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Experimental Study of Ion Heating and Acceleration in a Fast-flowing Plasma for the Advanced Plasma Propulsion

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Combined experiments of high power ion cyclotron heating and ion acceleration in a magnetic nozzle are performed in order to develop an advanced plasma propulsion system for the manned space mission. Ion heating is clearly observed in hydrogen plasma as well as in helium plasma, where those light ions are preferable for high specific impulse operation of the thruster. The increased thermal energy converts into exhaust energy by passing through a diverging magnetic nozzle. The exhaust velocity attains to 10^5 m/s and flow energy is successfully controlled by an input power of radio-frequency wave, which is one of the key technologies for the advanced thruster.

Keywords: Ion cyclotron heating, Magnetic nozzle, Magnetoplasma rocket, VASIMR, HITOP.

1. 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]. It is requisite to develop a high density plasma thruster with a higher specific impulse and a larger thrust, which are desirable features equipped in the advanced space propulsion system for a manned interplanetary space flight. The thruster should also have 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.

An ion heating and magnetic nozzle acceleration in a fast-flowing plasma attract much attention in such advanced electric propulsion systems. In the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project, it is proposed to control a ratio of specific impulse to thrust at constant power [3, 4]. This engine utilizes a combined system of an ion cyclotron heating and a magnetic nozzle. An exhausting plasma is heated by ion cyclotron range of frequency (ICRF) wave power. As ions are accelerated perpendicular direction to the magnetic field by cyclotron heating, conversion from perpendicular to parallel energy component along the magnetic field line is necessary for the thruster application. The increased thermal energy is converted to flow energy via a diverging magnetic nozzle. Utilization of a magnetic nozzle in electric propulsion systems will yield practical benefit not only for avoiding direct contact between a plasma and exhaust wall but for controlling a specific impulse by adjusting the nozzle shape.

We have demonstrated for the first time the combined experiments of ion cyclotron resonance heating and acceleration in a magnetic nozzle using a fast-flowing plasma in the HITOP device [5, 6]. A magneto-plasma-dynamic arcjet (MPDA) was used as a fast-flowing plasma source and operated with fast gas-puffing and quasi-steady discharge with short pulse duration of 1ms, which eliminated excess inlet of neutral gas flux and reduced charge-exchange loss of heated ions. When radio-frequency (RF) waves were excited by a helically-wound antenna, thermal energy and ion temperature of a helium plasma clearly increased during the RF pulse. The energy conversion in a diverging magnetic nozzle after the ICRF heating was also observed experimentally [7, 8].

In this research we have performed ICRF heating experiments in hydrogen as well as helium as propellant gas in order to obtain higher exhaust velocity of ions and to achieve ICRF heating in higher density region. It is effective to use lightweight ions for higher cyclotron frequency with lower magnetic field in order to operate with higher density plasmas. The exhaust velocity is also expected to be larger in lightweight ions. Fundamental characteristics of resonant magnetic field and dependence on plasma density were obtained. We have also investigated effects of a diverging magnetic nozzle and control of exhausting plasma energy by RF power were examined.

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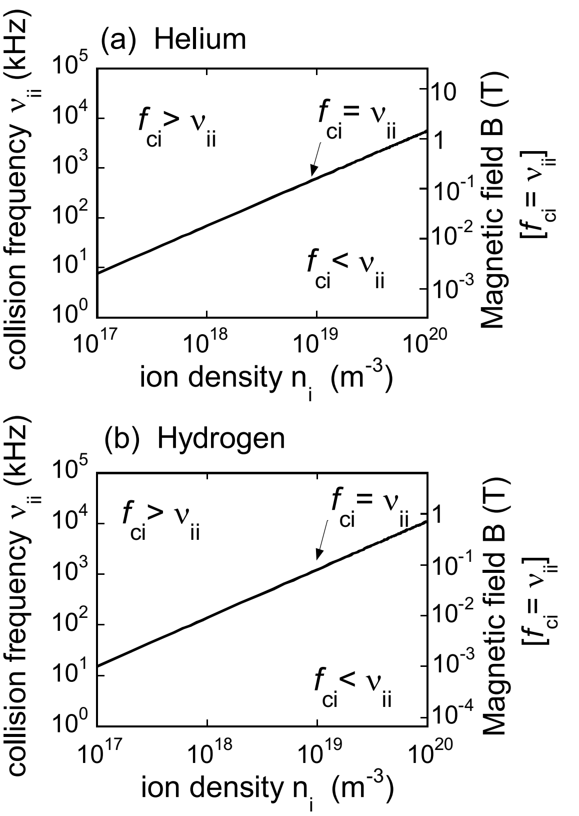

Fig. 1. The ion-ion collision frequency ν_{ii} as a function of the ion density n_i for (a) Helium (He^+) and (b) Hydrogen (H^+) plasmas. T_i =4eV is assumed. The right-hand axis of the ordinate corresponds to the magnetic field where $f_{ci} = \nu_{ii}$.

2. RF frequency and collision frequency

In the previous experiments [6], it was found that strong ion cyclotron heating occurred only when the ion cyclotron frequency was larger than ion-ion collision frequency. Here, the ion cyclotron frequency f_{ci} and the ion-ion collision frequency ν_{ii} are defined as the following equations,

$$f_{ci} = \frac{eB}{2\pi m_i} \quad , \qquad (1)$$

$$\nu_{ii} = \frac{n_i z_i^4 e^4 \ln \Lambda}{12\pi\sqrt{\pi}\varepsilon_0^2 m_i^{1/2} T_i^{3/2}} \quad , \qquad (2)$$

where, e is charge of electron, B is magnetic field strength, m_i, n_i, Z_i and T_i are mass, number density, charge number and temperature of ions, respectively. ε_0 is permittivity, and $\ln\Lambda$ is the Coulomb logarithm.

When an ion density increases and ν_{ii} becomes large, ions cannot gyrate in the Larmor motion between collisions and strong ion cyclotron damping of the wave can not occur. Even in the higher density regime, collisional damping is expected, and increase of stored energy was observed with weak dependence on magnetic field strength in the experiments. As the cyclotron absorption is preferable to the collisional one for the efficient operation of the thruster, usage of higher RF frequency is feasible. However, higher resonance frequency requires higher magnetic field that results in larger magnetic coils and power supply systems. Then, it is important to use an adequate RF frequency and magnetic field.

Figure 1 shows the relation between ν_{ii} and n_i for helium and hydrogen gases. The ion-ion collision frequency strongly decreases with increase of ion temperature. In the calculation T_i = 4eV is assumed according to the experimental data without RF heating. The condition of $f_{ci} > \nu_{ii}$ for cyclotron resonance is satisfied above the solid lines in the figure. The right-hand axis of the ordinate corresponds to the magnetic field where $f_{ci} = \nu_{ii}$. As is shown in the figure, ion cyclotron heating in hydrogen gas can be achieved in higher density region than that in helium gas under the condition of the same magnetic field strength.

3. Experimental setup

Experiments were carried out in the HITOP device of Tohoku University [9, 10]. The device 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 0.1T. Various types of magnetic field configuration can be formed by adjusting an external coil current.

A fast-flowing plasma was produced by an MPDA installed at one end-port of the HITOP. A discharge current I_d of the MPDA was supplied up to 10kA by a pulse-forming network system with quasi-steady duration of 1ms. It can generate a high density (more than $10^{20}m^{-3}$) plasma. As the produced plasma density was rather high in the MPDA, a stainless steel mesh with floating potential was set at the exit region for lower density experiments (lower than $10^{18}m^{-3}$), which was useful to eliminate unexpected current flow path in the plasmas.

We installed a right-handed helically-wound antenna at Z=0.6m downstream of the MPDA in the chamber. Here, Z=0 corresponds to the position of the MPDA cathode tip. RF waves can be excited in the direction downstream of the antenna preferentially with an azimuthal mode number of $m = -1$. RF power was supplied with two types of sources. One was an 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. The other was a vacuum tube RF amplifier operated with a 50-ohm matching circuit in the frequency range from 0.4MHz to 1.0MHz. The pulse length was limited to 0.1ms and an input power was changed up to 10kW.

A diamagnetic coil was set at Z=2.23m to measure plasma thermal energy $W_\perp$. Hereinafter, the suffix $\perp$ and

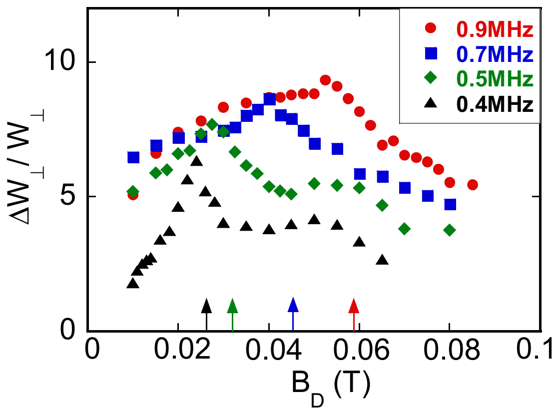

Fig. 2. Dependence of $\Delta W_\perp/W_\perp$ on the resonance magnetic field B_D. H plasma. n_e=2×10^{17}m^{-3}and P_{RF}=5kW at f_{RF}=0.5MHz.

// indicates perpendicular and parallel components to the axial magnetic field, respectively. Ion temperature and ion energy distribution function were measured by electrostatic energy analyzers (EEAs), which were set at Z=2.33m and Z=3.13m. The EEA consists of a metal plate with a small circular hole and three grids. Ions got through the small hole 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 $T_{i\perp}$.

In the experiments the magnetic field configuration was set as a magnetic-beach type with a constant B_U (=0.1T) at the antenna position and a variable B_D at the diamagnetic coil position. The magnetic nozzle shape was also arranged in the downstream by varying the magnetic field strength B_N near the end of the magnetic nozzle, where the EEA was located.

4. Experimental results

4.1 ICRF heating in fast-flowing plasmas

When RF waves were launched by the helically-wound antenna in a plasma, strong increase of plasma thermal energy $W_\perp$ was observed. The increase of $W_\perp$ during the RF excitation was observed in both of helium and hydrogen plasmas.

In order to confirm that the cause of large increase of $W_\perp$ is ion cyclotron resonance heating, we varied magnetic field strength B_D in the resonance region.

Figure 2 shows the obtained dependences of $\Delta W_\perp/W_\perp$ on the magnetic field B_D for different RF frequencies f_{RF} in hydrogen plasma. B_D corresponding to ω/ω_{ci}=1 for each f_{RF} are indicated as arrows 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. These shifts to lower magnetic field are caused by the Doppler effect due to fast-flowing ions in the plasma. These phenomena are similar to those in helium plasmas. The increment of

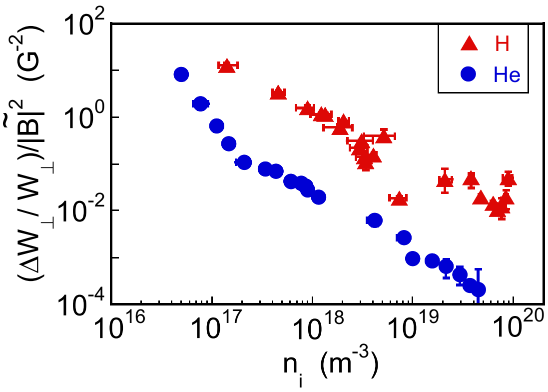

Fig. 3 Dependence of $\Delta W_\perp/W_\perp$ normalized by $|\tilde{B}|^2$ on n_i. f_{RF} = 0.24MHz in He plasma and f_{RF} = 0.41MHz in H plasma.

$W_\perp$ was, however, observed in broader B_D field than that in helium plasma. One possible reason why the resonance region becomes broad is that the resonance of molecular ions H_2^+ was occurred, where the resonant magnetic field is twice of H^+ ions. Slight increase of the ratio $\Delta W_\perp/W_\perp$ was observed at twice of B_D of $\omega=\omega_{ci}$ in case of f_{RF}=0.4MHz and 0.5MHz. Further consideration and experiments are necessary for the characteristics of cyclotron resonance condition in hydrogen plasmas.

The value of $W_\perp$ increased almost linearly with P_{RF}. Ion temperatures of parallel and perpendicular components are measured by the EEAs to confirm the ion heating. Strong increase of ion temperature, especially in the perpendicular direction was occurred at Z=2.33m, just before the magnetic nozzle. The ion temperature $T_{i\perp}$ increased from 2eV to nearly 60eV in hydrogen and 90eV in helium plasmas with the electron density of 1.5×10^{17}m^{-3}.

4.2 Comparison between hydrogen and helium plasmas

In order to compare the efficiency of ion heating between helium and hydrogen plasmas, we measured the increment ratio $\Delta W_\perp/W_\perp$ in various densities of plasmas. As the experimental conditions of magnetic field, RF frequency and input power were different in each plasma, it was somewhat difficult to compare the efficiency with each other. We measured excited wave magnetic field $\tilde{B}$ by using a magnetic probe located near the antenna to estimate wave power intensity excited in the plasmas. As the value of $|\tilde{B}|^2$ corresponds to power density of the excited waves, the ratio $\Delta W_\perp/W_\perp$ normalized by $|\tilde{B}|^2$ is considered to be proportional to the heating efficiency of the RF waves.

Figure 3 shows the dependence of $(\Delta W_\perp/W_\perp)/|\tilde{B}|^2$ on n_i in helium and hydrogen plasmas. As is shown in the figure, the efficiency gradually decreases with the increase of n_i. It is noted that the efficiency was higher in

Table 1. Comparison of achieved data between helium and hydrogen plasmas with n_i=1.5×10^{17}m^{-3}.

	B_U-B_D-B_N (mT)	f_{RF} (MHz)	P_{RF} (kW)	$T_{i\perp}$(eV) (Z=2.33m)	$T_{i//}$(eV) (Z=3.13m)	$U_{//}$ (m/s)	I_{sp} (s)
He	100-57.5-6.9	0.24	19	90.5	71.3	5.84×10^4	6.0×10^3
H	100-52.5-11.2	0.90	6.9	60.4	51.3	9.91×10^4	1.01×10^4

hydrogen plasma than that in helium plasma.

One of the reason why the heating efficiency is higher in hydrogen plasma is the difference of the ratio f_{ci}/ν_{ii} as discussed in section 2, where the condition of $f_{ci} = \nu_{ii}$ is satisfied in higher density in hydrogen plasma than in helium plasma. Another possible reason is the difference of charge exchange loss with neutral gas. The cross section of charge exchange process with the same gas species is much higher in He^+ than H^+ ions. The charge exchange process deteriorates the heating efficiency. Due to these effects, ion cyclotron heating in hydrogen plasma could be achieved in higher density region than that in helium plasma.

4.3 Magnetic nozzle acceleration

Energy conversion from $W_\perp$ to $W_{//}$ in a diverging magnetic nozzle was measured by EEAs, and increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the analyzer signals at the end of the magnetic nozzle. The energy conversion was occurred according to the conservation law of the magnetic moment, $\mu = W_\perp / B = mv^2/2B$. It was 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.

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. The spatial profile of plasma potential was measured by a Langmuir probe and an emissive probe in the magnetic nozzle region. There observed parallel electric field, which accelerates ions to the downstream direction. The potential profile corresponded well to the electron density profile in accordance with the Boltzmann equation.

The parallel energy of exhausting plasma was successfully controlled by varying the input RF power only. This feature corresponds to the direct control of exhaust energy demanded in advanced plasma thrusters.

The obtained $T_{i\perp}$ at Z=2.33m and $T_{i//}$ at Z=3.13m in helium and hydrogen plasmas are summarized in Table 1. Although the RF input energy was lower in hydrogen plasma experiments, exhaust ion velocity was faster than that of helium due to its light weight. The exhaust velocity of hydrogen ions attained to 10^5 m/s, which corresponds to the specific impulse of 10^4 s.

5. Summary

In order to establish an advanced plasma thruster with controllable exhaust energy of propellant, ion heating and acceleration experiments were performed in fast-flowing helium and hydrogen plasmas produced by an MPDA in the HITOP device. Strong ion heating occurred by RF wave excitation and energy conversion from perpendicular to parallel direction in a diverging magnetic nozzle was clearly observed in both of helium and hydrogen plasmas. The ion cyclotron resonance was confirmed from the dependence on the resonance magnetic filed. The absorption efficiency of the excited wave was higher in a hydrogen plasma than in a helium plasma. In a diverging magnetic nozzle the variation of $T_{i\perp}$ and $T_{i//}$ were measured and energy conversion from $W_\perp$ to $W_{//}$ was confirmed experimentally. The parallel energy of exhausting plasma could be changed by controlling the input RF power only. The feature of direct control of exhaust energy demanded in advanced plasma thrusters can be realized by controlling RF input power only.

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