Effect of Plasma Rotation on Acceleration of Ions Along the Magnetic Field Line

Kenichiro TERASAKA, Tetsushi KATAHIRA, Shinji YOSHIMURA[1)], Mitsutoshi ARAMAKI[2)] and Masayoshi Y. TANAKA[3)]

Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka 816-8580, Japan
[1)]National Institute of Fusion Science, Gifu 509-5292, Japan
[2)]Department of Electrical Engineering and Computer Science, Nagoya University, 464-8603, Japan
[3)]Department of High Energy Engineering Science, Kyushu University, Fukuoka 816-8580, Japan

(Received: 19 September 2008 / Accepted: 11 December 2008)

Supersonic ion flows accelerated from subsonic region have been observed in a weakly magnetized steady-state electron cyclotron resonance (ECR) plasma. The experiment revealed that the ions are accelerated by the electrostatic field along the magnetic field line. The acceleration rate along the magnetic field has been examined in terms of total angular momentum per unit mass and unit length. It is found that the acceleration rate is small when the angular momentum is large and is independent of the direction of rotation. Control of plasma rotation is important for the efficient acceleration of ions along the field line.

Keywords: ion acceleration, plasma rotation, directional Langumuir probe, ECR plasma

1. Introduction

Supersonic plasma flow plays an important role on developments of electric propulsion and is intensively studied so far. In a diverging magnetic field configuration, ions are accelerated along the filed line to reach a subsonic or supersonic velocity. According to the acceleration mechanism of a normal gas flow, a concept of "magnetic nozzle" has been proposed and the experimental studies have been also carried out.[1, 2] Magnetic nozzles have been widely used because they do not need material walls and produce supersonic flows efficiently. However, the acceleration mechanism including the electrostatic (and electromagnetic) field is not fully understood. In space plasmas, there are many phenomena with supersonic plasma flows. The astrophysical jets flowing from massive stars or proto stars are considered to be fast flowing plasmas, however, the acceleration mechanism is not fully understood yet.

In most of laboratory and space environments a magnetized plasma inevitably rotates around its axis due to the radial electric field, however, the effect of rotation on generation of axial flow has not been properly considered. When a plasma has an angular momentum, the parallel acceleration of ions may be different from that of a non-rotating case, which is formulated by the variational principle with the constraints of axial mass flux and helicity.[3, 4] In the experiments, on the other hand, the effect of rotation has not been studied so far.

We have experimentally studied the effect of plasma rotation on the axial acceleration of ions using directional Langmuir probes (DLPs)[5], which can measure the radial, azimuthal and axial ion flow velocity. The objectives of present study are as follows; (i) clarify the acceleration mechanism along the magnetic field line and (ii) estimate the effect of rotation on the ion acceleration.

author's e-mail: tera-225@aees.kyushu-u.ac.jp

In Sec. 2, the experimental apparatus and measurement method are shown. Section 3 shows the one dimensional momentum equation for ions to give the relation between plasma density and ion Mach number, which will be compared to the experimental results (Sec. 4). The total angular momentum and the ion acceleration rate along the axial direction are introduced to analyze the experimental data, and the effect of rotation on ion acceleration along the field line is clarified. The concluding remarks are summarized in Sec. 5.

2. Experimental Setup

The experiments are performed in the HYPER-I device at National Instiute for Fusion Science (NIFS), which is shown in Fig. 1.[6] The HYPER-I device consists of a cylindrical vacuum vessel (2.0 [m] in axial length and 0.3 [m] in inner diameter) and 10 magnetic coils, which produce a weakly diverging magnetic field along the axis of the chamber. A steady-state argon plasma is produced by ECR heating using a microwave of 2.45 GHz frequency, and sustained up to one minutes. Argon gas is used in the present experiments, and the pressure is 0.1-0.4 [mTorr].

The DLP has been used to measure the flow velocity and is consists of a tungsten electrode and an insulating tube (Al_2O_3), which has a small hole (0.7-1.0 [mm] in diameter) on the side surface to collect a directed ion flux normal to the hole opening. The Θ component of flow velocity is obtained by changing the hole (electrode) angle, Θ, and is given by

$$\frac{V}{C_{\mathrm{s}}}\cos\Theta = \alpha\,\frac{I_{\mathrm{is}}(\Theta+\pi)-I_{\mathrm{is}}(\Theta)}{I_{\mathrm{is}}(\Theta+\pi)+I_{\mathrm{is}}(\Theta)}\,, \tag{1}$$

where, V, C_{s} and I_{is} are the ion flow velocity, ion acoustic speed and ion saturation current, respectively. The quantity α is the correction factor, and is usually order unity. When $\alpha = 2$, Eq. (1) is identical to Stangeby's model

(Free Fall model [7]). In this experiment, the four radially-movable DLPs and one axially-movable DLP are installed in the radial and axial ports, and all the DLPs are biased at -90 [V]. The radially-movable DLPs are used to obtain the azimuthal and axial flow velocities, and are located at the axial positions: $z = 1.175,\ 1.400,\ 1.555$ and 1.828 [m] from the microwave injection point. The axially-movable DLP measures the axial and radial flow velocities. Since the correction factor α depends on the probe geometry, we compared an axial flow velocity measured with the axially-movable DLP to that with the radially-movable DLP, and corrected the factor α of axially-movable DLP.

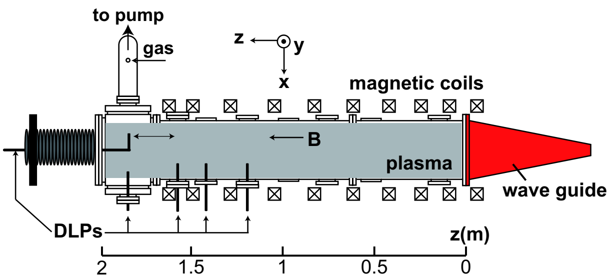

Fig. 1 Schematic diagram of HYPER-I device.

3. Model Equations

We consider one dimensional fluid model for ions to clarify the ion acceleration mechanism along the magnetic filed line. Here, the isentropic process along the flow line is assumed for ions. Under the present experimental conditions, all the collision processes can be neglected, because the mean free path for each collision processes is comparable to the device length. Since the electron temperature is constant along the magnetic field (experimentally confirmed), the electrons are assumed to be isothermal. The steady-state momentum equation is described by

$$\rho_{\mathrm{i}} V_z \frac{dV_z}{dz} = -\frac{dp_{\mathrm{i}}}{dz} + en_{\mathrm{i}} E_z \ , \tag{2}$$

where ρ_{i}, V_z, p_{i} and n_{i} mean the mass density, axial flow velocity, pressure, and density of ions, respectively. The quantities e and E_z are the electric charge and electrostatic field in the axial direction, respectively. The subscription “i” stands for ions. The second term in the right-hand side of Eq. (2) can be rewritten by using the Boltzmann’s relation for electrons and quasi-neutrality condition,

$$eE_z = -\frac{T_e}{n_{\mathrm{i}}} \frac{dn_{\mathrm{i}}}{dz} \ , \tag{3}$$

where T_{e} is the electron temperature expressed by energy unit. Substituting Eq. (3) into Eq. (2), we obtain

$$M\frac{dM}{dz} = -\left(\frac{\kappa(\gamma_{\mathrm{i}}-1)M^2+2}{2}\right)\frac{1}{\rho_{\mathrm{i}}}\frac{d\rho_{\mathrm{i}}}{dz} \ , \tag{4}$$

here,

$$\kappa = \frac{(T_{\mathrm{i}}/T_{\mathrm{e}})}{1+(T_{\mathrm{i}}/T_{\mathrm{e}})} \ . \tag{5}$$

The quantities M and γ_{i} are Mach number with respect to ion acoustic speed and specific heat ratio of ions, respectively. In case of high ion temperature (i.e., $T_{\mathrm{i}}/T_{\mathrm{e}} \gg 1$), Eq. (4) can be easily solved, and its solution is exactly the same as that of neutral gas cases[1, 2]. In other words, the pressure gradient term in Eq. (2) is dominant, and the flow field is determined by the ions only.

In case of low ion temperature (i.e., $T_{\mathrm{i}}/T_{\mathrm{e}} \ll 1$), Eq. (4) can be also solved, and the relation between mass density and ion Mach number is given by

$$\frac{\rho_{\mathrm{i0}}}{\rho_{\mathrm{i}}} = \exp\left(\frac{M^2-1}{2}\right) \ . \tag{6}$$

Here, ρ_{i0} means the mass density at the position where $M = 1$. This formula corresponds that given in Ref. [2], though the electrostatic field term in the momentum balance equation is not considered. When Mach number increases, the mass density decreases to conserve the density flux. In this case, the electric field in Eq. (2) is dominant, and the flow velocity is determined by the electrostatic potential, which is made by the fast moving electrons. When the ion temperature is comparable to the electron temperature, we cannot analytically solve Eq. (2) because κ is generally a function of z. The solution obtained by the numerical method may be different from both the solutions in limiting cases.

We apply the result of low ion temperature case since the electron temperature is much larger than the ion temperature in the present experiment.

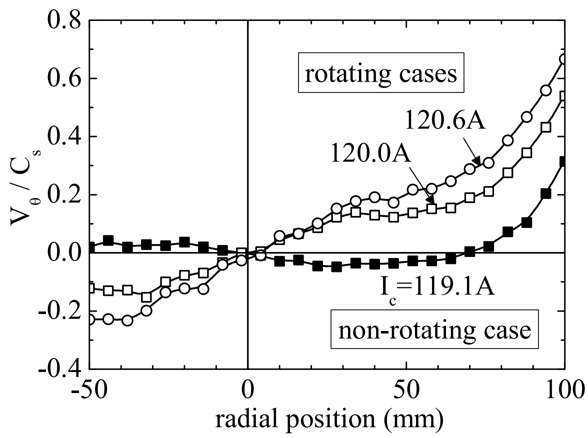

Fig. 2 Radial profiles of azimuthal ion flow velocity. Rotating plasma cases (open symbols) and non-rotating plasma case (closed symbol).

4. Experimental Results

By carefully choosing the magnetic field intensity, an axisymmetric rotating plasma and a non-rotating plasma were obtained at the operational pressure 0.1 mTorr and with the microwave power input of 6 [kW], which are shown in Fig. 2. The data shown in the figure were measured by the radially-movable DLP at $z = 1.175$ [m]. The positive sign of V_θ is counter-clockwise rotation around z-axis (see Fig. 1). Here, we assumed $\alpha = 2$ in Eq. (1). The quantities I_c means the coil current, and is proportional to the magnetic field strength. When $I_c = 119.0$ [A] ($B = 0.869$ [T] at $z = 1.175$ [m]), the ions do not rotate in the region of $r \leq 80$ [mm]. When $I_c = 120.0$ and 121.0 [A], on the other hand, the ions rotate. The velocity profiles exhibit rigid-body rotation at $|x| < 40$ [mm], and there is a velocity shear in the outer region. The radial profiles of density and axial flow velocity are almost flat (not shown in this figure), and there is no noticeable changes in these quantities between the rotating plasma and the non-rotating plasma. Thus, we can examine the effect of rotation on the parallel acceleration without changing other parameters.

Then, we measured the axial profiles of plasma density and axial flow velocity using the axially-movable DLP at $r = 0$ to clarify the ion acceleration mechanism along the field line, which are shown in Fig. 3. We obtained the plasma density by averaging the ion saturation current over the probe angle, and the symbol of the averaging is indicated by bracket of the vertical title in Fig. 3(a). In this experiment, we measured the ion saturation current at $\Theta =$ 0, 90, 180 and 270 degrees. The density monotonically decreases in the axial direction, and the profiles are almost the same for both cases. The axial flow velocity increases in 1.175 [m] $< z <$ 1.6 [m], and saturates at $z >$ 1.6 [m]. In the acceleration region, the axial Mach number (V_z/C_s) exceeds the unity near $z = 1.4$ [m] in both cases. Here, it should be noted that there exists a finite difference in axial flow velocity between the rotating and non-rotating cases. The axial Mach number in the non-rotating plasma case increases more rapidly than that in the rotating plasma case, in the acceleration region. The maximum value of the axial flow velocities are 1.1 and 1.25 for the rotating case and the non-rotating case, respectively.

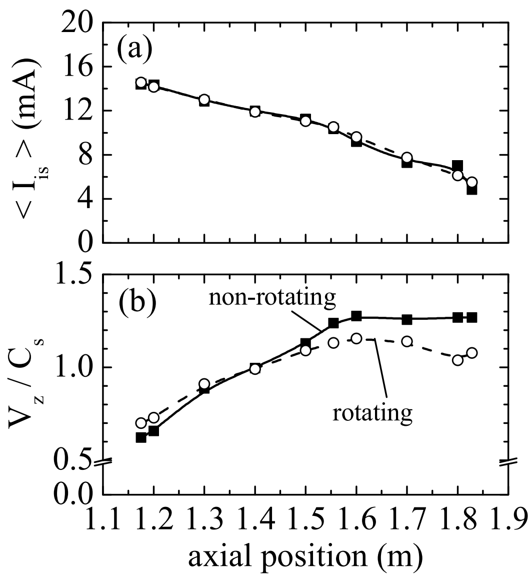

Fig. 3 Axial profiles of the density (a) and the axial flow velocity (b). The square with sold lines is for a rotating plasma case, and the open circle with dashed line is for a non-rotating plasma case.

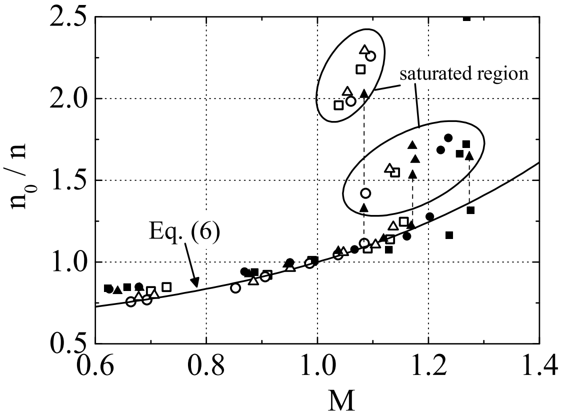

Fig. 4 Density ratio as a function of Mach number. The closed and open symbols mean the non-rotating plasma case and the rotating plasma case, respectively. The data at $r = 0$, 30 and 50 [mm] are presented by squared boxes, circles and triangles, respectively.

Figure 4 shows the comparison of experimental data in accelerating region with Eq. (6) (solid line). The closed and open symbols show the non-rotating plasma and the rotating plasma cases, respectively. The three different symbols mean the data at different radial positions. The quantity n_0 is taken at the position $M = 1$ by interpolating the axial flow velocity in Fig. 3(b). The experimental data show a good agreement with the theoretical result. At the saturation region, the experimental data deviate from the theoretical curve, which will be discussed in the last section.

We also measured the radial profiles of the radial ion flow velocity in the acceleration region using the axially-movable DLP, the results of which are shown in Fig. 5. The discharge condition in this figure is the same as that in the non-rotating plasma case. The shaded regions in the figure mean outflow. As seen in the figure, the radial flow velocity at $z = 1.2$ [m] is virtually zero at all radial positions. In the downstream region ($z >$ 1.4 [m]), the radial flow velocity increases with the axial position (z), and also the each radial profile is proportional to the radius It is interesting to note that when the plasma flow starts expansion ($z \geq$ 1.6 [m]) due to diverging magnetic field, the axial flow velocity saturates.

Here, we introduce two quantities to estimate the effect of rotation on ion acceleration along the magnetic field line. One is the total angular momentum per unit mass, L, and other is the ion acceleration rate along the axial direction, ΔM, which are defined as

$$L \equiv 2\pi \int_0^{r_s} (rV_\theta)\, rdr \,, \tag{7}$$

$$\Delta M \equiv \frac{M_1 - M_0}{\Delta z} \,, \tag{8}$$

where, the quantities r_s is the plasma size under consideration. The quantities M_0 and M_1 are ion Mach number at z_0 and z_1, respectively, and $\Delta z = z_1 - z_0$. Figure 6 shows the acceleration rate as a function of L , where $r_s = 0.08$ [m], $z_0 = 1.175$ [m] and $\Delta z = 0.325$-0.425 [m]. The closed symbols are taken under the same experimental conditions as in Fig. 2, and the rectangles, closed circles and triangles are for $\Delta z = 0.325,\ 0.38$ and 0.425 [m], respectively. The open circles correspond the different experimental conditions with operation gas pressure of 0.2-0.4 [mTorr], microwave input power of 5-10 [kW] and $\Delta z = 0.38$ [m]. It is found in the figure that when the total angular momentum is small (i.e., non-rotating plasma case), the acceleration rate is large. It is also noted that the sign of L does not affect the acceleration rate.

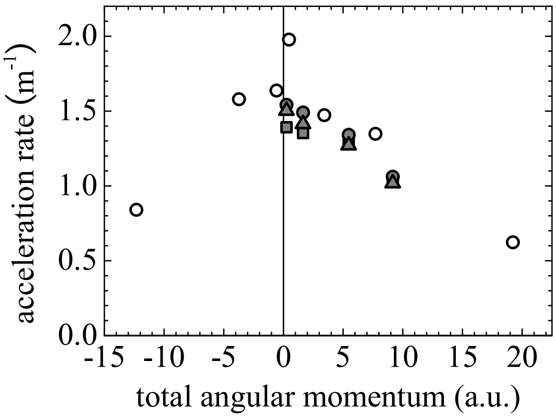

Fig. 6 L dependence of the acceleration rate. The closed and open symbols mean the experimental conditions at 0.1 [mTorr] and 0.2-0.4 [mTorr], respectively.

5. Conclusions

We have measured the radial, azimuthal and axial ion flow velocities using DLPs in a diverging magnetic field, and observed a supersonic ion axial flow accelerated from subsonic regime. The relation between mass density and ion Mach number has been derived from the momentum balance equation to clarify the ion acceleration mechanism along the field line. In the acceleration region, the experimental data well agree with the theoretical result of low ion temperature limit. This indicates that the ions are accelerated by parallel electrostatic field established by the fast moving electrons.

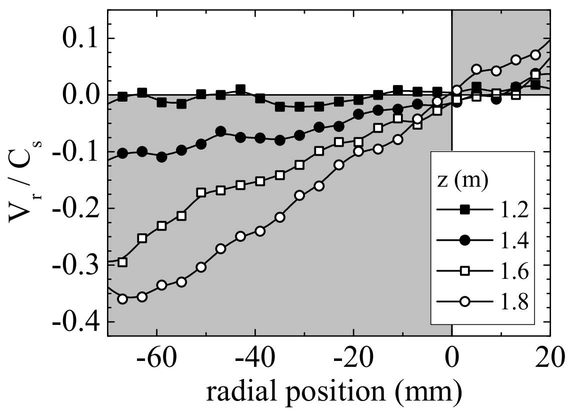

Fig. 5 Radial profiles of radial flow velocity at different axial positions.

In the saturation region, however, the theoretical model does not well describe the experimental data, which may be attributable to the effect of recombination process and neutral backflow near the end wall. To explain the acceleration mechanism near the end wall region, the model equation should be modified so as to include the effect of collisions, which is left for future works. We have also measured the radial ion flow velocity, and found that it increases in the saturation region.

The behavior of axial ion flow velocity is different between the rotating plasma and the non-rotating plasma. To estimate the effect of rotation on ion acceleration, we introduce the total angular momentum per unit mass and ion acceleration rate along the axial direction. Under the various discharge conditions, we have obtained the relation between two quantities. It is found that the acceleration rate becomes maximum for the non-rotating case, and linearly decreases with increasing the total angular momentum. This may cause deceleration of ions along the field even in a diverging magnetic field. It may be concluded that control of plasma rotation is an important issue to efficiently accelerate the ions. Further understanding of the effect of rotation on the plasma acceleration is left for future work.

Acknowledgment

This work is supported by collaboration program at NIFS (NIFS06KOAP016). The authors would like to thank ECW group for useful comments.

[1] D. S. Andersen, V. O. Jensen, P. Nielsen and N. D'Angelo, Phys. Fluids **12**, 557 (1968).
[2] M. Inutake, A. Ando, K. Hattori, H. Hiroyuki and T. Yagai, J. Plasma Fusion Res. **78**, 1352 (2002).
[3] K. Itoh, S. -I. Itoh, N. Yokoi and A. Yoshizawa, J. Phys. Soc. Jpn. **72**, 2781 (2003).
[4] N. Yokoi, A. Yoshizawa, K. Itoh and S. -I. Itoh, Phys. Fluids **16**, 1186 (2004).

[5] K. Nagaoka, A. Okamoto, S. Yoshimura and M. Y. Tanaka, J. Phys. Soc. Jpn. **70**, 131 (2001).
[6] M. Y. Tanaka, M. Bacal, M. Sasao and T. Kuroda, Rev. Sci. Instrum. **69**, 980 (1998).
[7] P. C. Stangeby, Phys. Fluids **27**, 2699 (1984).