§2. Studies on Ion Acceleration and Stream Line Detachment in the HYPER-I Device

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Plasma flow in an inhomogeneous magnetic field plays an important role in various research fields, for example the development of plasma propulsion systems. Commonly "magnetic nozzle effect" is considered to produce a fast ion flow,[1] however, it is still uncertain whether electrostatic acceleration is effective for ion acceleration, in spite of the existence of the electric field in an inhomogeneous plasma. For realizing and controlling the fast 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. Although some detachment scenarios have been proposed so far,[2] the experimental evidence has not been reported yet because of the difficulty of experiments. To clarify the ion flow structure in an inhomogeneous plasma, we are carrying out ion flow measurement.

Experiments have been performed in the HYPER-I device at the National Institute for Fusion Science. An argon plasma was produced by electron cyclotron resonance with a 2.45 GHz microwave. We measured the ion flow velocity using the directional Langmuir probes (DLPs), which were calibrated by the laser induced fluorescence spectroscopy.[3]

Figure 1 shows the axial profile of the ion Mach number measured with the DLP (circle). Two lines indicate the theoretical predictions by Bernoulli's relation calculated from the experimental results of the electron density and the potential. The data clearly shows that the electrostatic acceleration of ions is not negligible compared with the gas dynamic acceleration in $z < 1.5$ m, and the maximum ion Mach number is $V_i/C_s = 0.9$, which corresponds to the ion flow velocity of 4.2 km/s. In addition, the flow velocity almost saturates in $z > 1.6$ m.

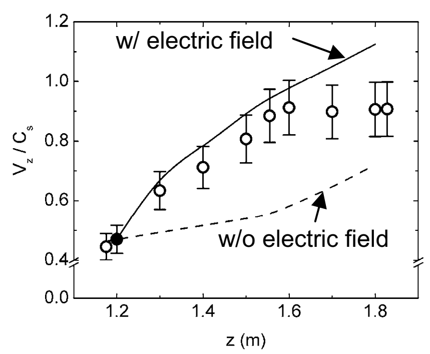

Fig. 1 Axial profiles of the ion Mach number. The experimental data are shown by open circles. A solid and a dashed lines show the theoretical predictions with and without the ambipolar electric field, respectively.

We also measure each component of the ion flow. Figure 2(a) shows a comparison between the measured ion flow velocity (arrow) and the magnetic field line (solid line) on a radial-axial plane. In the region $z < 1.5$ m, the ions flow along the magnetic field line. In the region $z > 1.6$ m, the stream lines clearly deviate from the magnetic field line, i.e., stream line detachment takes place.[4] In addition, the non-adiabaticity for the ions becomes order unity in the detachment observed region.

Figure 2(b) shows a contour map of the azimuthal flow velocity on the radial-axial plane. The azimuthal rotation is induced in the region $z > 1.5$ m (detachment observed region) and is the $\boldsymbol{E} \times \boldsymbol{B}$ drift due to the radial electric field. It is considered that this rotation is driven by the difference in motion between the magnetized electrons and unmagnetized ions.

We have studied the ion flow velocity field of an ECR plasma in a diverging magnetic field. The flow velocity field has been obtained with the calibrated DLPs and the evidence of the electrostatic acceleration is obtained. The detachment of ion stream line from the magnetic field line also experimentally measured for the first time. It is concluded that the ion detachment takes place when the non-adiabaticity becomes order unity.

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2. K. Sankaran and K. A. Polzin, Proc. *38th AIAA Plasma dynamics* (Miami, 2007), 4386.
3. K. Terasaka *et al.*, Jpn J. Appl. Phys. **49**, 036101 (2009).
4. K. Terasaka *et al.*, Phys. Plasmas, in press.

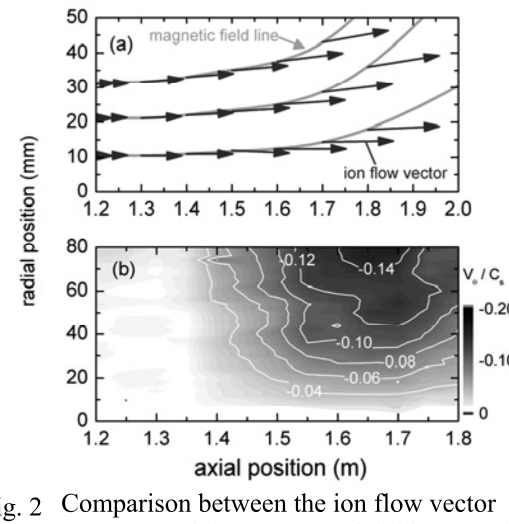

Fig. 2 Comparison between the ion flow vector (arrows) and the magnetic field line (solid lines), and (b) contour map of the azimuthal ion Mach number.