + T_i)$, and $\Phi = e\phi/(k_B T_e)$ are introduced. From Eq. (A2), the Bernoulli's relation is then given by

$$\frac{M^2}{2} + \kappa \ln(n) + (1 - \kappa)\Phi = \text{const.} \quad (\text{A3})$$

The ratio of the pressure term to the electric field term is estimated as

$$\left| \frac{d(\ln n)/dz}{d\Phi/dz} \right| \approx \frac{T_i}{T_e}, \quad (\text{A4})$$

where we assume that the characteristic scale length of the density is the same as that of the potential. When the ion temperature is much lower than the electron temperature ($T_i \ll T_e$), the electrostatic acceleration becomes important, which is the case for ECR plasmas²³ and helicon plasmas.²⁷ On the other hand, in cases of magnetoplasma dynamic arc-jet plasmas⁸ with $T_i \sim T_e$, the gas dynamic effect is important as well.

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