§1. Ion Heating and Acceleration in a Fast-flowing Plasma

Ando, A., Hattori, K., Inutake, M., Kasashima, Y.,
Hagiwara, T. (Dept. Electrical Eng. Tohoku Univ.)

Recently a plasma flow has been recognized to play an important role in space and fusion plasmas. Intensive researches to develop fast flowing plasma with high particle and heat fluxes are required for the purpose of basic plasma researches as well as various wall material researches and space applications.

Ion heating and magnetic nozzle acceleration in a fast-flowing plasma attracts much attention in an advanced electric propulsion system. In the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project, it is proposed to control a ratio of specific impulse to thrust at constant power.[1)] This is a combined system of an ion cyclotron heating and a magnetic nozzle, where a flowing plasma is heated by ICRF (ion cyclotron range of frequency) power and the plasma thermal energy is converted to flow energy by passing through a magnetic nozzle.

The purpose of this research is to investigate an ion heating and acceleration phenomena in a fast-flowing plasma for the advanced plasma thruster and other applications.

We have successfully demonstrated the ion heating and acceleration in a magnetic nozzle using helium gas in the HITOP device.[2)-4)] RF waves in the frequency range of 100kHz to 500kHz were launched by the right-hand helically wound antenna set at Z=0.6m downstream of the magneto-plasma-dynamic arcjet (MPDA). The increased thermal energy was converted to flow energy by passing through the diverging magnetic nozzle as illustrated in Fig.1. We have evaluated the effect of energy conversion in the magnetic nozzle by measuring the perpendicular and parallel component of ion temperature to the plasma flow. Electrostatic energy analyzers (EEAs) are set at Z=2.33m and Z=3.13m to measure ion energy distribution and ion temperature $T_{i\perp}$ and $T_{i//}$. Here, the suffix $\perp$ and // indicate perpendicular and parallel components to the axial magnetic field, respectively. Figure 2 shows $T_{i//}$ obtained at Z=3.13m in the three different magnetic nozzle shown in Fig.1. As the diverging angle becomes larger, $T_{i//}$ increases more rapidly. It is also confirmed that $T_{i\perp}$ varied so as to keep the magnetic moment constant. These data shows that the exhaust energy can be controlled by the shaping of the magnetic nozzle as well as the control of input RF power.

In order to obtain higher exhaust ion velocity, experiments using hydrogen gas were performed. The frequency of RF waves was raised up to 1MHz with the power of 10kW. The increase of plasma thermal energy $W_\perp$ was measured by a diamagnetic coil. Figure3 shows dependences of increment ratio of $\Delta W_\perp/W_\perp$ on the magnetic field B_D for different RF frequencies f_{RF}. B_D corresponding to ω/ω_{ci}=1 for each f_{RF} are indicated as solid lines in the figure. $\Delta W_\perp/W_\perp$ became large in the region of B_D slightly lower than the resonance field of ω/ω_{ci}=1, which corresponds to the Doppler effect caused by fast-flowing ions. The increment of $W_\perp$ was, however, observed in broader B_D field than that in the helium plasma. Energy conversion from $W_\perp$ to $W_{//}$ in a diverging magnetic nozzle was also confirmed in the hydrogen plasma. $T_{i//}$ attains to more than 50eV after the nozzle, which corresponds to the exhaust ion velocity of more than 100km/s.

References
1) F.R.ChangDiaz, et al., Proc. of 36th Joint Propulsion Conf., (Huntsville,2000), AIAA-2000-3756.
2) A.Ando, et.al., Physics of Plasmas, **13**, (2006) 057103.
3) M. Inutake, et.al., Plasma Phys. Cont. Fusion, **49**, (2007) A121.
4) A.Ando, et.al., Transaction of Fusion Science and Technology, **51**, (2007) 72.

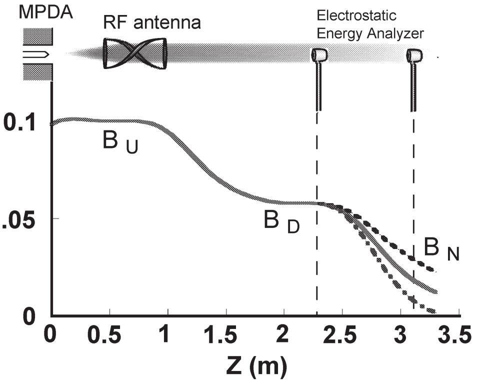

Fig. 1 Magnetic field configurations and locations of the helical antenna and the electrostatic energy analyzer (Faraday Cup).

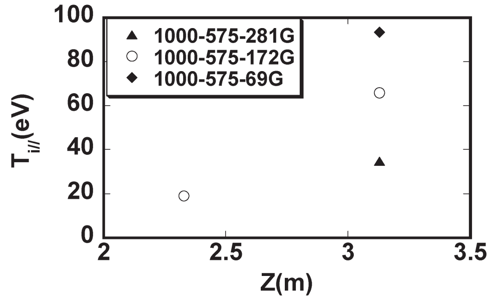

Fig. 2 Axial profile of $T_{i//}$ in three magnetic nozzle configurations.

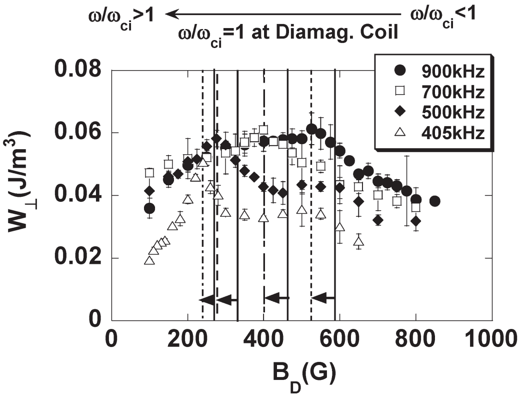

Fig. 3 Dependence of $\Delta W_\perp/W_\perp$ on B_D.
H plasma.