Electrodeless plasma acceleration system using rotating magnetic field method

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We have proposed Rotating Magnetic Field (RMF) acceleration method as one of electrodeless plasma accelerations. In our experimental scheme, plasma generated by an rf (radio frequency) antenna, is accelerated by RMF antennas, which consist of two-pair, opposed, facing coils, and these antennas are outside of a discharge tube. Therefore, there is no wear of electrodes, degrading the propulsion performance. Here, we will introduce our RMF acceleration system developed, including the experimental device, e.g., external antennas, a tapered quartz tube, a vacuum chamber, external magnets, and a pumping system. In addition, we can change RMF operation parameters (RMF applied current $I_{RMF}$ and RMF current phase difference $\phi_{RMF}$, focusing on RMF current frequency $f_{RMF}$) by adjusting matching conditions of RMF, and investigate the dependencies on plasma parameters (electron density $n_e$ and ion velocity $v_i$); e.g., higher increases of $n_e$ and $v_i$ (−360 % and 55 %, respectively) than previous experimental results were obtained by decreasing $f_{RMF}$ from 5 MHz to 0.7 MHz, whose RMF penetration condition was better according to Milroy’s expression. Moreover, time-varying component of RMF has been measured directly to survey the penetration condition experimentally. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.4998248

I. INTRODUCTION

In the field of a space propulsion, electric propulsion systems have been studied due to an advantage of the higher fuel efficiency than that of chemical ones. However, conventional electric thrusters, e.g., gridded ion thruster,1 Hall thruster,2 and Magneto-Plasma-Dynamics (MPD) thruster,3 have electrodes, which contact with plasma directly, and this interaction makes an operating time limited and a long space exploration difficult because of the erosion of the electrodes.

In order to accomplish a longer operating time, which is in proportion to a specific impulse (exhaust velocity divided by gravitational acceleration), and high thrust performance for a next generation space propulsion scheme, some electrodeless plasma thrusters have been proposed and studied on, e.g., Electron Cyclotron Resonance (ECR) plasma thruster,4 Variable Specific Impulse Magnetoplasma Rocket (VASIMR),5 ratio frequency (rf) plasma thruster.6 In these acceleration schemes, the plasma production and heating are conducted by external rf antennas, employing microwave ECR, Ion Cyclotron Heating (ICH), and a magnetic expansion scheme (so-called a magnetic nozzle). Among all, helicon electrodeless plasma acceleration,6,7 using a helicon wave6 excitation to generate plasmas (electron density $n_e$ is up to $\sim 10^{13}$ cm$^{-3}$) with additional acceleration methods have been studied under the Helicon Electrodeless Advanced Thruster (HEAT)7,8 project. Here, we have proposed one of the electrodeless plasma accelerations, i.e., Rotating Magnetic Field (RMF)9,10,11 acceleration scheme.7,8,12,13 This RMF method comes from the field of magnetically

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confined plasma fusion research in order to induce an azimuthal current to maintain the Field Reversed Configuration (RFC). In this acceleration scheme, an rf antenna, which is outside of a discharge tube, is used to produce a plasma, and the plasma acceleration is conducted by two pairs of opposed, facing RMF coils, wound around the discharge tube in the downstream of the plasma generation region. In our acceleration stage, the RMF coils are expected to induce an azimuthal current \( j_0 \), whose mechanism will be shown in the next section, and plasmas can be accelerated by the axial Lorentz force \( f_z \) by the product of induced \( j_0 \) and a radial component of an applied external magnetic field \( B_r \). Here, the process of generating \( f_z \) is described in Sec. II. It is very novel to apply this method to electromagnetic plasma acceleration under the divergent magnetic field, and this method will be a next generation electric propulsion scheme, if promising.

Our RMF experiment has been conducted using the Large Mirror Device (LMD),\(^ {14} \) and we can install RMF system and diagnostic instruments, which will be described in Sec. III. In our previous study on RMF acceleration, we applied RMF with RMF current frequency \( f_{\text{RMF}} = 5 \text{ MHz} \),\(^ {12} \) and surveyed the operation parameters (rf power \( P_{\text{rf}} \), gas flow rate \( fr \), and external magnetic field).\(^ {15} \) Here, we found that RMF could penetrate fully at a radial position of discharge tube \( r = 60 \text{ mm} \), where plasma radius \( R \) is 85 mm, and partially at \( r = 0 \sim 45 \text{ mm} \) into plasma, respectively, according to the Milroy’s expression of RMF penetration condition.\(^ {11} \) Recently, dependences of an electron density \( n_e \) and ion velocity \( v_i \) on \( f_{\text{RMF}} \) have been investigated by changing \( f_{\text{RMF}} \) form 5 MHz to 3 MHz.\(^ {13} \) Higher increasing rates of \( n_e \) and \( v_i \) denoted as \( \Delta n_e/n_e \) and \( \Delta v_i/v_i \), respectively, have been obtained: up to \( \sim 70\% \) and \( \sim 28\% \), respectively with \( f_{\text{RMF}} = 3 \text{ MHz} \) than these with 5 MHz.\(^ {10} \) We have also examined the RMF operation conditions, e.g., RMF current \( I_{\text{RMF}} \) and RMF current phase difference \( \phi \). Here, \( \phi \) represents the rotating direction of RMF, and \( \phi = 90 \text{ deg.} \) and -90 deg. denote an acceleration and deceleration phases, respectively. Moreover, we have found that \( \Delta n_e/n_e \) and \( \Delta v_i/v_i \) were increased in proportion to \( I_{\text{RMF}} \),\(^ {2} \) and they behaved nearly sinusoidal curves by changing \( \phi \).\(^ {13} \)

Here, we have further decreased \( f_{\text{RMF}} \) from 3 MHz to 1 MHz as well as 0.7 MHz with applying higher \( I_{\text{RMF}} \), since we can easily change the rf matching conditions, e.g., series/parallel capacitances and series inductance in matching boxes in a wide range of RMF excitation frequency, and made RMF penetration condition better, at the expense of lower induced \( j_0 \), which is proportional to \( f_{\text{RMF}} \) if a full penetration condition is satisfied. We have also investigated the dependencies of \( n_e \) and \( v_i \) on \( I_{\text{RMF}} \) and \( \phi \), where radial measurement positions were the same as previous experiments with \( f_{\text{RMF}} = 3 \text{ MHz} \). The present results show that the maximum \( \Delta n_e/n_e \) and \( \Delta v_i/v_i \) were \( \sim 55\% \) and \( \sim 360 \% \) with \( f_{\text{RMF}} = 1 \text{ MHz} \) (\( I_{\text{RMF}} = 46 \text{ A_{pp}} \)), respectively, and these results showed that decreasing \( f_{\text{RMF}} \) with an increment of \( I_{\text{RMF}} \) can enhance the thermal thrust, which is represented as surface integrals of a static pressure \( n_e k_B T_e \) and a dynamic pressure \( n_i m_i v_i^2 \), where \( n_i \) is ion density (= \( n_e \)), \( k_B \) is Boltzmann constant, \( T_e \) is electron temperature, \( n_i \) is ion density, and \( m_i \) is ion mass. This is caused by higher \( n_e \) and \( v_i \) obtained by the RMF method. Moreover, radial distributions of time-varying component of RMF, \( \bar{b}_z \), which is orthogonal to the axial direction of the discharge tube, were measured to examine the RMF penetration condition with \( f_{\text{RMF}} = 0.7 \text{ MHz} \) and 1.5 MHz by using a magnetic probe, and full and partial penetrations were consistent with expectation.\(^ {11} \)

This paper is organized as follows. Theoretical background of the RMF acceleration method, i.e., the process of inducing the azimuthal current \( j_0 \), and experimental setup, including our plasma source, RMF coils, and plasma diagnostics, are described in Sec. II and III, respectively. In Sec. IV, the present RMF experimental results with \( f_{\text{RMF}} = 0.7 \text{ MHz} \) and 1 MHz by changing external parameters are shown, accompanied by a better plasma performance than those with \( f_{\text{RMF}} = 5 \text{ MHz} \). Discussion, in particular, about RMF penetration condition and the thermal pressure, and conclusion of our present research is described in Sec. V and VI, respectively.

## II. RMF ACCELERATION METHOD

Originally, inducing an azimuthal current \( j_0 \) by using RMF has been performed in the field of nuclear fusion, as was mentioned, and we applied this method to space plasma propulsion with higher current frequency than that of general FRC operation by one order of magnitude, considering a higher \( j_0 \) to achieve a high axial thrust effectively. Here, \( f_{\text{RMF}} \) is in the range \( f_{ci} << f_{\text{RMF}} << f_{ce} \).
FIG. 1. Schematic diagram of the RMF coils to induce an azimuthal current $j_\theta$, generating the axial Lorentz force $f_z$ [(a) bird’s eye view and (b) cross section view].

where $f_{ci}$ and $f_{ce}$ are an ion and electron cyclotron frequencies, respectively, and electrons can rotate in the azimuthal direction, as shown in Fig. 1(b). We will theoretically explain the proposed RMF acceleration process as follows. First, Rotating Magnetic Field $B_{\text{RMF}}$ can be given as Eq. (1), considering a cylindrical plasma:

$$B_{\text{RMF}} = B_0 \cos (\omega_{\text{RMF}} t - \theta) e_t + B_0 \sin (\omega_{\text{RMF}} t - \theta) e_\theta. \quad (1)$$

Here, $\omega_{\text{RMF}}$ is RMF current angular frequency ($= 2\pi f_{\text{RMF}}$), and $B_0$ is an amplitude of the rotating magnetic field, and $\theta$ is an arbitrary initial phase angle. Second, an axial oscillating electric field $\tilde{E}_z$ is induced due to the faraday’s electromagnetic induction law:

$$\nabla \times \mathbf{E} = -\frac{\partial B_{\text{RMF}}}{\partial t}. \quad (2)$$

Then, a time-varying axial current $\tilde{j}_z$ is induced by the Ohm’s law, as shown in Eq. (3):

$$\mathbf{E} + \frac{1}{n_e e} (\mathbf{j} \times B_{\text{RMF}}) = \eta \mathbf{j}. \quad (3)$$

Here, $e$ and $\eta$ are elementary charge and plasma resistivity, respectively. Third, the Hall term $<\tilde{j}_\theta \tilde{B}_r>$ in the second term on the LHS of Eq. (3) is proposed with the radial component $\tilde{B}_r [= B_0 \cos(\omega_{\text{RMF}} t - \theta)]$ of $B_{\text{RMF}}$. Therefore, $j_0$ term, which is on the RHS of Eq. (3), has a steady and a time-varying ($2\omega_{\text{RMF}}$ component) parts. Electrons can rotate in the azimuthal direction with the velocity $v_{e\theta}$, which is derived from a force balance between the drag force due to particle collisions and the driving force, and dc component of $j_0$ is generated as shown in Eq. (4):

$$j_0 = -n_e e v_{e\theta}. \quad (4)$$

Finally, the axial Lorentz force $f_z$ is generated by the product of this $j_0$ and an external applied radial magnetic field $B_r$, as shown in Eq. (5), and this schematic diagram is shown in Fig. 1(a):

$$f_z = j_0 \times B_r. \quad (5)$$

In the full penetration condition of RMF, the electrons rotate in the azimuthal direction like a rigid body rotation, and $v_{e\theta}$ can reach the maximum value $v_{e\theta, \text{max}}$, as shown in Eq. (6):

$$v_{e\theta, \text{max}} = r \omega_{\text{RMF}}. \quad (6)$$

### III. EXPERIMENTAL SETUP

#### A. Large mirror device

In our experiment, we use Large Mirror Device (LMD) at Tokyo University of Agriculture and Technology, as shown in Fig. 2. The device has a 1,700-mm-long and 445-mm-inner diameter cylindrical vacuum chamber with a 1,000-mm-long quartz tube, and is evacuated by two turbomolecular pumps, whose pumping speeds are 1,000 l/s and 2,400 l/s, respectively, with a typical back
FIG. 2. Schematic diagram of LMD and peripheral apparatuses.

ground pressure of $\sim 10^{-4}$ Pa. This quartz tube has a tapered shape (100 $\sim$ 170-mm-inner diameter), expected to decrease an interaction between plasmas and the tube wall, considering a divergent magnetic field generated by permanent magnets and electromagnets. As a propellant gas, argon gas is injected continuously from a flange port located on an upstream side of the quartz tube via a mass flow controller, where the gas flow rate can be controlled up to 100 sccm. A half-helical antenna, whose azimuthal mode of $m = 1$, is wound around the quartz tube to generate a plasma, whose $n_e$ can be raised up to $\sim 10^{13}$ cm$^{-3}$ if we use electromagnets as well as permanent magnets, whose grade is N35 made by NeoMag Co. Ltd, located as shown Fig. 2. In our present experiment, only permanent magnets are used, which has non-uniform magnetic field profile, so-called magnetic nozzle. This field profile makes the axial thrust through the product of the radial component of the external magnetic field $B_r$ and the induced diamagnetic current in the azimuthal direction $j_\theta$. In our previous experiment, the magnetic nozzle effect was investigated by the use of Laser Induced Fluorescence (LIF) method and thrust measurement by means of a target type thrust stand w/o RMF method. An excitation rf frequency for plasma production is 7 MHz for a 75 ms pulsed discharge (5 % duty) at intervals of 1.5 s, which is controlled by a function generator. With respect to the rf discharge, a high power source (Thamway, T162-6746A), whose maximum power is $\sim 5$ kW for the frequency with a range of 3 - 15 MHz, and used with an impedance matching box (Thamway, T020-6326AK), which can change values of parallel/series capacitances, are utilized. Here, the typical input rf power is $\sim 1$ kW (3 kW is described only in Sec. E).

B. RMF coils

As an RMF acceleration antenna, two sets of 5 turns, opposing coils with 168-mm-axial and 115-mm-azimuthal length are at axial position of $z = -330 \sim -162$ mm in a downstream region of fr antenna, considering the divergent magnetic field shape to have the $B_r$ component [see Eq. (5)], as shown in Fig. 2. The material of this RMF coils is oxygen-free copper, which has a 15-mm-width and a 0.5-mm-thickness, shielded by an insulation tube. Phase difference $\phi$ between the two-set coils’ current $I_{\text{RMF}}$ can change the rotation direction of $B_{\text{RMF}}$: $\phi = 90$ and -90 degrees denote axial plasma acceleration and deceleration phases, respectively, as was mentioned. Here, $I_{\text{RMF}}$ can be controlled by using two sets of rf power supplies (Thamway, T145-6326CK and T145-6326B), and $\phi$ and $f_{\text{RMF}}$ are adjusted by a function generator, as shown in Fig. 3(a). Depending on $f_{\text{RMF}}$ and target plasma parameters, RMF matching condition can be adjusted by using matching boxes, as shown in Fig 3(a). We apply 30 ms RMF from $t = 35$ to 65 ms for the 75 ms rf pulsed discharge. This RMF operation enables us to compare the plasma performance between the cases of w/and w/o RMF easily in one shot, and it was confirmed that the rf discharge w/o RMF does not change compared to the one after finishing RMF application ($t = 65 - 75$ ms), as shown in Fig. 3(b).

C. Plasma diagnostics

In our plasma diagnostic of local plasma flow velocity in addition to plasma density, Mach probe method has been adopted to estimate the RMF acceleration effect. A straight type Mach probe is at $z = -130$ mm to measure $v_i$ and $n_e$ in the downstream of RMF antenna, as shown in Fig. 4(a).
FIG. 3. Schematics of (a) RMF antenna and peripheral apparatuses and (b) example of $v_i$ (red line) and $n_e$ (blue line) with 30 ms RMF application (green hatched region) during 75 ms rf discharge.

FIG. 4. Schematics of (a) a straight type Mach probe and (b) a magnetic probe.

Concerning electrodes to capture ion saturation current, two tungsten rods with a diameter of 0.8 mm are inserted into holes of an insulation $\text{Al}_2\text{O}_3$ tube, and an exposed length of both electrodes to a plasma is 4 mm, considering the sheath thickness. The insulation tube has a separating barrier to divide a plasma flow into an upstream and a downstream sides of the electrodes. Thus, ion Mach number can be calculated by a ratio of ion saturation current densities between the two electrodes,

FIG. 5. Measured $\Delta n_e/n_e$ (open red circle) and $\Delta v_i/v_i$ (open blue diamond) by changing $I_{\text{RMF}}$ at $r = 60$ mm and $z = -130$ mm with (a) $f_{\text{RMF}} = 0.7$ MHz and (b) $f_{\text{RMF}} = 1$ MHz ($P_{\text{rf}} = 1$ kW, $fr = 40$ sccm, and $\phi = 90$ deg.).
employing an unmagnetized model, whose model number $\kappa$ is 1.26,\textsuperscript{19,20} and then a local $v_i$ can be derived, using a typical $T_e$ of 5 eV in our experimental scheme. Generally, $v_i$ data by a Mach probe\textsuperscript{12} agree with the ones by Laser Induced Fluorescence (LIF) method within a factor of $\sim$ 1.5.\textsuperscript{21} A local value of $n_e$ can be also calculated by an average of ion saturation currents from both electrodes, and these experimental values are derived from time average of each discharge shot by shot, using eight discharges.

In addition, a measurement of time-varying component of RMF, $\tilde{b}_\perp$, which is orthogonal to the axial direction, has been conducted by using a magnetic probe, whose loop diameter and number of the turn are 10 mm and 2 turns, respectively. The probe consists of a co-axial cable inserted into insulation Al$_2$O$_3$ tube and a probe tip is coated with ceramic bond, as shown in Fig. 4(b). The coil surface, which detects the magnetic field, is vertical to the radial direction of the quartz tube, and can be scanned to obtain the radial distributions of $\tilde{b}_\perp$ at $z = -250$ mm, which is about the same position of the axial center of RMF coils.

IV. MEASUREMENTS RESULTS OF RMF ACCELERATION

To examine the RMF acceleration method, following experiments were performed under the experimental conditions, as shown in Table I, and experimental results presented as follows: Sec. A. $\Delta n_e/n_e$ and $\Delta v_i/v_i$ by changing $f_{\text{pp}}$ with $f_{\text{RMF}} = 0.7$ MHz and 1 MHz, Sec. B. Radial distributions of $n_e$ and $v_i$ by changing $f_{\text{pp}}$ with $f_{\text{RMF}} = 0.7$ MHz and 1 MHz, Sec. C. Comparisons of $\Delta n_e/n_e$ and $\Delta v_i/v_i$ between $f_{\text{RMF}} = 0.7$ MHz, 1 MHz, and 5 MHz. Sec. D. Dependences of $\Delta n_e/n_e$ and $\Delta v_i/v_i$ on $\phi$ with $f_{\text{RMF}} = 0.7$ MHz, and Sec. E. Radial distributions of radial component of RMF, $\tilde{b}_\perp$.

A. $\Delta n_e/n_e$ and $\Delta v_i/v_i$ by changing $f_{\text{RMF}}$ with $f_{\text{RMF}} = 0.7$ MHz and 1 MHz

Figures 3(a) and (b) show the plots of the measured $\Delta n_e/n_e$ and $\Delta v_i/v_i$ with $f_{\text{RMF}} = 0.7$ MHz and 1 MHz, respectively, as a function of $I_{\text{RMF}}$ at $r = 60$ mm and $z = -130$ mm for the case of $P_{\text{rf}} = 1$ kW, $f_{\text{pp}} = 40$ sccm, and $\phi = 90$ deg. The maximum value of $I_{\text{RMF}}$ was not the same between $f_{\text{RMF}} = 0.7$ MHz and 1 MHz due to a different impedance matching of an rf circuit, and $I_{\text{RMF}} = 0$ A$_{\text{pp}}$ means the case of without applying RMF to plasma. Here, $\Delta v_i/v_i$ as well as $\Delta n_e/n_e$ increased almost quadratically by increasing $I_{\text{RMF}}$. When $I_{\text{RMF}}$ is $\sim 60$ (46) A$_{\text{pp}}$ with $f_{\text{RMF}} = 0.7$ (1) MHz, the maximum $\Delta n_e/n_e$ and $\Delta v_i/v_i$ were $\sim 200$ (360) $\%$ and $\sim 27$ (55) $\%$, respectively. The increase of $n_e$ was much higher than that of $v_i$ in the present experimental conditions in both cases of $f_{\text{RMF}}$, and increasing rates of $n_e$ and $v_i$ were higher in the case of $f_{\text{RMF}} = 1$ MHz than that of $f_{\text{RMF}} = 0.7$ MHz at the same $I_{\text{RMF}}$. Therefore, a further increase of $I_{\text{RMF}}$ with $f_{\text{RMF}} = 1$ MHz is expected to have the better plasma performance. These high increases of $n_e$ contribute to the thermal thrust: dynamic pressure $n_e m_i v_i^2$ (the product of ion flux $n_i v_i$ and momentum $m_i v_i$), and static pressure $n_e k_B T_e$ increased by increasing $I_{\text{RMF}}$, which will be described in Sec. V.

B. Radial distributions of $n_e$ and $v_i$ by changing $f_{\text{pp}}$ with $f_{\text{RMF}} = 0.7$ MHz and 1 MHz

Figures 6(a)-1 and 2 show radial distributions of $n_e$ with $f_{\text{RMF}} = 0.7$ MHz ($I_{\text{RMF}} = 50$ A$_{\text{pp}}$) and 1 MHz ($I_{\text{RMF}} = 30$ A$_{\text{pp}}$), respectively, and Figs. 6(b)-1 and 2 show those of $v_i$, w/o and w/RMF, respectively. Here, $P_{\text{rf}} = 1$ kW, $\phi = 90$ deg., and $f_{\text{pp}}$ was changed: 20, 40, and 60 sccm.

| $f_{\text{RMF}}$ | $0.7$ (1) MHz |
|------------------|----------------|
| Phase difference $\phi$ of $I_{\text{RMF}}$ | $-180$ $\sim$ $180$ deg. |
| RMF current $I_{\text{RMF}}$ | $\sim 10$ A$_{\text{pp}}$ | $\sim 15$ A$_{\text{pp}}$ | $\sim 36$ A$_{\text{pp}}$ | $\sim 60$ A$_{\text{pp}}$ |
| Total input | $\sim 91$ W | $\sim 300$ W | $\sim 1.1$ kW | $\sim 2.6$ kW |
| RMF power | ($\sim 75$ W) | ($\sim 165$ W) | ($\sim 1.5$ kW) | (-) |
| $B_{\text{in}}$ (center) | $\sim 2.0$ G | $\sim 3.2$ G | $\sim 6.1$ G | $\sim 12$ G |
| Glass flow rate $f_{\text{pp}}$ | 20, 40, 60 sccm |
FIG. 6. (a)-1 and 2 show radial distributions of \( n_e \) with \( f_{RMF} = 0.7 \) MHz and 1 MHz, respectively, and (b)-1 and 2 show those of \( v_i \), w/ (solid lines) and w/o (dotted lines) applying RMF, respectively \([z = -130 \text{ mm for the case of } P_{rf} = 1 \text{ kW, } fr = 20 \text{ sccm (square), 40 sccm (triangle), and 60 sccm (circle), and } \phi = 90 \text{ deg.}]\).

For both cases of \( f_{RMF} = 0.7 \) MHz and 1 MHz, \( n_e \) increased with applying RMF, and the highest values are at \( r = 0 \) mm (center of the quartz tube), and the decreases of \( n_e \) toward the outer radial direction are found in both cases of w/ and w/o RMF regardless of \( fr \). The maximum \( \Delta n_e/n_e \) is \( \sim 220 \% \), obtained at \( r = 15 \) mm for the case of \( fr = 60 \) sccm with \( f_{RMF} = 0.7 \) MHz.

With respect to \( v_i \), it also increased with applying RMF in the entire radial positions, and the maximum value of \( \Delta v_i/v_i \) was \( \sim 37 \% \), at \( r = 0 \) mm for the case of \( fr = 40 \) sccm with \( f_{RMF} = 0.7 \) MHz. Compared to \( n_e \), \( v_i \) did not decrease appreciably toward the outer radial direction. This maximum increment of \( v_i \) corresponds to the high \( \Delta n_e/n_e \) around plasma center (pressure gradient along the z axis is also high near this region). As mentioned in Sec. A, \( \Delta n_e/n_e \) and \( \Delta v_i/v_i \) with \( f_{RMF} = 1 \) MHz were higher than those with \( f_{RMF} = 0.7 \) MHz with \( I_{RMF} = 30 \) A_{pp} in all radial positions.

By increasing \( fr \), \( \Delta n_e/n_e \) increased with both \( f_{RMF} \), and the maximum \( \Delta v_i/v_i \) was obtained at \( r = 0 \) mm for the case of \( fr = 40 \) sccm with both \( f_{RMF} \). However, the maximum thermal thrust was obtained for the case of \( fr = 60 \) sccm with both \( f_{RMF} \), since \( \Delta n_e/n_e \) is higher than \( \Delta v_i/v_i \) by \( \sim \) one-order of magnitude even though the maximum \( \Delta v_i/v_i \) were obtained for the case of \( fr = 40 \) sccm.

On the other hand, in terms of RMF acceleration, the degradation of an ionization rate or the collisions between an electron-ion and an electron-neutral particles by increasing \( fr \) should be considered, since these factors affect the RMF penetration and electromagnetic acceleration. In our gas pressure conditions, collision frequency between an electron-neutral particles, \( \nu_{en} \), which is much larger than Coulomb collision frequency, i.e., collision frequency between electron and ion, in our experimental condition, should be calculated in order to estimate the collision effects. In this calculation, the following relations can be utilized:

\[
\nu_{en} = 1.4 \times 10^6 T_e P_0. \tag{7}
\]

Here, \( P_0 \) is neutral pressure [mTorr], and \( T_e \) is taken in unit of eV. Equation (7) comes from approximation of Brown’s experimental data.\textsuperscript{23} For typical values, \( \nu_{en} \) is \( 5.5 \times 10^6 \) s\(^{-1} \), assuming that neutral density does not change in the pressure of the plasma, and the electron mean free path is \( \sim 17 \) cm for \( fr = 40 \) sccm \((P_0 = 0.73 \text{ mTorr at } r \text{ and } z \text{ of 0 and -130 mm, respectively})\). Needless to say, this
collision frequency is related to resistivity $\eta$, which affects the thruster performance in this RMF method.

As discussed above, for an optimal thrust performance, we should consider these target plasma conditions, also including $P_{rf}$ as well as RMF operation conditions. As for a thrust estimation from these radial distribution results, we will discuss this in Sec. V.

C. Comparisons of $\Delta n_e/n_e$ and $\Delta v_i/v_i$ between $f_{RMF} = 0.7$ MHz, 1 MHz, and 5 MHz

Figures 7(a) and (b) show radial distributions of $\Delta n_e/n_e$ and $\Delta v_i/v_i$, respectively, for the case of $P_{rf} = 1$ kW and $f_{tr} = 40$ sccm with $f_{RMF} = 0.7$ MHz, 1 MHz, and 5 MHz. With the decrease of $f_{RMF}$, $\Delta n_e/n_e$ and $\Delta v_i/v_i$ increased in the entire radial positions, although $I_{RMF} = 50$ A_{pp} is higher than other two cases of 30 A_{pp}. In particular, $\Delta v_i/v_i$ with $f_{RMF} = 0.7$ MHz and 1 MHz correspond to high $\Delta n_e/n_e$ at $r = 0$ mm, comparing those with $f_{RMF} = 5$ MHz. Decreasing $f_{RMF}$, increases of $\Delta n_e/n_e$ and $\Delta v_i/v_i$ were found near the plasma center, and a change of $\Delta n_e/n_e$ was higher than that of $\Delta v_i/v_i$. Nearly constant $\Delta v_i/v_i$ for the case of $f_{RMF} = 5$ MHz suggests a partial penetration of RMF, which will be discussed later. These decreases of $f_{RMF}$ are better ($f_{RMF} = 1$ MHz may be best if $I_{RMF}$ is same among three frequencies) compared to the case of $f_{RMF} = 5$ MHz with respect to plasma thrust, as was mentioned in Sec. B. Note that, as one of the important factors of these differences experimentally, the antenna-plasma coupling is also important: The RMF net power, which is absorbed by plasma, and calculated by plasma and antenna resistances, will be discussed in Sec. V.

We need to investigate experimental conditions of acceleration mechanism in addition to the electromagnetic acceleration derived from using the RMF method; e.g., the better efficiency of the axial Lorentz force, produced by diamagnetic current induced by the radial density gradient and axial force by a pressure gradient, in addition to the RMF method proposed. For future works, in order to clarify original electromagnetic acceleration, we plan to measure two-dimensional profiles of $n_e$ and $v_i$ to derive the density gradient in broader region of our...
experimental scheme. In addition, in order to distinguish the original RMF electromagnetic acceleration from that derived from diamagnetic current, as well as a measurement of time-varying $2\omega_{RMF}$ component of magnetic field of RMF (or $\omega_{RMF}$ component), introducing $j_\theta$, as will be described in Sec. V.

### D. Dependences of $n_e$ and $v_i$ on $\phi$ with $f_{RMF} = 0.7$ MHz

Figures 8(a) and (b) show the dependences od $n_e$ and $v_i$ on $\phi$ at $r = 60$ mm for the case of $P_{rf} = 3$ kW, $f r = 60$ sccm, and $I_{RMF} = 50$ A$_{pp}$ with $f_{RMF} = 0.7$ MHz. As was mentioned above, $\phi = 90$ deg. and -90 deg. indicate acceleration and deceleration phases, respectively. The highest $\Delta n_e/n_e$ was $\sim 33\%$ for $\phi = 90$ deg., and the lower was $\sim 1.7\%$ for $\phi = -90$ deg.. Here, the nearly sinusoidal curves of $n_e$ and $v_i$ w/RMF was obtained as a function of $\phi$, as is expected from the RMF scheme$^{10,13}$ (see Sec. II), especially, concerning $v_i$. The RMF coils’ current might also contribute to plasma generation for this experimental condition as well as plasma acceleration, since $n_e$ was increased with applying RMF in any phase except for $\phi \sim -90$ deg., and it is useful from a viewpoint of the thrust increment: Practically, in the case of $\phi = 90$ deg., where $n_e$ and $v_i$ were the highest values. Here, clear wave excitation condition, such as a helicon wave to contribute to a plasma production, was not found in a previous experiment,$^{12}$ but we need to examine the dependence of plasma acceleration on $\phi$ in more detail, trying other experimental conditions to be checked.

### E. Measurements of the orthogonal component of RMF

Measured distributions of $\tilde{b}_\perp$ with $f_{RMF} = 0.7$ MHz ($I_{RMF} = 55$ A$_{pp}$) and 1.5 MHz (20 A$_{pp}$), considering the full and partial penetration conditions od RMF, are shown in Fig. 9(a) and (b), respectively. Figure 7(a) shows that the field may penetrate almost fully into a plasma, since the magnitude w/plasma is slightly higher (lower) than that w/o plasma near the plasma center (outer region). On the other hand, the tendency of partially penetration of RMF can be seen in Fig. 9(b) due to the decrease (increase) of this field in the center (outer region), compared to the case w/o RMF. Therefore, this experimental results indicate that the RMF coils can work as a RMF generation antenna to induce $j_\theta$ due to the full penetration condition. Note that we have lowered $I_{RMF}$ to 20 A$_{pp}$ with $f_{RMF} = 1.5$ MHz, in order to examine the $\tilde{b}_\perp$ distributions in partial RMF penetration condition. Here,
FIG. 9. Measured radial distributions of $\tilde{b}_r$ with (a) $f_{\text{RMF}} = 0.7$ MHz ($I_{\text{RMF}} = 55$ A$_{pp}$) and (b) 1.5 MHz (20 A$_{pp}$), which represent full and partial penetration of RMF, respectively, for the case of $P_{\text{rf}} = 1$ kW and $fr = 40$ sccm. Open circle and square symbols represent w/and w/o plasma, respectively.

the total magnetic flux may be conserved, since the field magnitude was increased (decreased) in the outer (inner) region of $r > (<) 30$ mm.

V. DISCUSSION

Dependencies of plasma parameters on RMF operation conditions were presented before. Moreover, both decreasing of $f_{\text{RMF}}$ and increasing $I_{\text{RMF}}$ under the present experimental conditions are also expected theoretically to enhance the RMF penetration condition, which is discussed in this section by using the Milroy’s expression:

$$\frac{\gamma_c}{\lambda} = \begin{cases} 1.12, & (\lambda \leq 6.5) \\ 1.12 \left[ 1.0 + 0.12(\lambda - 6.5)^{0.4} \right], & (\lambda > 6.5). \end{cases}$$

Here, $\lambda$ is a plasma radius normalized by a typical skin depth and $\gamma_c$ is a critic value to determine RMF penetration boundary, i.e., Hall parameter: an electron cyclotron angular frequency, using the rotating magnetic field, normalized by a sum of an electron-ion and an electron-neutral collision frequencies.

The value of $\lambda$ and $\gamma$ can be calculated from the experimental results/conditions, and a full (partial) RMF penetration condition can be satisfied when $\gamma/\lambda$ is larger (lower) than $\gamma_c/\lambda$, and these values with four $f_{\text{RMF}}$ in the graph of Milroy’s expression are shown in Fig. 8. Generally, central (edge) region shows the lower (high) value of $\gamma/\lambda$, leading to a worse (better) penetration condition. With $f_{\text{RMF}} = 5$ MHz, this field penetration condition cannot be satisfied, since $\lambda$ and $\gamma/\lambda$ are 7.5 and 0.5, respectively, at $r = 0$ mm in our experimental condition, as shown in Fig. 8, considering lower $\gamma/\lambda$ value than $\gamma_c/\lambda$ one. On the other hand, RMF could fully penetrate with only $f_{\text{RMF}} = 0.7$ MHz, since $\lambda$ and $\gamma/\lambda$ are 3.8 (8.2) and 1.6 (0.6), respectively, with $f_{\text{RMF}} = 0.7$ (1) MHz at $r = 0$ mm. On the other hand, $\lambda$ and $\gamma/\lambda$ are 3.0 (5.4) and 4.6 (2.2), respectively, at $r = 60$ mm with $f_{\text{RMF}} = 0.7$ (1) MHz, and $\gamma/\lambda$ are increased with increasing $r$, as shown in Fig. 10. Here, in spite of a rough estimation, the full (partial) penetration condition by measuring radial distributions of RMF $\tilde{b}_r$ with $f_{\text{RMF}} = 0.7$ (1.5) MHz, as shown in Fig. 10, is consistent with the data in Fig. 9.
FIG. 10. Calculated $\gamma/\lambda$ and $\lambda$ with $f_{\text{RMF}} = 0.7$ MHz ($I_{\text{RMF}} = 50$ A$_{\text{pp}}$, circle), 1 MHz (46 A$_{\text{pp}}$, triangle), 1.5 MHz (20 A$_{\text{pp}}$, diamond), and 5 MHz (30 A$_{\text{pp}}$, square), in the graph of Milroy’s expression. Filled symbol represents $r = 60$ mm and the colors become thin gradually with approaching $r = 0$ mm.

In order to clarify this penetration more experimentally, a measurement of RMF oscillating component by using a magnetic probe is required. In addition, from a basic point of clarifying acceleration phenomena, $j_0$ component of the axial Lorentz force $f_z = j_0 \times B_r$ can be estimated by a Rogowski coil or a magnetic probe using $\nabla \times B = \mu_0 j$. Here, measuring $2\omega_{\text{RMF}}$ component of $j_0$ induced by the non-linear effects (mentioned in Sec. II), which is the same amplitude of dc component we are expecting theoretically. This can distinguish the dc component of $j_0$ by a radial pressure gradient from the RMF induced $j_0$, as was mentioned above.

In terms of plasma acceleration, a thermal thrust $F$, which is represented as a sum of surface integrals of a static and a dynamic pressures, can be calculated from radial distributions of $n_e$ and $v_i$, which are shown in Figs. 6(a) and (b):

$$F = \int_0^R \left(n_e m_i v_i^2 + n_e k_B T_e\right) 2\pi r \, dr. \quad (9)$$

Here, $R = 85$ mm is an inner radius of the quartz tube at $z = -130$ mm, $T_e$ is a typical value of 5 eV, and experimental $n_e$ values are taken. By applying RMF, the plasma thrust $F$ are calculated to be increased form $\sim 1.0$ mN w/o RMF to $\sim 2.4$ mN, $\sim 5.1$ mN, and $\sim 1.4$ mN with $f_{\text{RMF}} = 0.7$ MHz ($I_{\text{RMF}} = 50$ A$_{\text{pp}}$), 1 MHz (46 A$_{\text{pp}}$), and 5 MHz (30 A$_{\text{pp}}$), respectively. The thrust to net power ratio are changed from $\sim 1.7$ mN/kW w/o RMF to $\sim 3.2$ mN/kW, $\sim 6.7$ mN/kW, and $\sim 1.9$ mN/kW, with $f_{\text{RMF}} = 0.7$ MHz, 1 MHz, and 5 MHz, respectively. Here, net RF power is 580 W for $P_d = 1$ kW, and total net RMF power were $\sim 300$ W, $\sim 170$ W, and $\sim 200$ W with $f_{\text{RMF}} = 0.7$ MHz, 1 MHz, and 5 MHz, respectively. Here, we have introduced these ratios by using the net rf and RMF powers, which is important in a physical point of view. The maximum thermal thrust is obtained with $f_{\text{RMF}} = 1$ MHz, but the maximum total net power was the case with $f_{\text{RMF}} = 0.7$ MHz, and the maximum thrust to net power ratio is in the case with $f_{\text{RMF}} = 1$ MHz. Based on these thrust performance, we must examine the operation parameters to achieve the better performance with $f_{\text{RMF}} = 1$ MHz, also considering RMF penetration condition, for a future study. The present experimental conditions were not actually optimum ones: Lower electron density, comparing to previous helicon thruster experiments w/o additional accelerations, in order to demonstrate the RMF acceleration effect on plasma parameters, considering RMF penetration condition. For the purpose of increasing the thrust, in particular, with $f_{\text{RMF}} = 1$ MHz, the optimal experimental conditions, e.g., $I_{\text{RMF}}$ and a number of turns of RMF coils, i.e., total ampere-turns, which increase $B_{\text{RMF}}$, considering optimum $f_{\text{RMF}}$ and the inductance of RMF coils, and also a target plasma, e.g., $P_d$ and $f_r$, should be surveyed continuously.

Theoretically, the ideal maximum axial thrust derived from the RMF electromagnetic acceleration in a full penetration condition with $f_{\text{RMF}} = 0.7$ MHz can be calculated roughly by Eqs. (5) and (6), and the value is $\sim 40$ mN with an axial length of 168 mm, which is the same as the present RMF coils’ length, and radial integral region is $0 \sim 70$ mm, considering the tapered shape at $z = -230$ mm.

In order to clarify this penetration more experimentally, a measurement of RMF oscillating component by using a magnetic probe is required. In addition, from a basic point of clarifying acceleration phenomena, $j_0$ component of the axial Lorentz force $f_z = j_0 \times B_r$ can be estimated by a Rogowski coil or a magnetic probe using $\nabla \times B = \mu_0 j$. Here, measuring $2\omega_{\text{RMF}}$ component of $j_0$ induced by the non-linear effects (mentioned in Sec. II), which is the same amplitude of dc component we are expecting theoretically. This can distinguish the dc component of $j_0$ by a radial pressure gradient from the RMF induced $j_0$, as was mentioned above.

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Theoretically, the ideal maximum axial thrust derived from the RMF electromagnetic acceleration in a full penetration condition with $f_{\text{RMF}} = 0.7$ MHz can be calculated roughly by Eqs. (5) and (6), and the value is $\sim 40$ mN with an axial length of 168 mm, which is the same as the present RMF coils’ length, and radial integral region is $0 \sim 70$ mm, considering the tapered shape at $z = -230$ mm.
This is very high from a view point of a practical electric propulsion, but the particle confinement in the external divergent, open magnetic field is poorer than that in a closed magnetic field shape like FRC, due to a short particle axial transit time. In addition, by applying electromagnets, which have not been used in present experiment, magnetic field lines do not touch the inner surface of a discharge tube, and a wall loss is expected to be reduced.

VI. CONCLUSION

As an electrodeless plasma acceleration scheme, we have developed the RMF acceleration system and have carried out the experiment successfully. Here, we have utilized two pairs of 5 turns, opposed facing coils as RMF acceleration antennas with LMD, and changed RMF operation conditions including to $f_{\text{RMF}}$, $I_{\text{RMF}}$, and $\phi$, in addition to target plasma conditions.

The effects of RMF current value $I_{\text{RMF}}$ on plasma parameters, e.g., $n_e$ and $v_i$, changing the current frequency $f_{\text{RMF}}$, have been experimentally investigated, and higher $I_{\text{RMF}}$ leads to the higher $\Delta n_e/n_e$ as well as $\Delta v_i/v_i$. $I_{\text{RMF}}$ contributes to plasma generation in addition to an increment of the rotating magnetic field, leading to a velocity increment [see in Figs. 5(a) and (b)]. Moreover, the maximum $\Delta v_i/v_i$ was $\sim 55\%$ for the case of $P_{\text{rf}} = 1\,\text{kW}, fr = 40\,\text{sccm}, \phi = 90\,\text{deg}.$, and $I_{\text{RMF}} = 46\,A_{\text{pp}}$ with $f_{\text{RMF}} = 1\,\text{MHz}$, caused partly by the higher increase of $n_e$ [see Figs. 5(a) and (b)].

The penetration conditions could be also improved by a decrease of $f_{\text{RMF}}$ and an increase of $I_{\text{RMF}}$. In a full penetration condition, axial Lorentz force $f_z$ can be also saturated theoretically, which is in proportion to $f_{\text{RMF}}$. Moreover, time-varying component of RMF has been measured directly to verify the penetration condition experimentally. Therefore, the tradeoff of $f_{\text{RMF}}$ between RMF penetration conditions and acceleration should be considered; i.e., lowering $f_{\text{RMF}}$ is expected to improve the RMF penetration into a plasma, and on the other hand, a further increase of $I_{\text{RMF}}$ is needed to increase the azimuthal current $j_\theta$ induced by RMF method when the RMF full penetration condition is satisfied. From the experimental results, the thermal thrusts increased with decreasing $f_{\text{RMF}}$, and also increasing $I_{\text{RMF}}$, but the absolute values have not been so high compared to the high-dense helicon experiments due to the present experimental conditions (without these magnets), which have not been optimized.

The dependences of $n_e$ and $v_i$ on RMF current phase $\phi$ between two-facing RMF coils, in particular $n_e$, have been found, as a sinusoidal curve, which can be expected theoretically, and RMF coils’ current could also contribute to a plasma generation. Although the deceleration and acceleration phases have been clearly demonstrated, the wave excitation mechanism, which was discussed in a previous our experiment, have not been investigated this time.

In order to increase $j_\theta$, a further increase of $B_\theta$ is expected, i.e., increases of $I_{\text{RMF}}$ and RMF coils’ turns, with an optimum coil shape, and so on, regardless the tradeoff of $f_{\text{RMF}}$ between RMF acceleration and its field penetration. In terms of $I_{\text{RMF}}$, we plan to make a high-current power supply, e.g., $I_{\text{RMF}}$ is $\sim 300\,A_{\text{pp}}$ changing $f_{\text{RMF}}$ between 0.1 - 1 MHz. Measurements of $j_\theta$ by a Rogowski coil, or time-varying component of axial magnetic field $b_z$ by a magnetic probe to deduce $j_\theta$, are also helpful to estimate the axial Lorentz force and estimate the additional plasma acceleration by using RMF method.

Plasma diagnostics in addition to our present probe method, e.g., as non-contact measurements, Laser Induced Fluorescence (LIF) method, which can measure an ion velocity and temperature without disturbing plasma, and other spectroscopies, are effective to crosscheck our previous measurement. In addition, using a thrust measurement method, e.g., a target stand type, which has a cylindrical shape, considering the collision between the target and particle is an effective method to estimate this RMF acceleration effect.

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1. D. M. Goebel, *IEEE Trans. Plasma Sci.* **36**, 211 (2008).
2. V. V. Zhurin, H. R. Kaufman, and R. S. Robinson, *Plasma Source Sci. Technol.* **8**, R1 (1999).
3. M. Martinez-Sanchez and J. E. Pollard, *J. Propul. Power* **14**, 5 (1998).
4. F. Cannat, T. Lafleur, J. Jarrige, P. Chabert, P. -Q. Elias, and D. Packan, *Phys. Plasmas* **22**, 053503 (2015).
5. F. R. Chag-Díaz, *Sci. Am.* **283**, 90 (2000).
6. C. Charles, *J. Phys. D: Appl. Phys.* **42**, 163001 (2009).
7. S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, and K. P. Shamrai, *IEEE Trans. Plasma Sci.* **42**, 1245 (2015).
8. S. Shinohara, J. *Plasma Fusion Res.* **91**, 412 (2015) (project review paper) [In Japanese].
9. R. W. Boswell, *Phys. Lett.* **33A**, 457 (1970).
10. I. R. Jones, *Phys. Plasmas* **6**, 1950 (1999).
11. D. M. Goebel, *IEEE Trans. Plasma Sci.* **36**, 211 (2008).
12. V. V. Zhurin, H. R. Kaufman, and R. S. Robinson, *Plasma Source Sci. Technol.* **8**, R1 (1999).
13. M. Martinez-Sanchez and J. E. Pollard, *J. Propul. Power* **14**, 5 (1998).
14. F. Cannat, T. Lafleur, J. Jarrige, P. Chabert, P. -Q. Elias, and D. Packan, *Phys. Plasmas* **22**, 053503 (2015).
15. S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, and K. P. Shamrai, *IEEE Trans. Plasma Sci.* **42**, 1245 (2015).
16. S. Shinohara, J. *Plasma Fusion Res.* **91**, 412 (2015) (project review paper) [In Japanese].
17. F. R. Chag-Díaz, *Sci. Am.* **283**, 90 (2000).
18. C. Charles, *J. Phys. D: Appl. Phys.* **42**, 163001 (2009).
19. S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, and K. P. Shamrai, *IEEE Trans. Plasma Sci.* **42**, 1245 (2015).
20. S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, and K. P. Shamrai, *IEEE Trans. Plasma Sci.* **42**, 1245 (2015).
21. D. M. Goebel, *IEEE Trans. Plasma Sci.* **36**, 211 (2008).
22. V. V. Zhurin, H. R. Kaufman, and R. S. Robinson, *Plasma Source Sci. Technol.* **8**, R1 (1999).
23. M. Martinez-Sanchez and J. E. Pollard, *J. Propul. Power* **14**, 5 (1998).
24. F. Cannat, T. Lafleur, J. Jarrige, P. Chabert, P. -Q. Elias, and D. Packan, *Phys. Plasmas* **22**, 053503 (2015).
25. S. Shinohara, H. Nishida, T. Tanikawa, T. Hada, I. Funaki, and K. P. Shamrai, *IEEE Trans. Plasma Sci.* **42**, 1245 (2015).