24P140-P

Experimental Studies on Ion Stream Line Detachment and Onset of Azimuthal Rotation in a Diverging Magnetic Field
イオン流線のディタッチメントに伴う回転流の駆動と電磁場の運動量

Kenichiro Terasaka[1], Shinji Yoshimura[2], Mitsutoshi Aramaki[3], Hirotsugu Katanami[1], and Masayoshi Y. Tanaka[1]
寺坂 健一郎[1], 吉村 信次[2], 荒巻 光利[3], 片波 寛嗣[1], 田中 雅慶[1]

[1]*Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan*
九州大学 〒816-8580 福岡県春日市春日公園6-1
[2]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*
核融合科学研究所 〒509-5292 岐阜県土岐市下石町322-6
[3]*Nagoya University, Furu-cho, Chikusa, Nagoya 464-8603, Japan*
名古屋大学 〒464-8603 名古屋市千種布留町

The ion flow velocity in a diverging magnetic field has been measured with the calibrated directional Langmuir probe in an electron cyclotron resonance plasma. The ions are unidirectionally accelerated by the ambipolar electric field along with the magnetic field line in the weak diverging magnetic field region. When the effect of field-inhomogeneity is not negligible in the ion motion, the ion stream line detachment takes place and the plasma starts the azimuthal $\boldsymbol{E} \times \boldsymbol{B}$ rotation generated by the difference of motions between the magnetized electrons and the detached ions.

1. Introduction

Recently, plasma detachment from the magnetic field line is considered to be important in plasma propulsion research works. The control of plasma detachment is required for the development of plasma thrusters applying the external magnetic field, because the plasma return to the main body along with the magnetic field line even though the plasma is exhausted from an end of the thrusters. Then, many theoretical and numerical studies to optimize the plasma ejection have been performed.

The ion stream line detachment takes place when an adiabaticity of ions is not conserved along the stream line. Hooper suggested that the electric field is generated to avoid the charge-separation [1], since the location where the detachment takes place differs between the electrons and the ions due to the difference of each mass. In the detachment region, the angular momentum of the magnetic field also plays an important role in the structure formation of plasma flows perpendicular and parallel to the magnetic field line. However, the generation of the electric field and the effect of the angular momentum of electromagnetic field on the plasma flow structure formation in the detachment region have not been understood, so far.

In our previous experiment with a linear electron cyclotron resonance (ECR) plasma, we observed that the ion stream line detachment takes place when the non-adiabaticity of ions becomes to unity [2]. To understand the effect of electrostatic and electromagnetic fields on the plasma flow field in the detachment region, we have experimentally studied the structure formations of the ion flow velocity field and the electric field in a diverging magnetic field.

2. Experimental Setup

The experiments have been performed in high density plasma experiment-I device (HYPER-I [3]) at the National Institute for Fusion Science. Figure 1(a) shows a schematic of the HYPER-I device. The HYPER-I device consists a cylindrical vacuum vessel (0.3 m in inner diameter and 2.0 m in axial

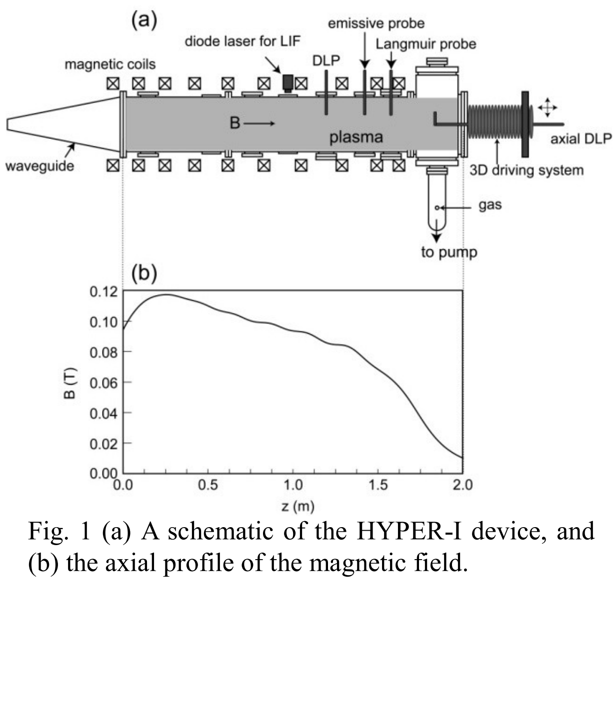

Fig. 1 (a) A schematic of the HYPER-I device, and (b) the axial profile of the magnetic field.

length). We adopted a diverging magnetic field configuration in this experiment as shown in Fig. 1(b). A steady-state argon plasma was produced by ECR heating with a 2.45 GHz microwave. The argon gas pressure and the input microwave power were set to 0.1 mTorr and 6 kW, respectively. The typical electron density and electron temperature are 10^{17} m^{-3} and 7.5 eV, respectively.

We measured the ion flow velocity with directional Langmuir probe (DLP [4]). To obtain the absolute ion flow velocity, we experimentally calibrated the DLP with a laser induced fluorescence (LIF) Doppler spectroscopy, and the calibration factor was evaluated as 1.1 ± 0.1 in this plasma [5]. An axially movable DLP was mounted on the 3-dimensional driving system, and was inserted from an end port of the device.

3. Experimental Results

Figure 2(a) shows the axial profile of the electrostatic potential normalized by the electron temperature ($e\phi/k_\mathrm{B}T_\mathrm{e}$), where, ϕ, e, k_B, and T_e are the electrostatic potential, elementary charge, the Boltzmann's constant, and the electron temperature, respectively. The normalized electron density ($\ln n$) is also shown with a solid line. In the upstream region $z < 1.6$ m, the Boltzmann's relation is well satisfied, and the ambipolar electric field along the magnetic field line is generated. In the downstream region $z \geq 1.6$ m in which the ion stream line detachment takes place, the potential decrease is less than that in density. This indicates that the ion fluid does not move along the magnetic field line as the electron fluid.

Figure 2(b) shows the axial ion flow velocity measured with the axially movable DLP. A dashed line shows the one dimensional Bernoulli's relation considering the ambipolar electric field. The electric field is evaluated from the electrostatic potential data shown in Fig.2(a). The experimental data show a good agreement with the theoretical prediction, and it is clear that the ions are axially accelerated by the ambipolar electric field.

We also show the axial profile of the azimuthal ion flow velocity at a radial position of 50 mm in Fig. 2(c). It is found that a rigid-body-like azimuthal rotation is generated in the region $z \geq 1.4$ m. From the comparison with the radial profiles of the flow velocity and the potential, this rotation is explained by the $\boldsymbol{E} \times \boldsymbol{B}$ drift, which is generated by the radial electric field and the external magnetic field. This result implies that the ions do not expand with the diverging magnetic field line to conserve its angular momentum in the detachment region.

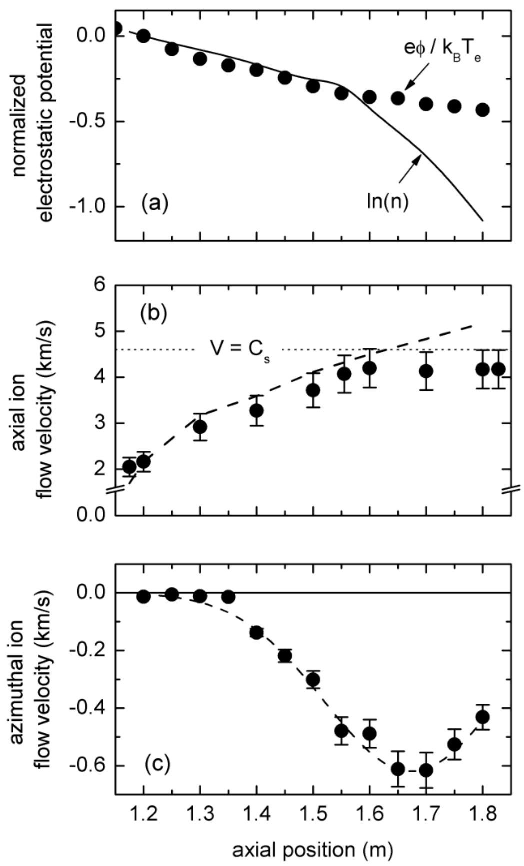

Fig. 2: Axial profiles of (a) the normalized electrostatic potential, (b) the axial ion flow velocity, and (c) the azimuthal ion flow velocity.

4. Conclusions

We have experimentally studied the ion flow velocity field of an ECR plasma in a diverging magnetic field. When inhomogeneity of the magnetic field is weak, the ions are accelerated by the ambipolar electric field generated along the magnetic field line. In the lower magnetic field region in which the ion stream line detachment takes place, it is found that an azimuthal $\boldsymbol{E} \times \boldsymbol{B}$ rotation is generated. The radial electric field is generated due to the difference of motions between the magnetized electrons and the detached ions. These results indicate that the ions are likely to flow straight to conserve the angular momentum in the detachment region.

References

[1] E.B. Hooper, J. Propul. Power **9** (1993) 757.

[2] K. Terasaka, S. Yoshimura, K. Ogiwara, M. Aramaki, and M.Y. Tanaka: Phys. Plasmas **17** (2010) 072106.

[3] M.Y. Tanaka, M. Bacal, M. Sasao, and T. Kuroda: Rev. Sci. Instrum. **69** (1998) 980.

[4] K. Nagaoka, A. Okamoto, S. Yoshimura, and M.Y. Tanaka: J. Phys. Soc. Jpn. **70** (2001) 131.

[5] K. Terasaka *et al.*: Jpn. J. Appl. Phys. **49** (2010) 036101.