Ion heating and acceleration experiment in hydrogen plasma for the VASIMR-type Thruster

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Abstract: Ion cyclotron resonance heating and acceleration in a magnetic nozzle were investigated in a fast-flowing plasma in the HITOP device in order to establish a Variable Specific Impulse Magnetoplasma Rocket (VASIMR) type plasma thruster. Ion heating was clearly observed in hydrogen plasma as well as in helium plasma. The resonance region of magnetic field was broader and wave absorption efficiency was higher in hydrogen plasma than those in helium plasma. Energy conversion from perpendicular to parallel components along a diverging magnetic nozzle was also observed in hydrogen plasma. Parallel component of ion temperature increased to more than 50eV after the nozzle and exhaust velocity of hydrogen ions attained to 10^5 m/s.

Nomenclature

I_d	=	discharge current	Z	=	axial position
e	=	charge of electron	m_i	=	ion mass
ε_0	=	permittivity	Z_i	=	charge number of ion
$\ln \Lambda$	=	Coulomb logarithm	T_i	=	ion temperature
B	=	magnetic field strength	T_e	=	electron temperature
B_U	=	magnetic field in upstream region	n_e	=	number density of electron
B_D	=	magnetic field at cyclotron resonance	M_i	=	ion acoustic Mach number
B_N	=	magnetic field in the magnetic nozzle exit	P_{RF}	=	input RF power
ω	=	angular frequency of excited wave	f_{ci}	=	frequency of ion cyclotron motion
ω_{ci}	=	angular frequency of ion cyclotron motion	ν_{ii}	=	ion-ion collision frequency
$W_\perp$	=	perpendicular component of plasma thermal energy			
$W_{//}$	=	parallel component of plasma thermal energy			

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I. Introduction

Near-future space exploration missions need further investigation of advanced electric propulsion systems, where high density plasma production and acceleration technique are inevitable. 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. 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.[1-4] This engine utilizes 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 plasma thermal energy is converted to flow energy via a diverging magnetic nozzle.

Though ion heating technique has been precisely investigated both theoretically and experimentally in many magnetically-confined fusion plasma researches, direct ion heating for fast flowing plasmas by RF waves were considered to be difficult, because ions pass quickly through the resonance region only once and strong absorption of RF waves is necessary for the one-pass absorption. Moreover, a charge-exchange energy loss by neutral gas deteriorates the heating evidence in a weakly-ionized plasma.

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.[5-9] A magneto-plasma-dynamic arcjet (MPDA) was used as a fast-flowing plasma source and operated with quasi-steady duration of 1ms, which eliminated excess inlet of neutral gas flux and reduced charge-exchange loss. When radio-frequency (RF) waves were excited by a helically-wound antenna, plasma thermal energy $W_\perp$ and ion temperature $T_{i\perp}$ clearly increased during the RF pulse. Here the suffix $\perp$ corresponds to perpendicular component to the axial magnetic field. As ions are accelerated perpendicular direction to magnetic field by the cyclotron heating, conversion from perpendicular to parallel energy component along the field line is inevitable for the thruster application. We also observed the energy conversion in a diverging magnetic nozzle after the ICRF heating. The effects of the magnetic nozzle were investigated and demonstrated that parallel energy of exhausting plasma was changed by controlling the input RF power P_{RF} only. It was confirmed experimentally that 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.[10]

These experiments were performed with working propellant gas of helium and frequency of RF waves was around 0.25MHz because of relatively low magnetic field of 0.05T in the HITOP device. As appeared in the previous experiments, cyclotron heating did not occurred in higher density plasma, where the collision frequency of ions became larger than the cyclotron frequency and ions could not rotate as Larmour motion.[7,8] It is effective to use lightweight ions for higher cyclotron frequency with lower magnetic field in order to operate higher density plasmas. The exhaust velocity is also expected to be larger in lightweight ions.

In this research we have performed ion cyclotron resonant heating (ICRH) experiments in hydrogen gas in order to obtain higher exhaust velocity of ions and to achieve ICRF heating in higher density region. Fundamental characteristics of resonant magnetic field and dependence on RF input power and plasma density were obtained. These results are compared with the data in helium plasmas.

II. RF frequency and collision frequency

In the previous experiments, 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,

$$f_{ci} = \frac{eB}{2\pi\, m_i} \quad , \tag{1}$$

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

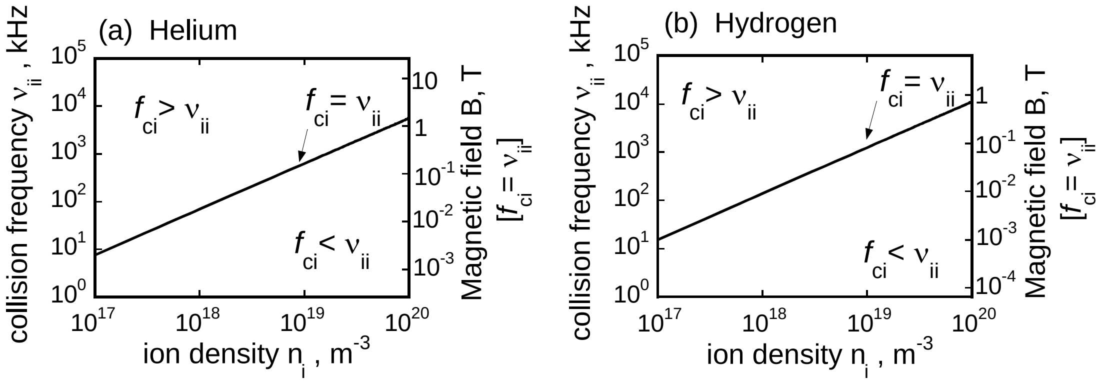

Figure 1. The ion-ion collision frequency ν_{ii} as a function of the ion density n_i for (a)Helium(He^+) and (b) Hydrogen(H^+) plasmas. T_i =4eV is assumed. The right-hand axis of the ordinate corresponds to the magnetic field where $f_{ci} = \nu_{ii}$.

Here, 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, which is given as the following equation.,

$$\ln\Lambda = 7.0 + 2.3\log_{10}\frac{\left(T\,[eV]\right)^{3/2}}{\left(n\,[10^{20}\,m^{-3}]\right)^{1/2}} \quad . \tag{3}$$

When an ion density increases and ν_{ii} becomes large, ions cannot gyrate in Larmour motion between collisions and strong ion cyclotron damping of the wave can not occur. Even in the higher density regime where collisional damping is expected, 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 vast magnet coils and power supply system. 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. 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 lower magnetic field, although slightly higher frequency is required than that in helium gas. As the ion-ion collision frequency strongly decreases with increase of ion temperature, this criterion depends on ion temperature. When ion temperature is low in an initial plasma, such as RF-produced plasma, higher RF frequency will be necessary.

III. Experimental setup

Experiments were carried out in the HITOP device of Tohoku University.[11-13] The schematic view of the device is shown in Fig.2. 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.

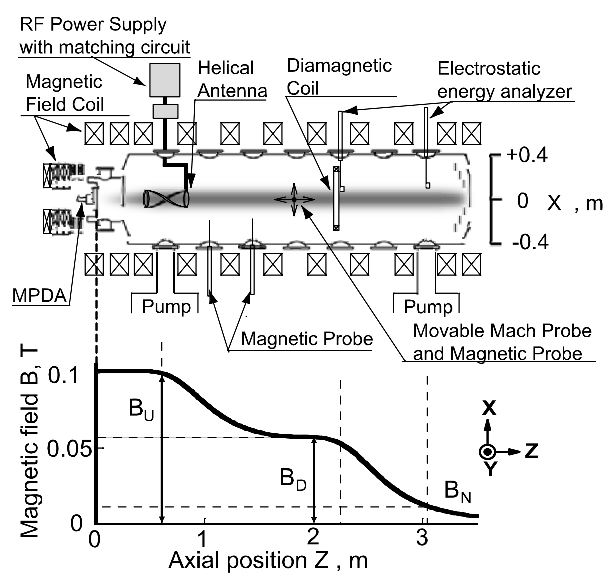

Figure 2. Schematic of the HITOP device. Magnetic field with magnetic beach configuration is also shown.

A high power, quasi-steady Magneto-Plasma-Dynamic Thruster (MPDT) 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. It can generate a high density (more than 10^{20}m^{-3}) plasma. As the produced plasma density is rather high in the MPDT, a stainless 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 plasma.

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 with a 50-ohm matching circuit in the range of frequency from 0.5MHz to 1.0MHz. The pulse length is limited to 0.1ms and an input power up to 10kW was supplied. A diamagnetic coil is set at Z=2.23m to measure plasma thermal energy $W_\perp$. Hereinafter, the suffix $\perp$ and // indicates perpendicular and parallel component to the axial magnetic field, respectively. The magnetic field configuration is of magnetic-beach type with a constant B_U (=0.1T) at the antenna position and a variable B_D (corresponding to ion cyclotron resonance condition) at the diamagnetic coil position, which is the same as the previous experiments.

IV. Experimental results

A. ICRF heating in hydrogen plasmas

Figure 3 shows typical waveforms of diamagnetic coil signals $W_\perp$ obtained in hydrogen plasmas. It drastically increased during the RF excitation, although it was not saturated during the short RF pulse period of 0.1ms. The maximum value of $W_\perp$ is plotted as a function of input RF power P_{RF} in Fig.4. It increased almost linearly with P_{RF} as shown in the figure. Ion temperatures of parallel and perpendicular components are measured by an electrostatic energy analyzer to confirm the ion heating. The ion temperature $T_{i\perp}$ increased from 2eV to nearly 60eV with the electron density of 1.5×10^{17}m^{-3}.

In order to clarify the ion cyclotron resonance heating of hydrogen, we varied the magnetic field B_D in the resonance region. Figure 5 shows the obtained dependences 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 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 that in helium plasma. The increment of $W_\perp$ 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 condition was satisfied at different position from the plateau B_D area. Another is the resonance of molecular ions H_2^+ was occurred, where the resonant magnetic field is twice to that of H^+ ions. Slight increase of the ratio $\Delta W_\perp/W_\perp$ was observed at B_D of ω/ω_{ci}=1/2 in case of

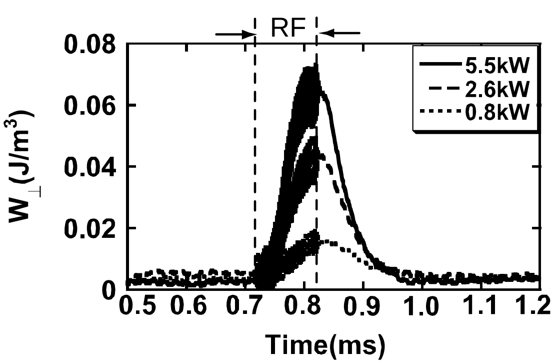

Figure 3. Time evolutions of $W_\perp$. P_{RF} = 0.8, 2.6 and 5.5kW. f_{RF}=0.5MHz. n_e=1.5×10^{17}m^{-3}. H plasma.

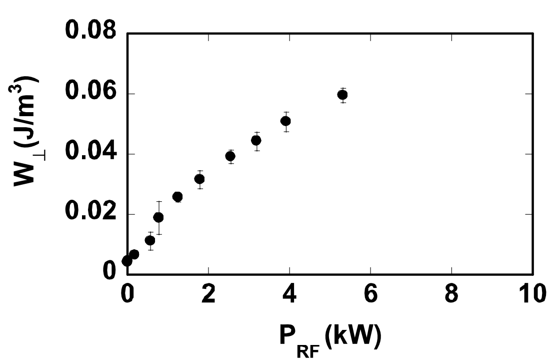

Figure 4. Dependence of $W_\perp$ on RF input power P_{RF}. f_{RF}=0.5MHz. n_e=1.5×10^{17}m^{-3}. H plasma.

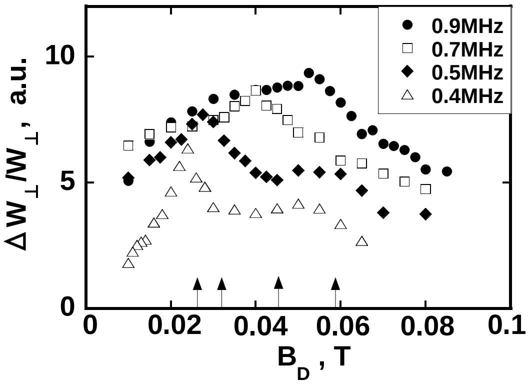

Figure 5. Dependence of $\Delta W_{\perp}/W_{\perp}$ on the resonance magnetic field B_D. H plasma.

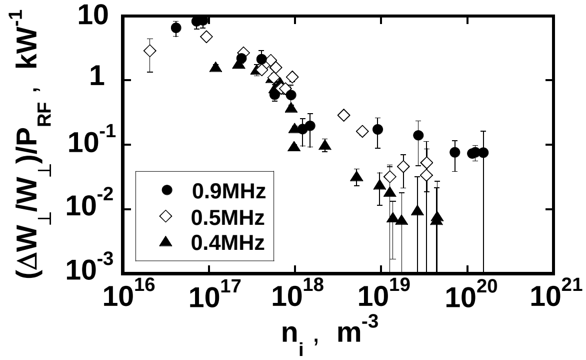

Figure 6. Dependence of $\Delta W_{\perp}/W_{\perp}$ normalized by P_{RF} on n_i. H plasma.

f_{RF}=0.4MHz and 0.5MHz. Further consideration and experiments are necessary for the characteristics of cyclotron resonance condition in hydrogen plasma.

We have changed the plasma density and obtained the dependence of $\Delta W_{\perp}/W_{\perp}$ normalized by input RF power on n_i as shown in Fig.6. Although the increment ratio decreased with the increase of n_i, the normalized increment ratio was larger in higher f_{RF} in the region of n_i more than 10^{18}m^{-3}. This indicates that higher frequency is feasible for higher density plasma heating.

Energy conversion from $W_{\perp}$ to $W_{//}$ in a diverging magnetic nozzle was measured by electrostatic energy analyzers, which were set at the diamagnetic coil position of Z=2.33m (before the nozzle) and in the downstream region of Z=3.13m (after the nozzle). Increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the diverging magnetic nozzle in the hydrogen plasma as well as in the helium plasma. Although the RF input power is low of 6.9kW, $T_{i//}$ attains to more than 50eV after the nozzle, which corresponds to the specific impulse of 10^4sec.

B. Comparison with 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 magnetic fluctuation signal $\tilde{B}$ using a magnetic probe 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 absorption efficiency of the RF waves. Figure 7 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, efficiency of wave absorption was higher in hydrogen plasma than that in helium plasma.

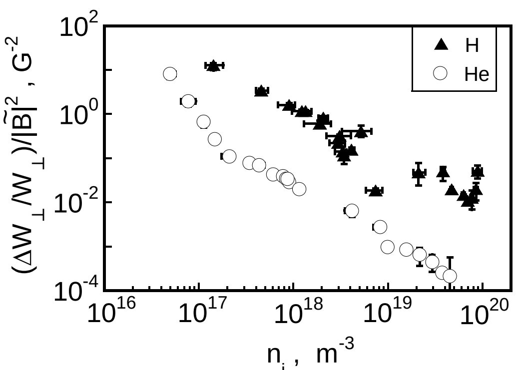

Figure 7. Dependence of $\Delta W_{\perp}/W_{\perp}$ normalized by $|B|^2$ on n_i. f_{RF}=0.24MHz in He plasma and f_{RF}=0.41MHz in H plasma.

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	0.238	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

The achieved exhaust energies 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, and attained to more than 10^5m/s.

V. 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.

Ion heating was clearly observed in a hydrogen plasma as well as in helium plasma. The ion temperature $T_{i\perp}$ increased from 2eV to nearly 60eV with the electron density of 1.5×10^{17}m^{-3}. The resonance region of magnetic field was broader than that in helium plasma. The effect of Doppler shift of ion cyclotron resonance was also observed. The absorption efficiency of the excited wave was compared between helium and hydrogen plasmas. It was higher in hydrogen plasma than in heliumplasma. Increase of $T_{i//}$ and decrease of $T_{i\perp}$ were observed in a divergent magnetic field and $T_{i//}$ attained to more than 50eV after the nozzle, which corresponds to the specific impulse of 10^4sec.

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