§6. Spatial Structures of Ion Flow and Electric Fields in a Diverging Magnetic Field

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It has been well known that the electrostatic and hydrodynamic plasma accelerations take place in a non-uniform magnetic field region. When the electron temperature is much higher than the ion temperature, the electrostatic acceleration is dominant. It is crucial that the flow structure is characterized only by the configuration of the magnetic field line.

The accelerated ions in the strong and weakly-diverging magnetic field region flow toward the weaker and more diverging magnetic field region. In this region, the non-uniformity of the magnetic field becomes important for the ion gyro motion, and the ion detachment from the magnetic field line takes place. Note that the electron still strongly magnetized in this region because of its small mass. From this difference of motion between the ions and the electrons, it has been considered that the flow structure in the detachment region is different from that in the magnetized region. However, the experimental studies have not been performed, so far. To clarify the flow structure formation in the detachment region, we have measured the ion flow velocity and the plasma potential in a diverging magnetic field.

Experiments were performed in the HYPER-I device at the National Institute for Fusion Science. A steady-state electron cyclotron resonance plasma was produced with a 2.45 GHz microwave. An argon gas was used, and the gas pressure was set to 0.1 mTorr. The typical electron density and temperature are 10^{17} m^{-3} and 7.5 eV, respectively. In this plasma, the mean free path of ion-neutral collision is comparable with the device length. We adopted a diverging magnetic field configuration, and the scale length of the magnetic field variation ($L_B = |\nabla B/B|^{-1}$) in the measuring region is 0.2-5 m. A directional Langmuir probe (DLP) was used to measure the ion Mach number. The DLP is calibrated by a laser induced fluorescence Doppler spectroscopy with a tunable diode laser, and thus, we can also evaluate the absolute ion flow velocity.

Figure 1(a) shows a comparison between the ion flow velocity (arrows) and the magnetic field line (solid lines). The magnetic field strength is also shown by gray scale gradation.[1] The ions flow along the magnetic field line in the region $z \leq 1.4$ m, where z denotes the axial position. The length of arrow is proportional to the ion flow velocity, and the ion flow velocity increases from 1.9 km/s at $z = 1.2$ m to 4.2 km/s at $z = 1.6$ m. From the electrostatic potential measurement, it is found that the ions are accelerated by the ambipolar electric field parallel to the magnetic field line.

It is found that the ion stream line separates from the magnetic field line in the region $z \geq 1.5$ m. In this region, the non-adiabaticity of ion, $|f_{\mathrm{ci}} L_B/V_{\mathrm{i}z}|$, becomes order of unity, where f_{ci} and $V_{\mathrm{i}z}$ are the ion cyclotron frequency and the ion flow velocity parallel to the magnetic field, respectively. In this plasma, the observed stream line detachment is non-adiabatic detachment, since the ion-neutral collision mean free path is longer than the device length and the plasma kinetic beta value is much smaller than the unity.

Figure 1(b), (c) and (d) show the flow structure on the plasma cross section (x-y plane) at $z = 1.2$, 1.4, and 1.6 m. The azimuthal plasma rotation is generated in the detachment region ($z \geq 1.5$ m) although the plasma does not rotate in the magnetized region ($z < 1.4$ m). The radial profile of azimuthal rotation is the rigid-body-like, and its angular velocity increases in the axial direction. From the electrostatic potential measurement with an emissive probe inserted at $z = 1.4$ m, this rotation is driven by the $\boldsymbol{E} \times \boldsymbol{B}$ drift ($V_{\mathrm{i}\theta} = -E_r/B_z$), where $\boldsymbol{E}$ is the electric field. The direction of the rotation is ion diamagnetic direction, but the variation of the external magnetic field due to the diamagnetic current can be neglected in this case.

We have measured the ion flow velocity in a diverging magnetic field. The flow structure in the detachment region is clearly different from that in the magnetized region. The plasma starts to rotate in the detachment region. In the detachment region, the perpendicular electric field is important for the flow structure formation, and the further experiments will be performed to clarify the structure formation of both the flow and the electric field in our future work.

1) K. Terasaka et al. : IEEE Trans. Plasma Sci. **39** (2011) 2470.

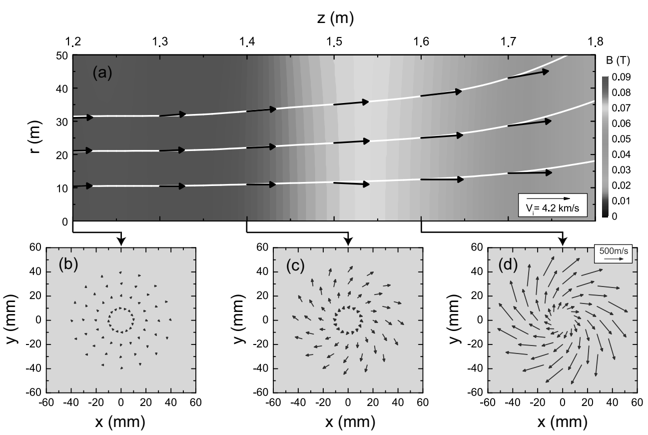

Fig. 1: (a) A comparison between the ion stream lines (arrows) and the magnetic field lines (solid lines). The magnetic field strength is shown by gray scale. The ion flow structures on x-y plane at $z = 1.2$, 1.4, 1.6 m are shown in (b), (c) and (d).