Experiments of Ion Acceleration in a Magnetic Nozzle for an Advanced Plasma Thruster

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Abstract: Experiments of ion acceleration in a magnetic nozzle were performed with an ion-heated plasma in the HITOP device in order to investigate an advanced space propulsion such as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) thruster. The plasma thermal energy increased with an excitation of radio frequency (RF) waves of ion cyclotron range of frequency by a helically-wound antenna. When the ion-heated plasma passed through a diverging magnetic nozzle, the increased perpendicular component to the magnetic field of ion energy decreased, whereas parallel component increased along the diverging magnetic field. The energy conversion occurred as keeping the magnetic moment constant, but some discrepancy was observed in larger gradient of magnetic field. The exhausting plasma energy can be controlled not only by the shaping of the magnetic nozzle but by the RF input power. The axial electric field was appeared in a diverging magnetic nozzle due to the ambipolar effect, which acted as ion acceleration along the field line.

Nomenclature

I_d	=	discharge current	Z	=	axial position
e	=	charge of electron	m_i	=	ion mass
B	=	axial component of magnetic field	T_i	=	ion temperature
B_U	=	magnetic field in upstream region	T_e	=	electron temperature
B_D	=	magnetic field at cyclotron resonance	n_e	=	number density of electron
B_N	=	magnetic field in the magnetic nozzle exit	P_{RF}	=	input RF power
ω	=	angular frequency of excited wave	μ	=	magnetic moment

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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
M_i = ion acoustic Mach number
V_s = plasma potential

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] There are some desirable features provided in the advanced space propulsion system for a manned interplanetary space flight. First is a high power density plasma thruster which has a higher specific impulse and a larger thrust. Second is a thruster which has capability of varying a specific impulse. The ability to vary its specific impulse contributes to the operation in a mode with suitable propellant utilization and thrust performance. Utilization of a magnetic nozzle in electric propulsion systems will yield practical benefit not only for avoiding direct contact between a plasma and an exhaust wall but for controlling a specific impulse by adjusting the nozzle shape.

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) has been proposed and tested,[3-6] in order to control a ratio of specific impulse to thrust at constant power, which will allow for optimum low thrust interplanetary trajectories resulting in shorter trip times than that in a fixed specific impulse system. The rocket provides a helicon plasma source and a combined system of ion cyclotron heating and magnetic nozzle. A diverging magnetic nozzle plays an important roll in converting plasma thermal energy heated by ion cyclotron resonance heating (ICRH) to its flow energy.

In order to confirm the VASIMR-type thruster operation, we have performed combined experiments of ion cyclotron resonance heating and acceleration in a magnetic nozzle using a fast-flowing plasma in the HITOP device.[7-10] A magneto-plasma-dynamic arcjet (MPDA) was used as a fast-flowing plasma source. The plasma was heated by RF waves launched by a right-handed helically-wound antenna. Ion acceleration along the field line was successfully demonstrated in a diverging magnetic nozzle in the HITOP device.[9,10]

It was also reported that exhaust plasma velocity in a magneto-plasma-dynamic thruster (MPDT) could be controlled by a diverging and Laval-type magnetic nozzles.[11-16] 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. 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, was observed to be slightly lower than unity. It was demonstrated that a subsonic plasma flow exhausted from the MPDT was converted into a supersonic one (M_i increases more than unity) through a Laval-type magnetic nozzle attached in front of the MPDT muzzle. 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. In spite of various advantages of the magnetic nozzle, there remain unclear problems to be solved, such as plasma detachment from magnetic field, acceleration of ions by an electric field appeared by the ambipolar effect. It should be investigated experimentally how ions in a plasma behave in a magnetic nozzle.

In this research we have investigated effects of a diverging magnetic nozzle on a plasma heated by ion cyclotron resonant heating (ICRH). Conversion of ion energy along a diverging magnetic nozzle were observed and plasma exhaust energy increased in a diverging magnetic nozzle. The exhaust energy was controlled by changing the nozzle shape. It was also controlled by changing the heating power without varying the nozzle shape. Axial electric field was appeared in the magnetic nozzle and is discussed in relation with an ambipolar effect.

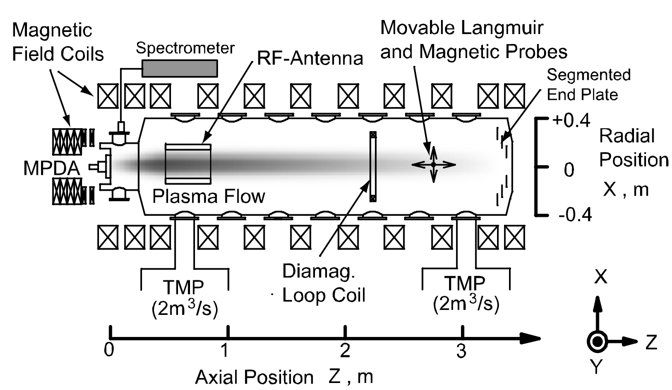


Figure 1. Schematic view of the HITOP device.

II. Experimental setup

Experiments were carried out in the HITOP device of Tohoku University. The schematic view of the device is shown in Fig.1. 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. Various types of magnetic field configuration can be formed by adjusting an external coil current.

A high power, quasi-steady MPDA was installed at one end-port of the HITOP. 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. Helium was used as a working gas in the experiments.

Plasma flow characteristics were measured by several diagnostics installed on the HITOP device. Electron temperature T_e and density n_e profiles were measured by a movable triple probe and a fast-voltage-scanning Langmuir probe. Ion temperature T_i was measured by an electrostatic energy analyzer. A diamagnetic coil with a diameter of 0.4m is set at Z=2.33m to measure plasma thermal energy $W_\perp$. Hereinafter, the suffix $\perp$ and // indicate perpendicular and parallel component to the axial magnetic field, respectively. The measured $W_\perp$ is the averaged value within the cross section of the coil. Here, Z=0 corresponds to the position of the MPDA cathode tip. Ion temperature T_i and ion energy distribution function were measured by electrostatic energy analyzers (EEA), which were set at the diamagnetic coil position of Z=2.33m and Z=3.13m. 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 a 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 $T_{i\perp}$.

We installed a right-handed helically-wound antenna at Z=0.6m downstream of the MPDA in the chamber. RF waves can be excited in the direction downstream of the antenna preferentially with azimuthal mode numbers of m= -1. RF power was supplied by a inverter-type RF wave amplifier operated with a pulsed mode. It was operated with a frequency from 0.1MHz to 0.5MHz with a pulse length of 0.5ms and an input power up to 20kW in the experiments.

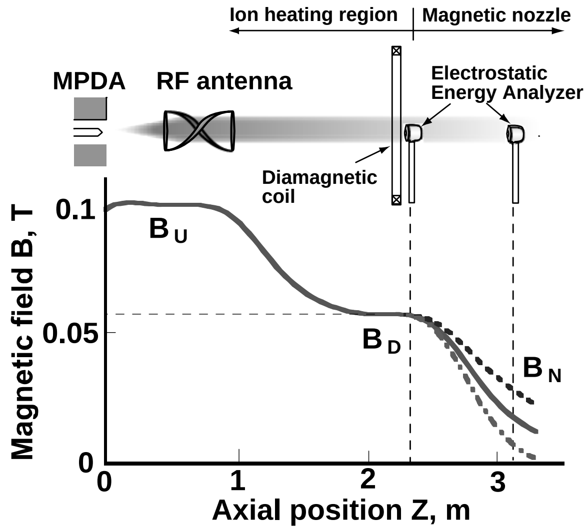


Figure 2. Magnetic field configurations and locations of the RF antenna, the diamagnetic loop coil and the electrostatic energy analyzer.

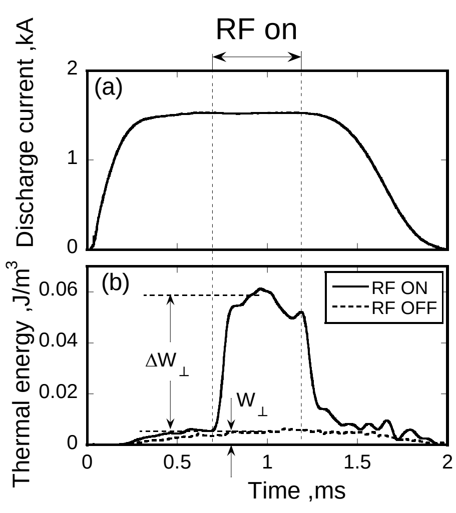


Figure 3. Time evolutions of (a) I_d and (b) $W_\perp$. He plasma. f_{RF}=0.24MHz.

III. Experimental results

A. Ion heating and energy conversion at the magnetic nozzle

Experiments were performed with a magnetic-beach type magnetic field configurations. Figure 2 shows the three magnetic field configurations with a constant B_U (=0.1T) at the antenna position, a variable B_D (corresponding to ion cyclotron resonance condition) at the diamagnetic coil position, and a variable B_N (corresponding to the EEA position of downstream region).

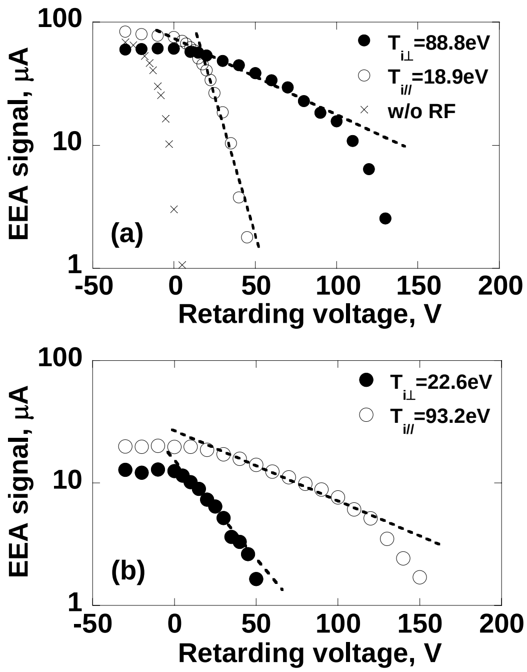


Figure 4. Electrostatic energy analyzer signals measured at (a) Z=2.33m and (b) Z=3.13m. He plasma. P_{RF}=19kW, f_{RF}=0.24MHz, n_e=1.0×10^{17}m^{-3}, B_D=57.5mT, and B_N=6.9mT.

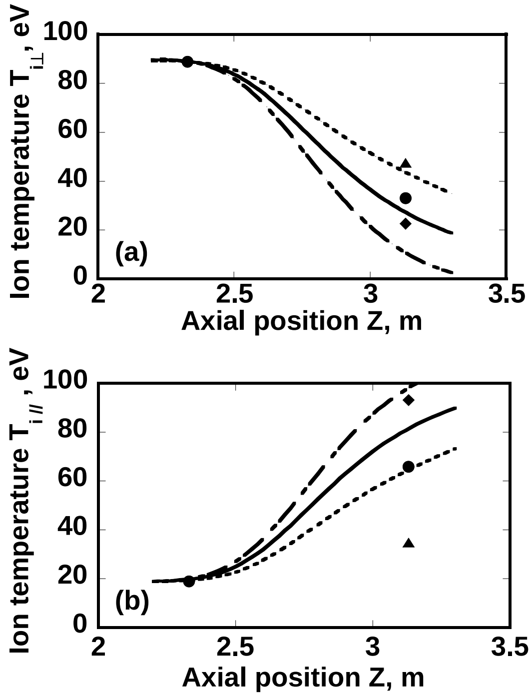


Figure 5. Axial profile of (a) $T_{i\perp}$ and (b) $T_{i//}$ in the three magnetic nozzle configurations shown in Fig.2. Lines are calculated ones assuming μ=const. Closed triangles :B_N=28.1mT, closed circles :B_N=17.2mT, closed diamonds :B_N=6.9mT.

When the RF wave was excited during the MPDA discharge, the diamagnetic coil signal $W_\perp$ drastically increased as shown in Fig.3, which indicates a strong increase of plasma thermal energy by ion cyclotron heating.[8-10] We have confirmed that the strong increase of $W_\perp$ occurred when the magnetic field B_D was slightly lower than that of the ion cyclotron resonance condition, $\omega / \omega_{ci} = 1$. This shift was caused by the Doppler effect. Here, ω and ω_{ci} are the angular frequency of excited RF wave and ion cyclotron motion, respectively, and ω_{ci} is expressed as $\omega_{ci} = eB/m_i$ with electron charge e and ion mass m_i.

We measured ion temperatures by the EEAs in three types of magnetic nozzle configurations. Figure 4 shows typical EEA signals obtained before and after the nozzle with B_D (Z=2.33m) = 57.5mT and B_N (Z=3.13m) = 6.9mT. Strong increase of ion temperature, especially in the perpendicular direction was occurred before the magnetic nozzle. $T_{i\perp}$ increased from 5eV to 89eV with the RF input power of 19kW. The EEA signal decreased above the retarding voltage of 100V as in Fig.4(a). The Larmour radius of helium ions becomes 5cm with $T_{i\perp}$ = 100eV and B = 57.5mT, which almost equals to the plasma radius. The highly heated ions expanded to outer region and the signal measured at the center position decreased above the retarding voltage of 100V.

By passing through the diverging magnetic nozzle, increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the analyzer signals. Figure 5 shows an axial profiles of measured $T_{i\perp}$ and $T_{i//}$ in the three magnetic fields. It is shown that parallel energy of an exhausting plasma can be controlled by changing the magnetic nozzle configuration.

This energy conversion was occurred due to the conservation law of the magnetic moment, $\mu = W_\perp / B = mv^2/2B$. Profiles of $T_{i\perp}$ and $T_{i//}$ calculated by assuming μ=const. are also shown in Fig.5 (a) and (b), respectively. It is confirmed that $T_{i\perp}$ varied so as to keep the magnetic moment constant but some discrepancy was observed in larger gradient of the magnetic field. It was probably caused by a particle motion along magnetic field with larger gradient, because the adiabatic assumption where the magnetic field is kept constant in a single cyclotron motion became invalid.

The parallel energy of exhausting plasma can be changed by controlling the input RF power P_{RF}. Figure 6 shows dependences of $T_{i\perp}$ and $T_{i//}$ on P_{RF} measured at Z=2.33m (before the magnetic nozzle) and Z=3.13m (after the magnetic nozzle). As shown in Fig.6(a), $T_{i\perp}$ increased linearly with the increase of P_{RF}, whereas $T_{i//}$ slightly increased with P_{RF} in the ion heating region (Z=2.33m). After the energy conversion in the magnetic nozzle, $T_{i//}$ strongly increased linearly with the increase of P_{RF} as shown in Fig.6(b). The experimental data clearly demonstrated that the parallel energy of exhausting plasma can be controlled by input RF power only. This feature corresponds to the variable I_{sp} control demanded in the VASIMR-type thruster. Here I_{sp} was varied from 1600 sec to 6000 sec in the experiments.

B. Axial electric field in the magnetic nozzle

Along the magnetic field, electrons escape from a diverging magnetic nozzle more easily than ions. Due to the quasi-neutrality condition of plasmas, there appears an ambipolar electric field along the field line. Electron density is determined by plasma potential V_s as following the Boltzmann equation,

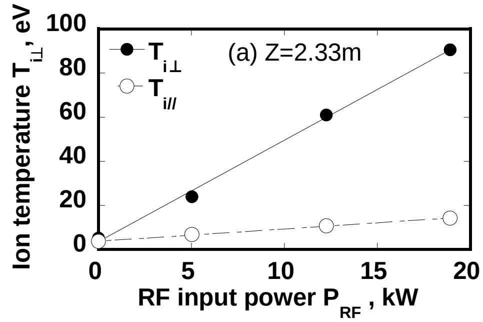
$$n_e = n_0 \exp(eV_s / k_B T_e) \quad . \qquad (1)$$

Here, T_e is electron temperature and k_B is Boltzmann's constant.

In order to confirm the existence of axial electric field, we measured an axial profile of plasma potential V_s in the magnetic nozzle. An electrostatic Langmuir probe and an emissive probe are used in the measurement. As shown in Fig.7, the potential decreased along the magnetic field line and the decrease became large when RF wave was excited and ion heating was occurred. During the RF heating, ion velocity became large and density decreased largely so as to keep ion particle flux constant along the field line. Then the plasma potential decreased largely. The direction of the electric field appeared in a magnetic nozzle is to accelerate ions to the downstream direction.

According to the Equation (1), the difference of plasma potential $\Delta V = V_s$ (Z=2.2m) - V_s (Z=2.9m) is related with the difference of electron density. We measured electron density and temperature profiles along the magnetic nozzle. T_e was almost constant at 5eV. As the calculated ΔV well corresponds to the experimental data, the formation of the electric field is probably due to the ambipolar electric field.

We have found that the ion velocity distribution in parallel direction to the magnetic field was determined not only by the energy conversion from the increased thermal energy but by the acceleration by the electric field. However, further study is necessary to understand the effect of the axial electric field on the thruster performance.



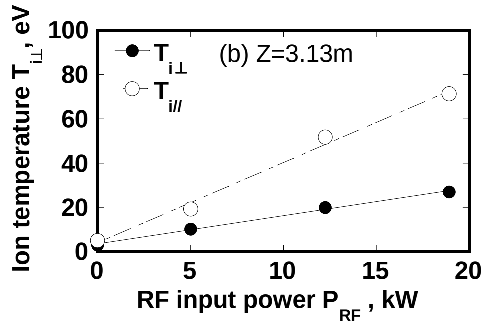


Figure 6. Dependence of $T_{i\perp}$ (closed circles) and $T_{i//}$ (open circles) on RF input power measured at (a) Z=2.33m and (b) Z=3.13m. f_{RF}=0.24MHz, n_e=1.0×10^{17}m^{-3}, B_D=57.5mT, and B_N=17.2mT.

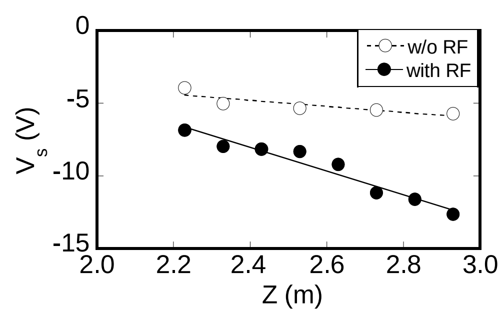


Figure 7. Axial profile of plasma potential V_s with (closed circles) and without (open circles) RF power of 19kW. f_{RF}=0.24MHz, n_e=1.0×10^{17}m^{-3}, B_D=57.5mT, and B_N=17.2mT.

IV. Conclusion

In order to establish a VASIMR-type plasma thruster, ion heating and acceleration experiments were performed in a fast-flowing hydrogen plasma produced by an MPDA in the HITOP device. Strong ion heating occurred by RF wave excitation and energy conversion from perpendicular to parallel direction was clearly observed in a diverging magnetic nozzle. This variation of $T_{i\perp}$ follows the conservation of the magnetic moment μ, although some discrepancy was observed in larger gradient of magnetic field. The parallel energy of exhausting plasma can be changed by controlling the input RF power P_{RF} without the shaping of magnetic nozzle. The feature of variable I_{sp}

control demanded in the VASIMR-type thruster can be realized not only by shaping the magnetic nozzle configuration but by controlling the RF input power. In the divergent magnetic nozzle region, an axial electric field, which accelerates ions, was formed. The experimental data indicated that the parallel component of ion velocity distribution function to the magnetic field was affected by the acceleration due to the electric field as well as the energy conversion in the magnetic nozzle.

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