Two-Dimensional Characteristics of Electromagnetic Plasma Acceleration by Using Rotating Magnetic Field

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Abstract: Limitation of Operation time in recent electric plasma thrusters leads to difficulty of deep space exploration e.g., the Jupiter and further away, since these thrusters have electrodes to generate and accelerate a plasma, causing wear of the electrodes and contamination of them. As one of the solutions, we have been studying on Rotating Magnetic Field (RMF) acceleration method under the Helicon Electrodeless Advanced Thruster (HEAT) project. Here, we use two sets of opposing coils as RMF generation antennas, and apply AC current to them by 90 deg. phase difference. We have changed operation parameters, e.g., rf power, gas flow rate, RMF current, and RMF current frequency to investigate the optimal operation condition. In addition, 2D measurements of ion velocity and electron density have been conducted to examine spatial plasma acceleration effect and the acceleration mechanisms.

Nomenclature

f_{ci}	=	ion cyclotron frequency
f_{ce}	=	electron cyclotron frequency
j_θ	=	azimuthal current
ϕ	=	RMF coils' current phase difference
B_{RMF}	=	Strength of RMF
f_z	=	axial force
B_r	=	radial component of divergent magnetic field
P_0	=	neutral pressure
v_i	=	ion velocity
n_e	=	electron density
fr	=	gas flow rate
P_{rf}	=	radio frequency power
I_{RMF}	=	RMF coil current
f_{RMF}	=	RMF current frequency
r	=	radius
m	=	azimuthal mode
z	=	axial length
t	=	time
κ	=	mode constant
T_e	=	electron temperature
γ	=	Hall parameter
λ	=	plasma radius normalized by skin depth
R	=	plasma radius

I.Introduction

IN the field of space propulsion systems, electric propulsion has been developed because of higher fuel efficiency than that of chemical one. However, previous electric thrusters, e.g., ion engine, Hall thruster, and Magneto-Plasma-Dynamics (MPD),[1] have erosion of electrodes for plasma generation and acceleration processes by contacting directly with plasma, causing a limitation in the operating time and a contamination. As one of the solutions, helicon electrodeless plasma thruster has been conducted under the Helicon Electrodeless Advanced Thruster (HEAT)[2] project. In this scheme, a helicon wave[3] is excited by RF (Radio Frequency) antenna wound around outside of a discharge tube with an excitation frequency between f_{ci} and f_{ce}, which are an ion and an electron cyclotron frequencies, respectively, leading to high plasma density (~ 10^{13} cm^{-3}) with a high ionization (several tens of percent) obtained.

As one of the electrodeless plasma acceleration scheme, HEAT project has proposed Rotating Magnetic Field (RMF)[4,5] acceleration scheme.[6,7] Originally, the RMF method has been used to induce an azimuthal current j_θ to maintain the Field Reversed Configuration (FRC)[4,5] in the field of a magnetically confined fusion plasma research. In our RMF acceleration scheme, we use two pairs of opposed, facing coils as an RMF antenna, and apply AC currents to them by a phase difference ϕ of 90 deg., which represents an acceleration phase. First, magnetic field B_{RMF} is generated by the RMF antenna, and an axial electric field is induced due to the Faraday's law. Second, an axial current is induced by the Ohm's law, causing an azimuthal electric field. Third, as time goes on after applying RMF, electrons can rotate with RMF in the azimuthal direction, and the azimuthal current j_θ is induced by the non-linear effects. Finally, the axial Lorentz force f_z is generated by the product of j_θ and external radial magnetic field B_r, which accelerates the plasma axially.

We measured an ion velocity v_i and an electron density n_e by a Mach probe mounted on a developed 2D scanning instrument to estimate the RMF acceleration effect. In order to derive the optimum RMF applying conditions, we have surveyed RMF operating parameters, e.g., gas flow rate fr, rf power P_{rf}, RMF coil current I_{RMF}, and RMF coil current frequency f_{RMF}, and so on.[7] We have lowered f_{RMF} to 0.7 MHz from 5 MHz to enhance RMF penetration condition according to Milroy's expression in addition to increasing I_{RMF}, and then higher increases of v_i and n_e were obtained. The maximum increasing rates of v_i and n_e were ~ 30 % and ~ 210 %, respectively at $r = 0$ mm in the case of $P_{RF} = 1$ kW, $fr = 60$ sccm, and $I_{RMF} = 55$ A_{pp} with $f_{RMF} = 0.7$ MHz. We found a possibility that the increase of v_i was made by the increment of n_e with $f_{RMF} = 0.7$ MHz due to the high increasing rate of n_e in addition to the electromagnetic acceleration effect, which we are proposing.

II.Experimental setup

A. High-dense plasma source

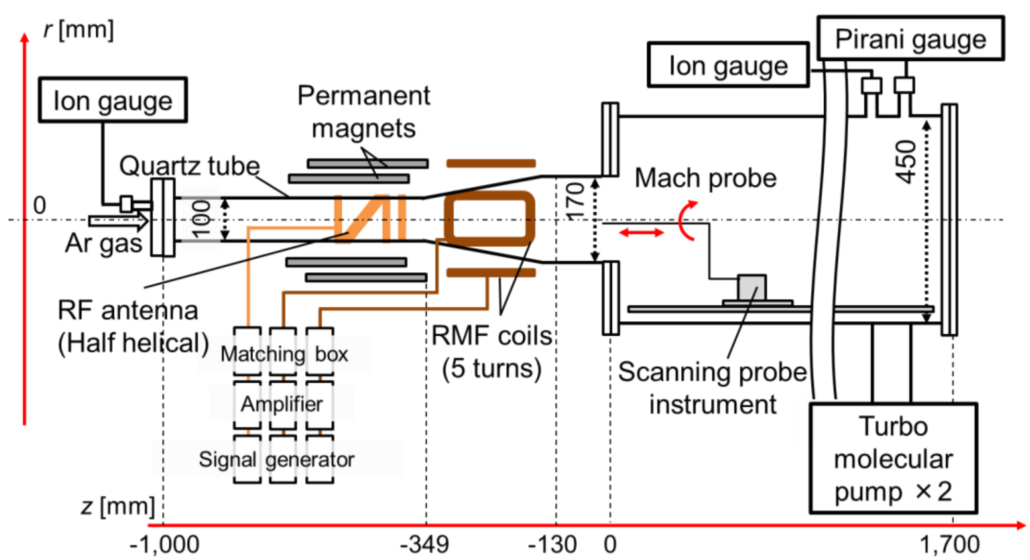

Fig. 1. Schematic view of LMD and 2D scanning instrument.

In our present experiment, Large Mirror Device (LMD),[8] shown in Fig. 1 was utilized. This device has a quartz tube (1,000 mm in axial length) with a tapered shape (100 ~ 170 mm in inner diameter) to decrease a wall loss of plasma in the presence of a divergent magnetic field generated by external permanent magnet arrays,[9] whose grade is N35, made by NeoMag Co. Ltd. As a propellant gas, Ar gas (typical gas pressure of ~ 0.1 Pa) was injected with a background pressure of ~ 10^{-4} Pa. The axial length and inner diameter of the chamber are 1,700 mm and 445 mm, respectively. As a high dense-plasma source, we use a half helical antenna, whose azimuthal mode is m = 1,[10] is wound around the quartz tube. Here, we use only permanent magnet arrays as an external magnetic field. Ar gas is ionized by the rf antenna with excitation rf frequency f_{rf} of 7 MHz and P_{rf} is ~ 1 kW.

B. RMF acceleration scheme

As RMF antennas, two set of 5 turns, opposing coils (168 and 115 mm in axial and azimuthal directions, respectively) are wound around the discharge tube and the location is from z = -330 to -162 mm, as shown in Fig. 3. Oxygen-free copper, which has a 15 mm width and 0.5 mm thickness and is in a isolation tube, is used as the RMF coils. AC current is applied to both sets of RMF coils (hereafter, we call I_{RMF}) to generate the rotating magnetic field with current phase difference ϕ between those RMF coils. In our present RMF experiment, 30 ms RMF application from t = 35 to 65 ms during 75 ms rf pulse discharge is done, which enables us to compare the plasma performance easily between w/ and w/o RMF in the same pulse discharge shot. In addition, we have found that the discharge condition after finishing RMF application is not different from that before the application (t = 65 - 75 ms). As our experimental definition, this ϕ value determines an azimuthal rotation direction of RMF; ϕ = 90 and -90 degs. denote an acceleration and a deceleration phases respectively, considering an electron current in the azimuthal direction. Here, the current frequency f_{RMF} is between f_{ci} and f_{ce}, and electron is expected to rotate in the azimuthal direction, as shown Fig. 2 (b). Then, an azimuthal current j_θ can be generated by nonlinear effect, and the axial Lorentz force f_z is generated by the cross product of j_θ and radial component of external divergent magnetic field, b_r. In our present RMF experiment, some RMF operation parameters, e.g., gas flow rate fr, rf power P_{rf}, I_{RMF}, f_{RMF}, and ϕ, are changed and these dependencies of plasma parameters were investigated.

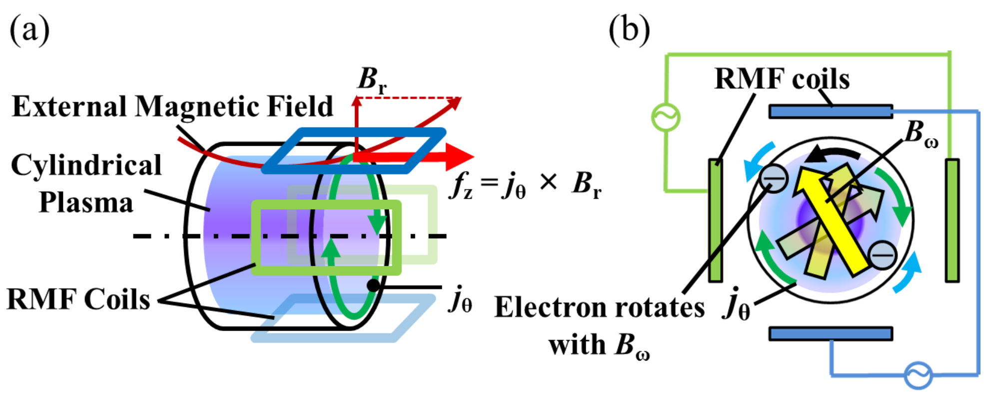

Fig. 2. Schematic view of RMF acceleration: a) bird eye view and b) cross sectional view.

C. 2D measurement of plasma parameters

2D measurements of plasma parameters (v_i and n_e) are conducted in order to investigate spatial RMF acceleration performance and mechanisms. Here, a developed scanning instrument was utilized, as shown in Fig. 1. As a plasma velocity measurement in addition to plasma density, a Mach probe mounted on the developed scanning instrument was utilized. Two tungsten rods with a 0.8-mm diameter are inserted into two separated holes of an isolation pipe (Al_2O_3). Ion saturation currents detected at the probe tips with 4-mm length are divided into an upstream and a downstream sides by a separation barrier, leading to an ion Mach number expressed as the current ratio. Unmagnetized model (model constant κ = 1.26[11,12]) is applied in our experimental scheme, and electron temperature T_e is assumed to be a constant value of 5 eV in the entire measurement region. By the use of these parameters, v_i can be derived from the ion Mach number, since the Mach number is defined as a ion velocity normalized by ion sound velocity. Calculated those plasma parameters are averaged shot by shot for 8 times.

III.Experimental results

A. Radial distributions of v_i and n_e changing fr with f_{RMF} = 0.7 MHz

Figures 4 (a) and (b) show radial distributions of v_i and n_e, respectively, w/o and w/ RMF for the case of P_{rf} = 1 kW and I_{RMF} = 50 A_{pp}, changing fr = 20, 40, and 60 sccm at z = -130 mm, which is in a downstream region of RMF antenna. The increments of v_i were obtained with RMF application in the entire radial positions and the maximum value of the increasing rate was ~ 37 % at r = 0 mm for the case of 40 sccm.

In terms of n_e, it also increased w/ RMF in the entire radial positions for all fr cases, and the highest values were obtained at r = 0 mm, which is the center of the discharge tube regardless of fr. The maximum increasing rate of n_e is ~ 220 % at r = 15 mm in the case of fr = 60 sccm.

Considering these n_e increments by applying RMF, the increment of v_i may correspond to high increases of n_e, and that suggests axial and radial pressure gradient effects, which will be described in the next section with spatial distributions of v_i and n_e. In addition, compared to n_e, v_i did not decrease appreciably toward the outer radial direction.

With respect to the RMF acceleration, the degradation of an ionization rate or the collisions between an electron-ion and an electron-neutral particles due to increasing fr should be considered, since these factors affect the RMF penetration and electromagnetic acceleration. Therefore, for an optimal thrust performance, we should consider these target plasma conditions, including P_{rf} as well as RMF operation conditions.

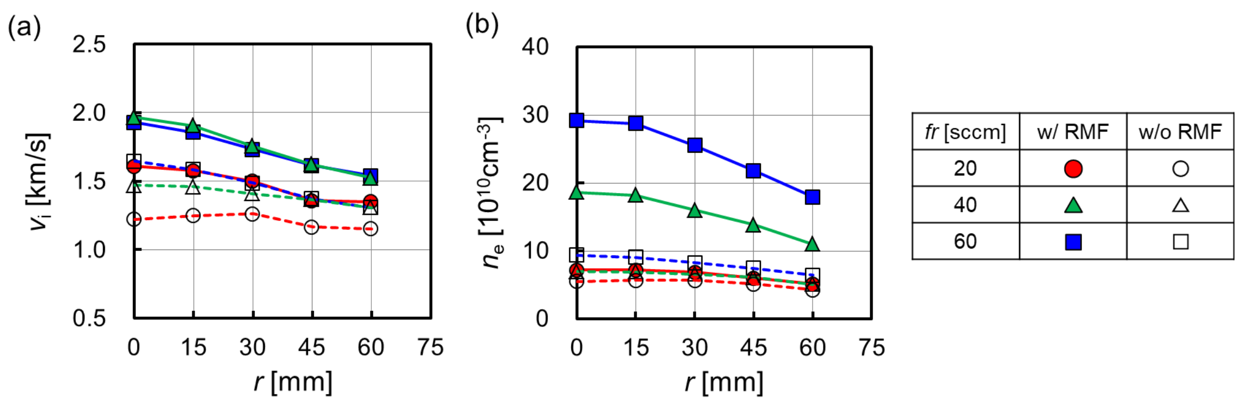

Fig. 3. Radial distributions of (a) v_i and (b) n_e using three gas flow rates (fr = 20, 40, and 60 sccm) for the case of P_{rf} = 1 kW and I_{RMF} = 50 A_{pp} with f_{RMF} = 0.7 MHz at z = -130 mm. Dotted and solid lines are w/o and w/ RMF conditions respectively.

B. Spatial distributions of v_i and n_e with f_{RMF} = 0.7 MHz

Figures 4 (a) and (b) show radial distributions of v_i and n_e by using the developed scanning instrument at r of 15 mm and z of 50 mm in the downstream and RMF antenna regions, respectively, for the case of P_{rf} = 1 kW, fr = 40 sccm, and I_{RMF} = 55 A_{pp} with f_{RMF} = 0.7 MHz. In terms of n_e, the axial decrease from upstream of the RMF antenna region to the downstream appeared in the presence of divergent magnetic field caused by the permanent magnets, regardless of w/ and w/o RMF. The increment of n_e was found in the entire region, and the maximum value up to 1.2 $\times 10^{12}$ cm^{-3} at r and z of -15 and -330 mm w/ RMF was obtained. This suggests that the RMF method can contribute to plasma generation as well as plasma acceleration. The maximum increasing rate of n_e was ~ 30 % at r and z of -15 and -130 mm, respectively.

With regard to v_i, axial decrease is also found in Figs. 4 (a) and (b). The collision between neutral particles and ions can be a reason in the downstream of RMF antenna. In the outer radius region, v_i was higher than that around r = 0 mm w/o and w/ RMF. This may be due to the assumed constant spatial distributions of T_e, which determines the local ion sound velocity. However, the difference is not so appreciable, since ion velocity is proportional to square of T_e root.

The increasing rates of v_i were not so appreciable in the upstream region of RMF antenna w/ RMF though the maximum value was obtained in the outer region of plasma. The optimal azimuthal current j_θ is expected to be induced in the radial outer region when full penetration condition of RMF into plasma is satisfied where electron starts to rotate azimuthally like a solid body rotation. Therefore, in the present experiment, original RMF acceleration effect might be small and another acceleration effect might contribute to the high increasing rates of v_i in the downstream region considering high increment of n_e in the center region of the plasma; radial and axial density gradients lead to diamagnetic azimuthal current, leading to the axial force in the presence of the diamagnetic field and axial pressure gradient, respectively. Here, the spatial characteristics of plasma parameters were obtained, which enables us to understand spatial acceleration mechanisms. Needless to say, estimation of j_θ is also important. The evaluation of j_θ having a DC component is expected to be done by using a magnetic probe, which can detect a oscillating component with twice as much as f_{RMF} , so as to introduce the axial Lorentz force for future works.

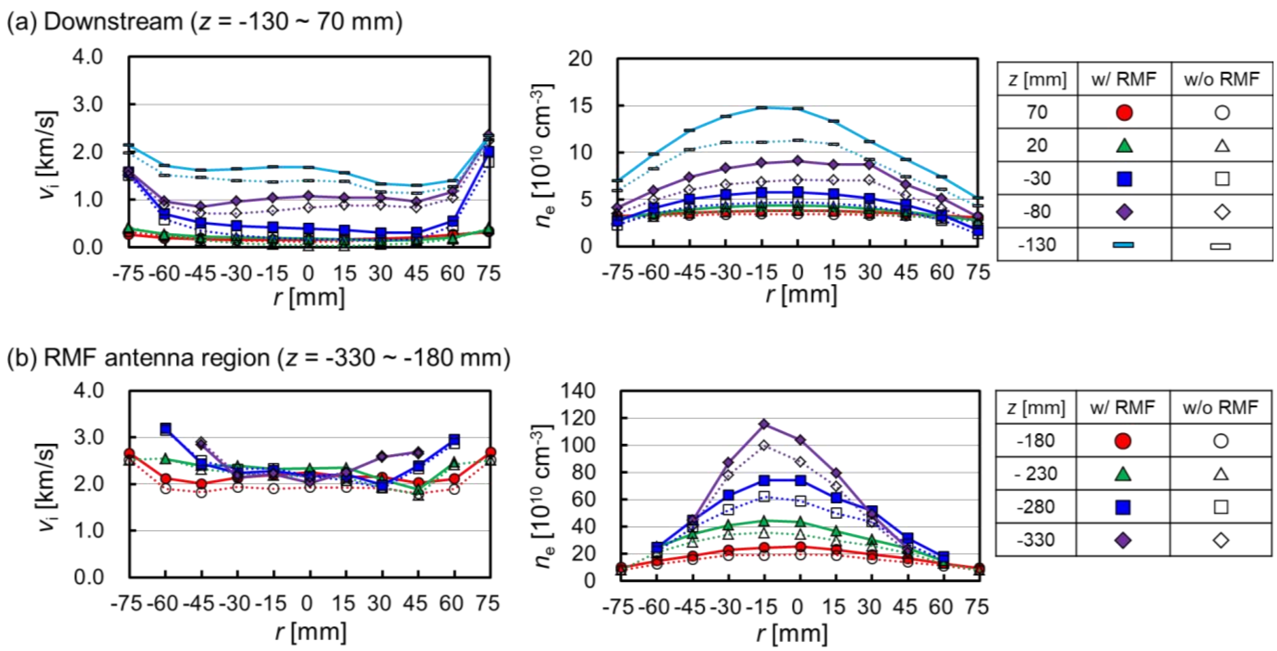

Fig. 4. Radial distributions of (a) v_i and n_e in the downstream region (z = -130 ~ -70 mm) and (b) those in the RMF antenna region for the case of P_{rf} = 1 kW, fr = 40 sccm, and I_{RMF} = 55 A_{pp} with f_{RMF} = 0.7 MHz.

IV.Conclusion

As one of the electrodeless plasma acceleration systems, RMF acceleration method has been proposed and being investigated for the feasibility. In this paper, spatial distributions of plasma parameters, which are ion velocity v_i and electron density n_e, were measured by using a Mach probe mounted on the developed scanning probe instrument, and some spatial characteristics of RMF acceleration from RMF antenna region to the downstream region were obtained: The increments of n_e by applying RMF acceleration method was obtained in the entire region, which suggests that the RMF method may contribute to plasma generation as well. The axial n_e decrement was found, which might be caused by a radial loss of plasma by divergent radial magnetic field and a collision with neutral particle. In future, application of electromagnets will be applied to converge the external magnetic field shape in addition to the use of permanent magnets, for the purpose of decreasing the radial loss and enhancement of plasma axial exhaust.

Higher value of v_i in the outer region than that is the inner region was found regardless of w/ and w/o RMF, and that can be caused by distribution of T_e, which is used to calculate ion Mach number leading to v_i, so that detailed temperature survey will be required by using electrostatic probes. Considering the possibility of the contribution to plasma generation by using the RMF method, the high v_i increment in the center of plasma can be caused by the density gradient including radial and axial directions in present experimental conditions.

For future works, we will try to introduce $2f_{RMF}$ component of induced azimuthal current by using a magnetic probe mounted on the developed, scanning instrument and derive the dc part j_θ by the RMF, leading to the axial Lorentz force.

In order to estimate the RMF penetration condition, a parameter represented by γ / λ (γ: electron cyclotron angular frequency normalized by an electron-ion and an electron-neutral collision frequencies, δ: plasma radius R normalized by skin depth), is utilized and is proportional to I_{RMF}, and $f_{\mathrm{RMF}}^{-1/2}$, as is derived theoretically. According to Milroy's expression,[5] full (partial) RMF penetration can be expected when γ / λ is larger (lower) than 1.12 for $\lambda < 6.5$. The full penetration condition into plasma was satisfied at r = 0 mm and z = -250 mm, which represents the z axis center of RMF antenna, with f_{RMF} = 0.7 MHz, since λ and γ / λ were 3.8 and 1.5 (r = 0 mm) and 3.0 and 4.6 (r = 60 mm) with λ being lower than 6.5 in this experimental condition. Measurement of x-y component of RMF with f_{RMF} by using a magnetic probe is also required to examine the field penetration experimentally in our RMF acceleration scheme.

Acknowledgments

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