Demonstration of Ion Heating and Acceleration in a Fast-flowing Plasma for the VASIMR Thruster

IEPC-2005-29

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

A.Ando[*], M.Inutake[†], K.Hattori[‡], H.Tobari[§], M.Hatanaka[**], and M.Shibata[††]

Department of Electrical Engineering, Graduate School of Engineering, Tohoku University
6-6-05, Aoba-yama, Sendai, 980-8579, Japan

Abstract: Experiments of both ion cyclotron resonance heating and acceleration in a magnetic nozzle are performed in a fast-flowing plasma in the HITOP device in order to investigate an advanced space propulsion such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) thruster. Radio frequency (RF) waves with an ion cyclotron range of frequency are excited by a helically-wound antenna in a fast flowing plasma produced by a magneto-plasma-dynamic thruster (MPDT). Dispersion relations of the propagating waves are measured and compared with theoretical ones. When RF power is launched by the helical antenna, a plasma thermal energy $W_\perp$ and an ion temperature T_i drastically increase during the RF pulse. This large increase is observed under low density condition, where a ratio of ion cyclotron frequency to ion-ion collision one becomes high. The value of resonance magnetic field is affected by the Doppler shift due to the fast-flowing plasma. Ion acceleration along the field line is also observed in a diverging magnetic nozzle. Perpendicular component to the magnetic field of ion energy decreases, whereas parallel component increases along the diverging magnetic field.

Nomenclature

I_d	=	discharge current
J_r	=	radial component of current density
B_z	=	axial component of magnetic field
B_θ	=	azimuthal component of magnetic field
B_U	=	magnetic field in upstream region
B_D	=	magnetic field in downstream region
P_{RF}	=	input RF power
ω	=	angular frequency of excited wave
ω_{ci}	=	angular frequency of ion cyclotron motion
m	=	azimuthal mode number of excited wave
$W_\perp$	=	perpendicular component of plasma thermal energy
$W_{//}$	=	parallel component of plasma thermal energy
Z	=	axial position
M_i	=	ion acoustic Mach number
M_A	=	Alfvén Mach number
T_i	=	ion temperature
T_e	=	electron temperature
n_e	=	number density of electron
μ	=	magnetic moment

[*] Associate Professor, Department of Electrical Engineering, akira@ecei.tohoku.ac.jp.
[†] Professor, Department of Electrical Engineering, inutake@ecei.tohoku.ac.jp.
[‡] Researcher, Department of Electrical Engineering, hattori@ecei.tohoku.ac.jp.
[§] Researcher, Department of Electrical Engineering, tobari@ecei.tohoku.ac.jp.
[**] Graduate student, Department of Electrical Engineering, hatanaka@ecei.tohoku.ac.jp.
[††] Graduate student, Department of Electrical Engineering, shibata@ecei.tohoku.ac.jp

I. Introduction

AN electric propulsion system is one of the key elements in future space exploration projects and has been developed for various space missions.[1,2] Development of a high power-density plasma thruster with a higher specific impulse and a larger thrust is prerequisite for a manned interplanetary space thruster.

One feature of the advanced space propulsion system is the ability to vary its specific impulse so that it can be operated in a mode with suitable propellant utilization and thrust performance. The ability to control a ratio of specific impulse to thrust at constant power will allow for optimum low thrust interplanetary trajectories and results in shorter trip times than that in a fixed specific impulse system.

According to this scenario the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) has been proposed and under development in NASA.[3,4] The rocket provides a helicon plasma source and a combined system of ion cyclotron heating and magnetic nozzle, where a flowing plasma is heated by ICRF (ion cyclotron range of frequency) heating and plasma thermal energy is converted to flow energy in the diverging magnetic nozzle. Then, the magnetic nozzle effect and ICRF heating in a fast flowing plasma are two key issues for the development of the advanced space thruster.

Plasma acceleration in a divergent magnetic nozzle has been successfully demonstrated in the HITOP device using a magneto-plasma-dynamic thruster (MPDT). An MPDT is one of the representative devices for a space thruster and is also utilized as a source of supersonic plasma flow. The plasma produced in an MPDT is accelerated by Lorentz force $J_r \times B_\theta$, where J_r is a radial component of a discharge current and B_θ is an azimuthal component of self-induced magnetic field.[1,5] An ion acoustic Mach number M_i of the exhausted plasma, which is defined as a ratio of plasma flow velocity to ion acoustic one, is observed to be nearly unity.[6] In an externally-applied divergent magnetic nozzle configuration, a supersonic plasma flow with M_i up to 3 has been obtained in the far downstream region of the MPDT, where no $J_r \times B_\theta$ acceleration is exerted.[7] It is also demonstrated that a subsonic plasma flow exhausted from the MPDT is converted into a supersonic one (M_i increases more than unity) through a Laval-type magnetic nozzle attached in front of the MPDT muzzle.[8-11]

To establish the VASIMR thruster, ion heating of a flowing plasma by using radio-frequency(RF) waves is inevitable. Though ion heating in a magnetically-confined plasma has been precisely investigated both theoretically and experimentally in many researches, few attempt of direct ion heating for fast flowing plasmas by RF waves has been done. Ion heating in a fast flowing plasma might be difficult partly because of short transit time for ions to pass through a heating region only once, and partly because of modification of ion cyclotron resonance due to the effect of Doppler shift. So far, only a few of bulk-ion-heating by RF waves have been observed, because ions pass quickly through the resonance region only once and also a charge-exchange energy loss by neutral gas deteriorates the heating evidence in a thin plasma.

We performed an ion heating experiment in a supersonic plasma flow for the first time in the HITOP device with a pair of loop-type antennas.[8,12] It is found that plasma thermal energy measured by a diamagnetic loop coil increases when RF waves are launched with a non-axisymmetric azimuthal mode (m=±1) with a magnetic-beach heating configuration. As we utilized a pulsed MPDT as a plasma source, the charge-exchange effect of neutral gas does not serious compared with a steady helicon plasma source.

In this research we used a helically-wound antenna to excite RF waves more efficiently than the loop-type ones, and performed ICRF heating experiments in the fast flowing plasma. Plasma acceleration in a diverging magnetic nozzle was also successfully demonstrated in the HITOP device. Experiments of both ICRF heating and magnetic nozzle acceleration to demonstrate the VASIMR thruster operation are reported in this paper.

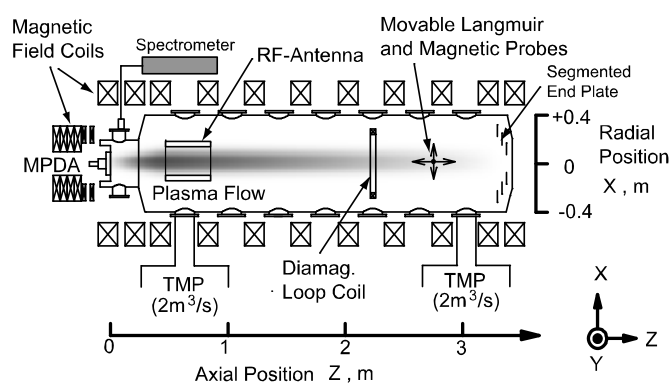

Figure 1. Schematic view of the HITOP device.

II. Experimental Apparatus

A. HITOP device

Experiments are carried out in the HITOP device of Tohoku University. It consists of a large cylindrical vacuum chamber (diameter D = 0.8m, length L = 3.3m) with eleven main and six auxiliary magnetic coils, which generate a uniform magnetic field up to 1kG, as shown in Fig.1. Various types of magnetic field configuration can be formed by adjusting an external coil current. A high power, quasi-steady MPDT is installed at one end-port of the HITOP as a source of a fast flowing plasma. It has a coaxial structure with a center tungsten rod cathode (10mm in diameter) and an annular molybdenum anode (30mm in diameter). A discharge current I_d up to 10kA is supplied by a pulse-forming network (PFN) system with the quasi-steady duration of 1ms. The current I_d is kept nearly constant during a discharge with a typical voltage of 200V-300V and can be controlled by varying a charging voltage of capacitor banks of the PFN power-supply. It can generate a high density (more than $10^{20}m^{-3}$) and a fast-flowing plasma with M_i up to 3 in an axial magnetic field B_z up to 1kG. Helium and argon gases are used as a working gas in the experiments.

Plasma flow characteristics are measured by several diagnostics installed on the HITOP device. Electron temperature T_e and density n_e profiles are measured by a movable triple probe and a fast-voltage-scanning Langmuir probe. Ion temperature T_i is measured by an electrostatic energy analyzer. Plasma thermal energy is measured by a diamagnetic loop coil located at Z=2.23m. A plasma flow is characterized by an ion acoustic Mach number M_i which is defined as a ratio of the plasma flow velocity to ion acoustic velocity. Profiles of M_i and plasma density along and across the field lines are measured by a movable Mach probe[13] and an array of 13-channel Mach probes set at 1.7m downstream of the MPDT outlet in the HITOP. Magnetic field variation is measured by magnetic probes.

B. Helical antenna and RF power source

We prepared two types of helically-wound antennas to excite RF waves in the plasma. Figure 2 shows schematic view of a half-turn helically-wound antenna with 160mm in diameter. There are two winding directions of a conductor. One is a right-handed helical winding, clockwise along the B_z field, which is called a right helical antenna. The other is a left-handed one, which is called a left helical antenna, hereinafter. These antennas are expected to excite RF waves in the direction downstream of the antenna preferentially with azimuthal mode numbers of m=-1 and +1, respectively.[14] One of the antennas is set at Z=0.6m downstream of the MPDT. An antenna current is supplied by inverter-type power-supplies operated with a pulsed mode as shown in Fig.3. We can change oscillation frequency of the sources by controlling an external oscillator. One of the RF sources can excite an oscillating current with a frequency from 20kHz to 160kHz and is used to measure wave propagation in a flowing plasma. The other one can excite RF power up to 15kW with a frequency from 100kHz to 400kHz and is used mainly for an ion heating.

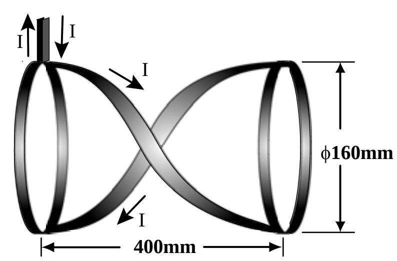

Figure 2. Schematic of the right helical antenna.

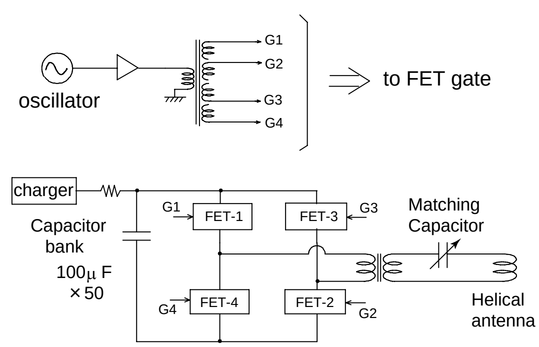

Figure 3. Electric circuit diagram of the RF power supply.

III. Experimental Results

A. Wave excitation and dispersion relations

In order to identify propagating RF waves we measured wave amplitudes and phase shifts by magnetic probes in a downstream region. Wavelength was obtained from a phase difference between two magnetic probe signals set at Z= 1.03m and 1.43m.

Dispersion relations of the waves excited by the two types of antenna were obtained experimentally in a uniform magnetic field configuration. The right helical antenna tends to excite RF wave propagating downstream with a non-axisymmetric azimuthal mode of m=-1, which corresponds to a slow wave, a shear Alfvén wave, in a low frequency region. The left helical antenna, on the other hand, tends to excite RF wave propagating downstream with m=+1, which corresponds to a fast wave, a compressional Alfvén wave.

The Alfvén wave is a typical low-frequency wave propagating along a magnetic field line. The shear Alfvén wave is a left-handed circularly polarized wave and also called an ion cyclotron wave near $\omega/\omega_{ci} = 1$, because thermal ions resonate with the wave and are heated by absorbing the wave energy.[15]

Figure 4 shows dispersion relations observed in an argon plasma with uniform magnetic field of 0.79kG, where an ion cyclotron resonance frequency ($f_{ci}=\omega_{ci}/2\pi$) is 30kHz in an argon plasma. Dispersion relations of shear and compressional Alfvén waves are calculated by taking account of the Doppler effect due to a plasma flow with an Alfvén Mach number M_A of 0.13 and are also plotted in the figure. RF waves were excited by the right or left helical antenna. Dispersion relations of the propagating wave were obtained by changing RF frequency f_{RF}. The wave excited by the right helical antenna agrees well with the dispersion curve of the shear Alfvén wave in the region of $\omega/\omega_{ci} < 1.5$ and coincides well with that of the compressional one in the region of $\omega/\omega_{ci} > 2$. The wave excited by the left helical antenna well corresponds to that of compressional one in all ranges of frequency.

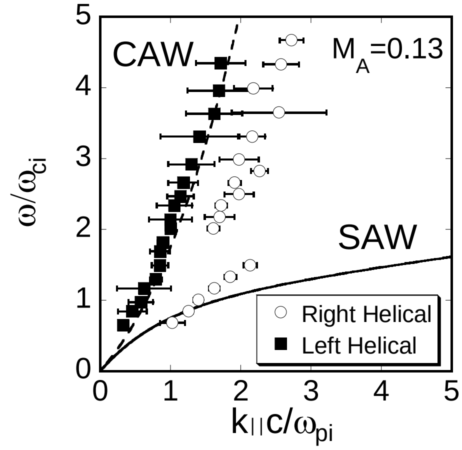

Figure 4. Dispersion relations of the propagating wave in an argon plasma. RF waves are excited by the right (○) and left (■) helical antennas. B_Z =0.79kG(uniform). Solid and dashed lines are calculated dispersion relations of the shear and compressional Alfvén waves, respectively, with Alfvén Mach number M_A= 0.13.

Spatial structures of the time-varying magnetic field associated with the waves are also mapped from three dimensional (3-D) spatial data measured by magnetic probes. Time evolutions of the field structure indicate the behavior of left- and right-handed, circular polarizations near on-axis with azimuthal modes of m= -1 and m= +1, excited by the right and left helical antennas, respectively.

B. Ion heating experiments and relations between ion cyclotron and ion-ion collision frequencies

Figure 5 shows locations of the RF antenna and the diamagnetic coil together with an axial profile of the magnetic field strength. The upstream magnetic field B_U is kept constant and the downstream one B_D can be varied to form a uniform magnetic field as well as a magnetic beach configuration. RF wave is excited in $\omega/\omega_{ci} < 1$ region and propagates downward approaching in the region of $\omega/\omega_{ci} = 1$. In the downstream region a magnetic nozzle is formed to convert ion thermal energy to flow energy.

Figure 6 shows typical waveforms of a discharge current I_d and an observed diamagnetic coil signal $W_\perp$. The diamagnetic coil signal corresponds to plasma thermal energy in a magnetic field. $W_\perp$ drastically increased during the RF excitation.

We measured spatial profiles of an ion temperature T_i and a plasma density. The ion temperature T_i increased from 3.9eV to nearly 40eV with the RF input power P_{RF} of 15kW. The increment of T_i and $W_\perp$ was almost linearly proportional to P_{RF} as shown in Fig.7. The electron density n_e was $0.5\times10^{18}\mathrm{m}^{-3}$ and slightly decreased during the RF excitation. It was measured by a Langmuir probe just after RF turn-off to eliminate the RF effect in the probe measurement. The increment of $W_\perp$ is qualitatively consistent with that of T_i and T_e.

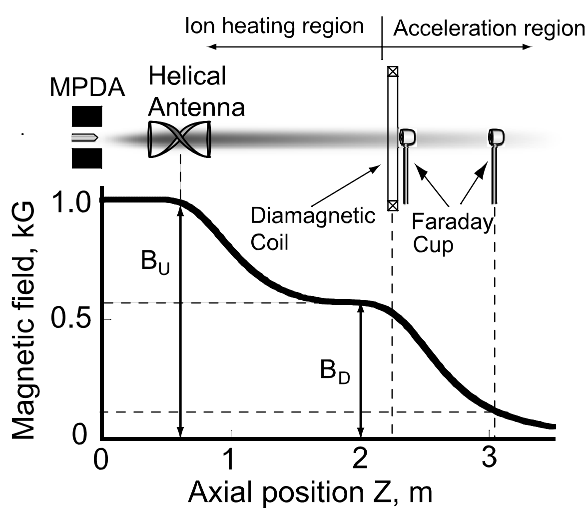

Figure 5. Magnetic field configurations and locations of the helical antenna, the diamagnetic loop coil and the electrostatic energy analyzer.

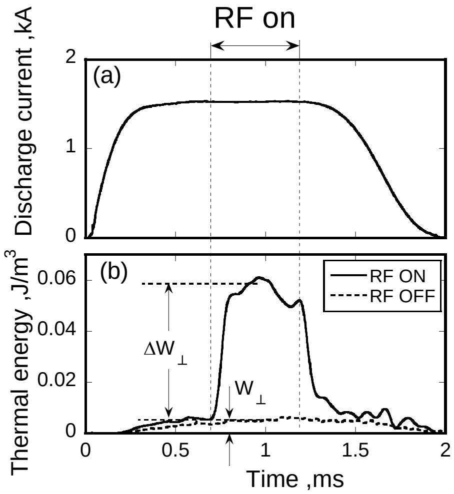

Figure 6. Time evolutions of (a) I_d and (b) $W_\perp$. He plasma. f_{RF}=236kHz.

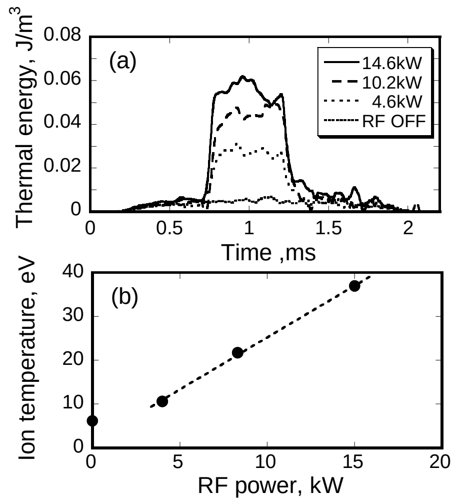

Figure 7. (a)Time evolutions of diamagnetic coil signals $W_\perp$ for different RF powers. (b)Dependence of ion temperature T_i as a function of input RF power. He plasma. f_{RF}=236kHz.

In order to clarify the ion cyclotron resonance heating, we varied the magnetic field B_D in the downstream region. Figure 8 shows dependences of $\Delta W_\perp/W_\perp$ on the magnetic field B_D for three different RF frequencies. The magnetic field configuration is of a magnetic-beach type with a constant B_U of 0.7kG at the antenna position and a variable B_D at the diamagnetic coil position. As the plasma conditions did not change at the antenna position, the excited wave intensity should be kept to be constant. Solid lines indicate the B_D corresponding to ω/ω_{ci} =1 for the excited RF frequencies. $\Delta W_\perp/W_\perp$ becomes large near B_D of ω/ω_{ci} =1 for three different RF frequencies. It was also observed that the peak position is slightly shifted to lower B_D field than that corresponding to ω/ω_{ci} =1, i.e. ω/ω_{ci} is higher than 1. This is due to the Doppler effect caused by the fast plasma flow.

We have found these strong ion cyclotron heating occurred when a plasma density was lower than 10^{18}cm^{-3}. Figure 9 shows dependence of the ratio $\Delta W_\perp/W_\perp$ on B_D for three different plasma densities. As is shown in the figure, a clear indication of the ion cyclotron resonance is observed only in the case with a plasma density of n_e =0.5×10^{18}m^{-3}. Under higher density conditions, an ion-ion collision frequency ν_{ii} becomes larger than an ion cyclotron frequency f_{ci} and the waves are damped not by cyclotron resonance but by collisional damping. Ions cannot gyrate in the Larmour motion between collisions and ion cyclotron heating does not occur. When the ratio of f_{RF} / ν_{ii} is low, $\Delta W_\perp/W_\perp$ does not show a large difference for different magnetic configurations, though the increment of plasma thermal energy still observed under these conditions. This damping mechanism also plays an effective role under the condition of a high density plasma with a lower magnetic field. This heating scenario seems to be feasible in space applications because it is possible to eliminate large superconducting magnets to produce a strong magnetic field.

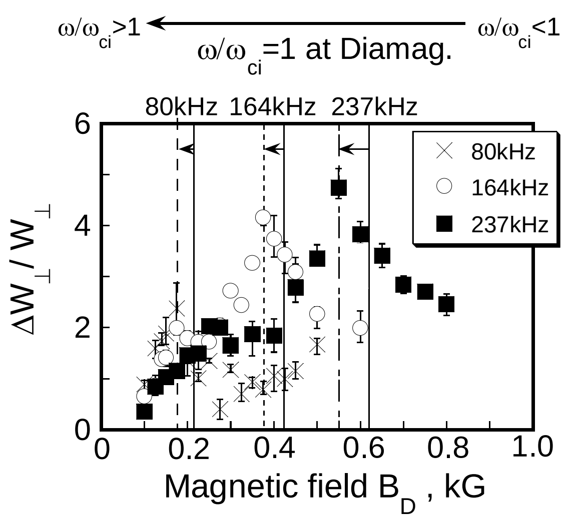

Figure 8. Ratio of $\Delta W_\perp/W_\perp$ as a function of magnetic field B_D. Helium plasma. n_e =0.5×10^{18}m^{-3}. Solid lines correspond to ω/ω_{ci} =1 in each condition.

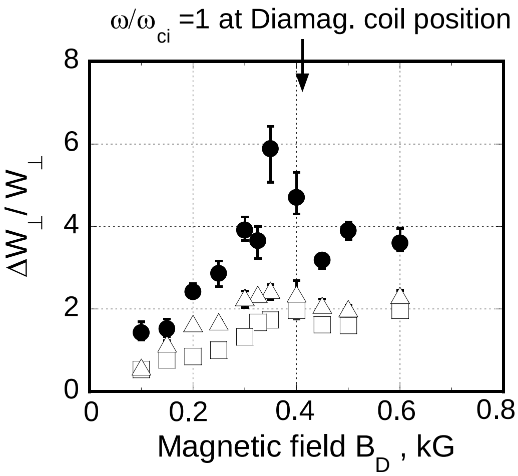

Figure 9. Ratio of $\Delta W_\perp/W_\perp$ as a function of magnetic field B_D. Helium plasma. B_U =0.7kG. f_{RF} =160kHz. (●):f_{RF} /ν_{ii} = 8.4 (n=0.52×10^{18}m^{-3}), (△): f_{RF} /ν_{ii} = 2.4 (n =1.9×10^{18}m^{-3}), (□):f_{RF} /ν_{ii} = 1.6 (n=2.7×10^{18}m^{-3}).

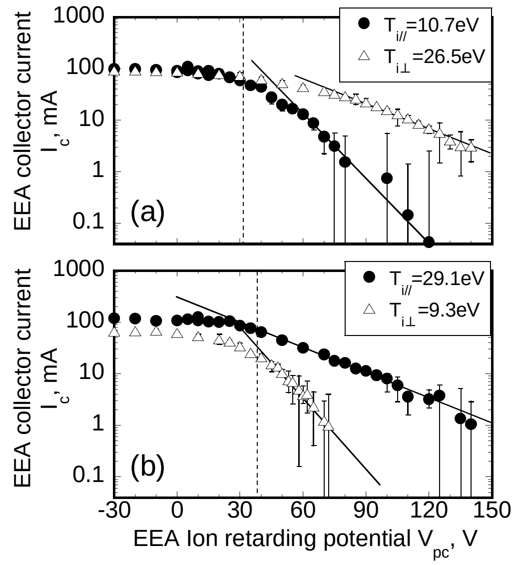

Figure 10. Electrostatic energy analyzer (EEA) signals measured at (a) Z=2.23m and (b) Z=3.03m. Helium plasma. f_{RF} =236kHz.

C. Plasma acceleration in a magnetic nozzle

Energy conversion from $W_\perp$ to $W_{//}$ in a diverging magnetic nozzle was measured by electrostatic energy analyzers (EEA), which were set at the diamagnetic coil position of Z=2.23m (before the nozzle) and in the downstream region of Z=3.03m (after the nozzle) as shown in Fig.5. The EEA consists of a metal plate with a small circular hole and three grids. Ions get through the small hole and are reflected by an retarding voltage applied between the grids. By facing the normal of the hole parallel and perpendicular to the plasma flow, we can obtain both components of ion temperature, $T_{i//}$ and $T_{i\perp}$.

Figure 10 shows detected currents as a function of the retarding voltage. As ions are heated perpendicularly by ICRF heating, $T_{i\perp}$ is larger than $T_{i//}$ at Z=2.23m. After the plasma go through the diverging magnetic nozzle, increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the analyzer signals as shown in the figure. This energy conversion did not occur when the magnetic field configuration was uniform in the downstream region.

The variation of $T_{i\perp}$ along the magnetic field was measured and compared with the prediction from the conservation of magnetic moment μ =(1/2)$mv_\perp^2/B$. We confirmed that the magnetic moment was kept to be constant in the diverging magnetic nozzle.

IV. Conclusion

In order to establish an advanced plasma thruster, ion heating and acceleration experiments are performed in a fast flowing plasma produced by an MPDT in the HITOP device.

Waves with a non-axisymmetric (m=±1) mode are launched by right- and left-handed, helically-wound antennas. Both wave amplitude and phase shift are measured to obtain dispersion relations of the propagating waves. The right helical antenna excites dominantly a shear Alfvén wave in the region of ω/ω_{ci} < 1.5, while the left helical one excites a compressional wave.

When RF waves near an ion cyclotron frequency with a non-axisymmetric (m= -1) mode are launched by right-handed, helically-wound antennas, plasma thermal energy $W_\perp$ and ion temperature T_i are observed to increase drastically in the downstream region of the plasma flow. The magnetic field dependence of the measured $W_\perp$ shows clear indication of the ion cyclotron resonance of thermal ions when the plasma density is low and the condition of $f_{ci} \gg \nu_{ii}$ is satisfied . The features of ion cyclotron resonance affected by the Doppler shift is clearly observed

Increase of $T_{i//}$ and decrease of $T_{i\perp}$ are observed in a divergent magnetic field, which corresponds to the fact that the heated energy is converted to the flow energy in a magnetic nozzle.

Acknowledgments

This work was supported in part by Grant-in-Aid for Scientific Researches from Japan Society for the Promotion of Science.

References

[1]Jahn R.G., *Physics of Electric Propulsion*, McGRAW-HILL, 1968.

[2]Frisbee. R.H., "Advanced Space Propulsion for the 21st Century," *J. Propulsion and Power*, Vol.19, No.6, 2003, pp.1129-1154.

[3]ChangDiaz, F.R. et al., "The Physics and Engineering of the VASIMR Engine," *Proceedings of 36th Joint Propulsion Conference*, Huntsville, AIAA-2000-3756, 2000, pp.1-8.

[4]ChangDiaz, F.R. et al.,"T The VASIMR Engine: Project Status and Recent Accomplishments", *Proceedings of 42nd Aerospace Sciences Meeting and Exhibit*, Reno, AIAA 2004-0149, 2004, pp.1-8. ; Bulletin of APS (46th APS-DPP),NM2A-3, 2004.

[5]Kuriki K. and Inutake M., "Super-Alfvénic Flow and Collision-free Shock-wave in a Plasma Wind-tunnel," *Phys. Fluids*, Vol.17, No.1, 1974, pp.92-99.

[6]Ando A., et al., "Spectroscopic Studies of a High Mach-Number Rotating Plasma Flow," *Journal of Plasma Fusion Research, SERIES*, Vol.4, 2001, pp.373-378.

[7]Inutake M., et al., "Characteristics of a Supersonic Plasma Flow in a Magnetic Nozzle," *Journal of Plasma Fusion Research*, Vol.78, 2002, pp.1352-1360. URL:http://jasosx.ils.uec.ac.jp/JSPF/JSPF_TEXT/jspf2002/jspf2002_12/jspf2002_12-1352.pdf [cited 3 October 2005].

[8]Inutake M., et al., "Magnetic-Nozzle Acceleration and Ion Heating of a Supersonic Plasma Flow," *Transactions of Fusion Technology*, Vol.43, No.1T, FUSTE8, 2002, pp.118-124.

[9]Inutake, M., Ando, A., et al., "Improvement of an MPD Thruster Performance with a Laval-type Magnetic Nozzle," *Proceedings of the 29th International Electric Propulsion Conference*, IEPC-2005-83, 2005.

[10]Tobari, H., Inutake, M., Ando, A. and Hattori, K., "Spatial Distribution of Lorentz Forces in an Applied-Field Magneto-Plasma-Dynamic Arcjet Plasma," *Journal of Plasma Fusion Research*, Vol.80, 2004, pp.651-652.
URL: http://jasosx.ils.uec.ac.jp/JSPF/JSPF_TEXT/jspf2004/jspf2004_08/jspf2004_08-651.pdf [cited 3 October 2005].

[11]Tobari, H., Ando, A., Inutake, M., and Hattori, K.,, "Direct Measurement of Lorentz Forces in an Applied-Field MPD Thruster," *Proceedings of the 29th International Electric Propulsion Conference*, IEPC-2005-65, 2005.

[12]Ando, A. et al., "An Ion Heating Experiment in a Supersonic Plasma Flow," *Proceedings of 11th International Congress on Plasma Physics*, Sydney, Vol.1, No.497, 2002, pp.1-4,

[13]Ando, A. et al., "Evaluation of Para-Perp Type Mach Probe by Using a Fast Flowing Plasma" *Journal of Plasma Fusion Research*, Vol. 81, 2005, pp.451-457. URL:http://www.jspf.or.jp/Journal/PDF_JSPF/jspf2005_06/jspf2005_06-451.pdf [cited 3 October 2005].

[14]Amagishi, Y. et al., "Non-axisymmetric Alfvén wave excited by a helical coupler", *Jpn. J. Appl. Phys.* Vol.20, 1981, pp.2171-2179.

[15]Cross, R.C. *An Introduction to Alfvén Wave*, The Adam Hilger Series on Plasma Physics, IOP, 1988.