§4. Ion Heating in a Supersonic Plasma Flowing Through a Magnetic Nozzle

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Recently a plasma flow has been recognized to play an important role in space and fusion plasmas. Intensive researches to develop a 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.

A magnetic nozzle acceleration and ion heating 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 via a magnetic nozzle.

The purpose of this research is to investigate effective methods of wave excitation and to establish an ion heating technology in a fast flowing plasma for the advanced plasma thruster and other applications.

We have performed an ion heating experiment in a supersonic plasma flow produced in the HITOP device.[2,3] RF waves are launched by a right-handed helically-wound antenna in a helium plasma. This antenna is set at Z=0.6m downstream of the Magneto-Plasma-dynamic Arcjet (MPDA) and excite RF waves with an azimuthal mode number of m= -1. The RF frequency can be changed from 100kHz to 500kHz with an input power up to 15kW.

When RF waves excited in a flowing plasma with a density around 1×10^{13}cm^{-3}, we observed an increase of plasma stored energy $W_\perp$ measured by a diamagnetic coil located at Z=2.23m downstream from the MPDA. Ion temperature T_i also increased during the RF pulse. However, no clear indication of the cyclotron resonance is observed, because the ion-ion collision frequency ν_{ii} is larger than the ion cyclotron frequency f_{ci} in the high density region and the waves are damped not by cyclotron resonance but by collisional damping. We decreased a plasma density from 1×10^{13}cm^{-3} to 5×10^{11}cm^{-3} so that the cyclotron heating phenomena appeared and a diamagnetic coil signal $W_\perp$ increases drastically as shown in Fig.1. It is also observed that the peak position is shifted to lower magnetic field than that corresponding to ω/ω_{ci}=1, i.e. ω/ω_{ci} higher than 1. This is due to the Doppler effect caused by the fast plasma flow.[4]

Figure 2 shows a dependence of $W_\perp$ on the RF input power P_{RF}. It linearly increases with P_{RF}. We have also measured ion temperature by an electrostatic energy analyzer, of which collection surface faces to perpendicular direction to the plasma flow. The perpendicular component of ion temperature $T_{i\perp}$ can be obtained. When P_{RF} increases, $T_{i\perp}$ increases almost linearly as shown in Fig.3. Experimental researches on the energy conversion from thermal energy to flow energy by a magnetic nozzle should be pursued further.

Reference
1) F.R.ChangDiaz, et al.: Proc. of 36th Joint Propulsion Conf., (Huntsville,2000), AIAA-2000-3756.
2) M.Inutake, et al.: Proc. of 26th ICPIG, Vol.**1**, (2003). p.127.
3) A.Ando, et al.: Advances in Applied Plasma Science, **4** (2003) 193.
4) A.Ando, et al.: Proc. the 7th APCPST, (Fukuoka, 2004), **A2** (2004) 45.

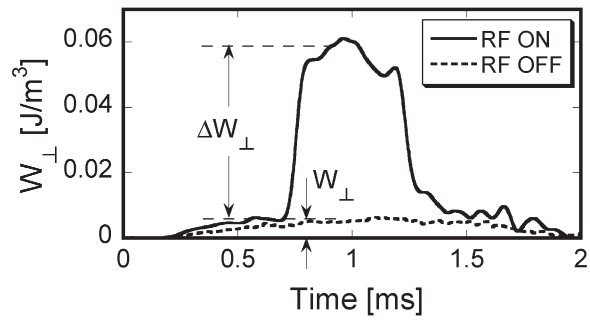

Fig.1 Time evolutions of diamagnetic coil signal $W_\perp$. f_{RF}=236kHz, P_{RF}=15kW.

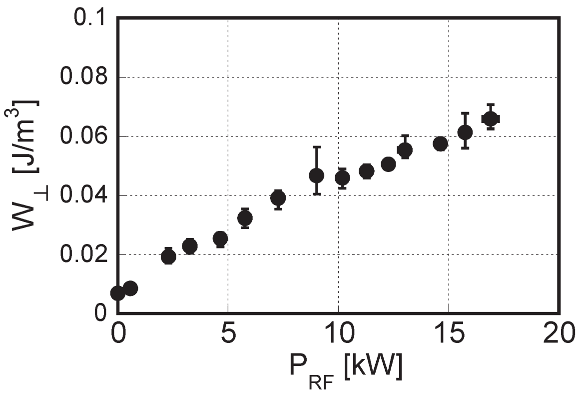

Fig.2 Dependence of diamagnetic coil signal $W_\perp$ on input RF power P_{RF}. f_{RF}=236kHz.

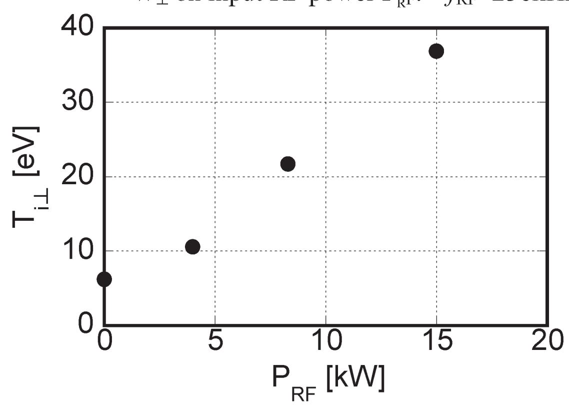

Fig.3 Dependence of perpendicular component of ion temperature $T_{i\perp}$ on input RF power P_{RF}. f_{RF}=236kHz.