

Experimental Investigation of Plasma Acceleration by Rotating Electric Field for Electrodeless Plasma Thruster

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Abstract: In order to realize a long lifetime of an electric propulsion system, we have been investigating various electrodeless electric propulsion concepts utilizing a helicon plasma source. In one of our concepts, helicon plasma is electromagnetically accelerated using a rotating electric field in the presence of a diverging static magnetic field. This acceleration concept is called as the Lissajous acceleration. Plasma acceleration experiments have been conducted and plasma acceleration was evaluated using a Mach probe. Although the experiments showed some plasma acceleration, most increment of the plasma velocity is caused by the increment of the electron temperature. The thrust ($4.95 \mu\text{N}$) has not reached feasible values for real applications, and therefore, it is important to find a better operational condition with the aid of a theoretical thrust model. We have developed a theoretical thrust model which consists of a trajectory analysis and an electric field penetration model in the electrostatic approximation. The model shows that present experimental parameters divide from an optimum operational condition which provides the maximum thrust.

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Nomenclature

e	=	electron charge
$\mathbf{B}$	=	magnetic flux density vector
$\mathbf{E}$	=	electric field vector
m	=	plasma particle mass
n	=	plasma particle density
q	=	charge of plasma particle
$\mathbf{v}$	=	velocity
t	=	time
r	=	radial distance
r_0	=	cross sectional radius of thruster
R_L	=	Lamor radius
R_D	=	$\mathbf{E} \times \mathbf{B}$ drift gyration radius
C, D	=	initial position of particle
α	=	initial direction of thermal velocity
β	=	reduction rate of plasma density
ω	=	angular frequency of REF
ω_c	=	angular frequency of cyclotron motion
ω_p	=	plasma frequency
L	=	axial length of acceleration area
V	=	amplitude of the REF voltage
a	=	magnetic coil radius
F	=	thrust force
j_θ	=	azimuthal electric current density
ε	=	angular frequency ratio
μ	=	dimensionless parameter

I. Introduction

AN electric propulsion system is suitable for long-time space missions such as interplanetary flights and satellite attitude control. The Japanese asteroid explorer “Hayabusa” has four ion engines called $\mu 10$ which are one of electric propulsion systems, and the mission was successfully accomplished. However, conventional electric propulsion systems have some problems: e.g. the lifetime due to electrode erosion and contamination caused by contacts between electrodes and the plasma.

The plasma thruster using high-frequency electromagnetic power, in which the electrodes (antennas) do not contact with the plasma, is one of solutions for these problems¹. Some of typical examples of such plasma thruster adopt the electro-thermal plasma acceleration {Variable Specific Impulse Magnetoplasma Rocket (VASIMR)²} or electro-static plasma acceleration {Helicon Double Layer Thruster (HDLT)^{3, 4}}. The plasma source of these thrusters is based on the helicon plasma discharge. The helicon plasma source is one of the radio frequency (RF) plasma production methods which can remove the contact between the antenna and plasma. In VASIMR, the plasma is heated by ion cyclotron resonance and subsequently accelerated through a magnetic nozzle. In HDLTs, the plasma is accelerated by the electrical potential gap between high density plasma inside the source region and low density plasma in the exhaust. On the other hand, the electromagnetic plasma acceleration is expected to achieve a higher performance than the electro-thermal plasma acceleration⁵⁻⁷. However, electrode-erosionless electromagnetic acceleration method has not been particularly studied and not been established yet. In this study, we focus on the electrodeless electromagnetic plasma acceleration.

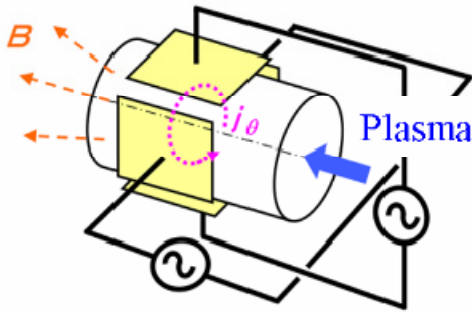


Figure 1. Lissajous acceleration method.

In order to develop the electrode-erosionless electromagnetic plasma thruster, we have initiated the HEAT (Helicon Electrodeless Advanced Thruster) project in Japan and have been investigating several concepts utilizing a helicon plasma source⁸⁻¹⁰. In this paper, recent research results about Lissajous acceleration concept which

is shown in Fig. 1, are reported.

In this study, electromagnetic plasma acceleration by a rotating electric field (REF) called as Lissajous acceleration is discussed. Figure 2 shows the configuration of the Lissajous acceleration type thruster. The thruster consists of a plasma production part and a plasma acceleration part. In the plasma production part, a compact helicon plasma source produces high density plasma by applying an RF power under a static magnetic field. In the plasma acceleration part which lies downstream of the helicon plasma source, a rotating electric field (REF) in the cross-sectional plane of the thruster is applied to the plasma by the two pairs of deflection plates in order to induce an azimuthal electron current. Here radial direction is in the x - y plane in Fig. 2 and the z direction is refereed as the axial direction. The Lorentz force, which is a product of the azimuthal electron current and the radial magnetic field, accelerates the helicon plasma in the axial direction. This acceleration method is called as the Lissajous acceleration. The entire process in this thruster can be conducted without contacts between electrodes (antennas) and the plasma.

In our previous works, an experimental model of the Lissajous plasma thruster was constructed, and high density helicon plasma up to 10^{19} m^{-3} has been successfully produced in the glass tube of 25 mm I.D.¹¹⁻¹³. Some plasma acceleration were observed when REF was applied to the plasma,^{14, 15} however, the apparent electromagnetic acceleration has not been observed. In order to find a parameter range where Lissajous acceleration dominates other acceleration processes such as the electron thermal acceleration, an analytical thrust model is developed^{15, 16}. The analytical model requires radial profiles of plasma parameters. Therefore, it is important to obtain the detailed spatial distributions of the plasma plume and production region.

In this paper, detailed measurements of the plasma plume by use of a Mach probe and an evaluation of the thrust based on the experimental parameters are reported. Several remaining issues in our experiment are discussed, and some guidelines for improving the thrust performance based on a theoretical thrust model.

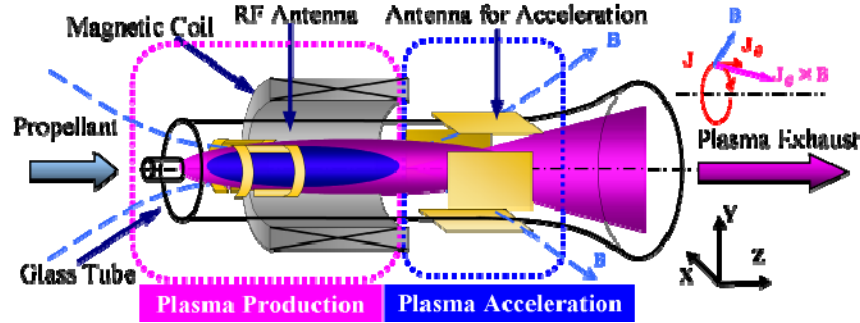


Figure 2. Schematic of Lissajous acceleration thruster.

II. Principle of the Lissajous Acceleration

The principle of Lissajous acceleration is briefly explained using a two-dimensional electron trajectory analysis. Here, we consider the two-dimensional motion of an electron in the cross-sectional plane (x - y plane) in the acceleration area. The REF lies in the x - y plane. A uniform static magnetic field is assumed to be in the z direction. The motion equation of a charged particle under the electric field and the magnetic field in above mentioned geometry can be written as,

$$m_e \frac{d\mathbf{v}_e}{dt} = q(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}). \quad (1)$$

The REF and the static magnetic field are represented in following equations and are substituted into Eq. (1).

$$\mathbf{E} = \begin{pmatrix} E_0 \cos(\omega t) \\ E_0 \sin(\omega t) \\ 0 \end{pmatrix}, \quad (2)$$

$$\mathbf{B} = (0, 0, B_z). \quad (3)$$

Solutions of velocities are obtained as follows,

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} v_0 \cos(-\omega_{ce}t + \alpha) - \frac{eE_0}{m_e\omega - \omega_{ce}/\omega + 1} \sin(\omega t) \\ -v_0 \sin(-\omega_{ce}t + \alpha) + \frac{eE_0}{m_e\omega - \omega_{ce}/\omega + 1} \cos(\omega t) \end{pmatrix}. \quad (4)$$

The trajectory of the electron can be obtained by integrating Eq. (4).

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -\frac{v_0}{\omega_{ce}} \sin(-\omega_{ce}t + \alpha) + \frac{eE_0}{m_e\omega^2 - \omega_{ce}/\omega + 1} \cos(\omega t) + C \\ -\frac{v_0}{\omega_{ce}} \cos(-\omega_{ce}t + \alpha) + \frac{eE_0}{m_e\omega^2 - \omega_{ce}/\omega + 1} \sin(\omega t) + D \end{pmatrix}. \quad (5)$$

The first term in the right hand side of Eq. (5) expresses the cyclotron motion and the second term expresses the motion due to the REF. The particle rotates around the magnetic field by the REF. When the REF frequency ω is chosen to be much higher than the lower hybrid frequency and much lower than the electron cyclotron frequency, the Larmor radius and the gyration radius by the REF are given for the electron as follows:

$$R_L = \frac{v_0}{\omega_{ce}}, \quad R_D = \frac{E_0}{B_z \omega}. \quad (6)$$

Figure 3 (a) shows a typical trajectory of the electron; in the case of $R_L/R_D = 0.11$ and $\omega_{ce}/\omega = 28$. As shown in Fig. 3 (a), the trajectory of the electron is a superposition of the small cyclotron gyration and the large $\mathbf{E} \times \mathbf{B}$ drift gyration.

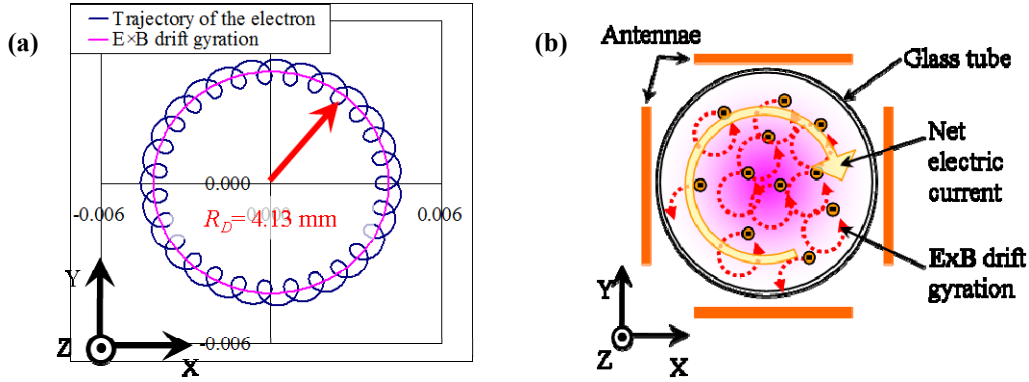


Figure 3. (a) Trajectory of the electron under REF and uniform magnetic field: $R_L/R_D = 0.11$ and $\omega_{ce}/\omega = 28$. (b) Induction of azimuthal electric current by superposition of the $\mathbf{E} \times \mathbf{B}$ gyration motions.

The azimuthal electric current, which is indispensable source for the electromagnetic acceleration, can be produced by superposition of the $\mathbf{E} \times \mathbf{B}$ gyration motions of all electrons, as shown in Fig. 3 (b). A radial density gradient is important for producing the azimuthal electric current. The theoretical thrust model of the Lissajous acceleration has been proposed by using the two-dimensional electron trajectory analysis and by a one-dimensional RF sheath model in the electrostatic field assumption¹⁶. The induced azimuthal electric current density j_θ can be obtained as Eq. (7) by integrating individual electron trajectories for an axial symmetric density profile. The theoretical thrust force F [N] is obtained as Eq. (8) by spatial integration of $j_\theta(r) \times B_r(r)$ with $B_r(r) = B_z/2a$ in the acceleration area. Eq. (7) and (8) are represented under the following assumptions: $R_L \ll R_D \ll r_0$, $v_i \ll v_e$ and the plasma density distribution $n(r) = n_0(1 - \beta r^2/r_0^2)$.

$$j_\theta = -\frac{2}{3} e \beta n_0 \left(\frac{v_D R_D}{r_0} + \frac{v_0 R_L}{r_0} \right), \quad (7)$$

$$F = \frac{\pi}{4} e \beta n_0 L \frac{r_0^2}{a} \left(\frac{E_{p0}^2}{\omega B_z} + \frac{v_0 m_e}{e} \right). \quad (8)$$

Here, the amplitude of the REF penetration into a uniform magnetized plasma (E_{p0}) is obtained from a 1D analysis¹⁶ and is given by,

$$\frac{E_{p0}}{V_0} = 1 - \frac{1}{\mu} \left[\varepsilon - \sqrt{\varepsilon^2 + \mu} \right]^2, \quad (9)$$

$$\varepsilon = 1 - \frac{\omega^2}{\omega_{ce}^2} \approx 1, \mu = \frac{2eV_0\omega_{pe0}^2}{m_e r_0^2 \omega_{ce}^4}. \quad (10)$$

III. Experiment of Lissajous Acceleration

Experiments of Lissajous plasma acceleration are conducted in order to obtain the spatial distribution of the plasma parameters (electron temperature, plasma density and ion acoustic Mach number) of the plume for evaluating the plasma acceleration.

A. Experimental Setup and Procedures

A 26 mm I.D. with totally 400 mm long glass tube is connected to a vacuum chamber (Fig. 4). The setup of the plasma production part and the plasma acceleration part is shown in Fig. 5. Ar gas is supplied from a metallic end plate with a gas port into the glass tube. Three power suppliers provide RF power for plasma production and acceleration independently. A saddle type antenna is used for the plasma production and two pairs of deflection plates are used for the plasma acceleration. A coil which surrounds the glass tube applies magnetic fields up to 0.145 T at the center of the coil. The vacuum pump evacuated the chamber down to 10^{-3} Pa or lower, and the Ar gas is fed by a mass flow controller at a predetermined mass flow rate of 0.5 mg/s which corresponds to the background pressure of 8.2×10^{-2} Pa. A signal generator and a 500 W RF amplifier are used for the plasma production. For plasma acceleration, two RF signals are fed from a function generator, and the relative phase (δ) between those two RF signals is set by the function generator. Subsequently the RF signals

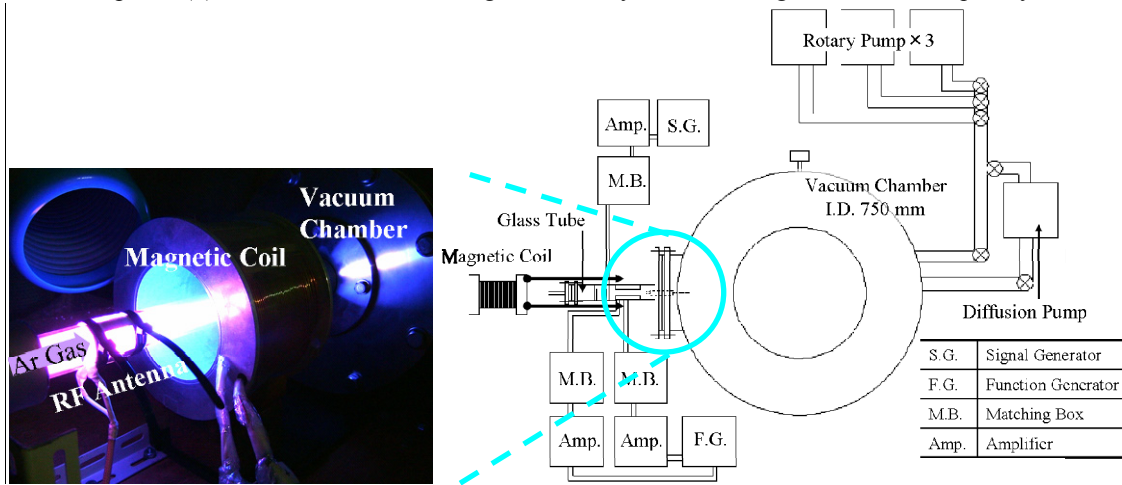


Figure 4. Experimental facility.

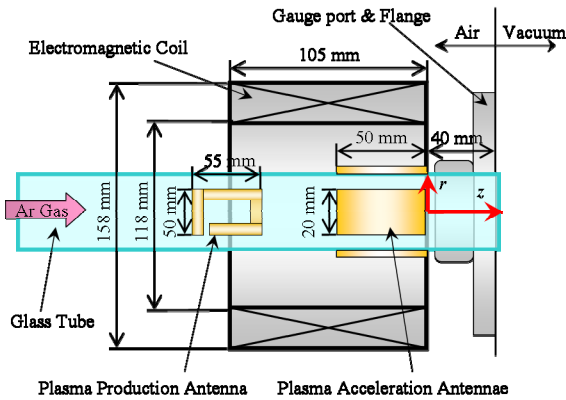


Figure 5. Enlarged view of the thruster.

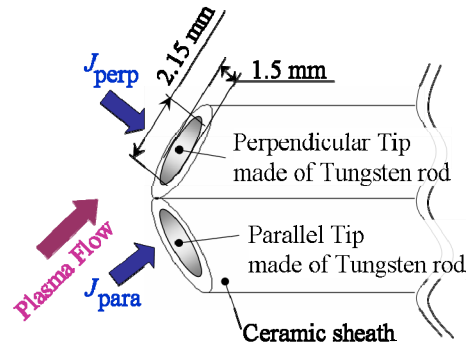


Figure 6. Para-perp type Mach probe.

are amplified by two 200 W amplifiers. The frequency range of the amplifiers is between 20 and 60 MHz. Each amplified signal is transferred to a set of deflection plates through a matching box. Acceleration antennae consist of two pairs of deflection plate and each plate is 50 mm long and 20 mm width.

A para-perp type Mach probe is used for measuring the ion acoustic Mach number, the electron temperature and plasma density. The Mach probe has two directional tips, which are facing parallel and perpendicular to the plasma flow respectively, as shown in Fig. 6.

Experiments are conducted by varying the relative phase (δ). The direction of the electric field oscillation is changed by varying the phase difference as shown in Fig. 7 and the direction of the electromagnetic force is also changed by changing the rotating direction of the electric field. If the electromagnetic force is acting on the plasma, the plasma is accelerated or decelerated depending on the phase difference. The plasma is accelerated (decelerated) at $\delta = 90^\circ$ (-90°).

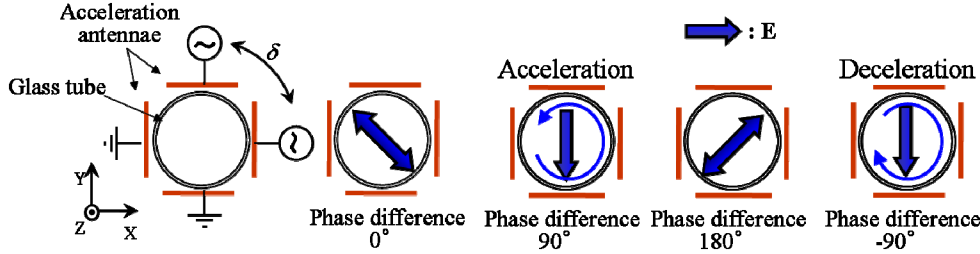


Figure 7. Applied electric field varying the phase difference between two pairs of the antennae.

B. Experimental Conditions

Experimental conditions are shown in Table 1.

Table 1. Experimental conditions.

Vacuum pressure	8.2×10^{-2} Pa
Mass flow rate of Ar gas	0.5 mg/s
Axial magnetic field intensity at acceleration area	0.0950 T
Plasma production power	290 W
Plasma acceleration power	125 W
REF frequency	27.12 MHz

C. Experimental Results

Figures 8 (a), (b), (c) and (d) show the Mach number, electron temperature, plasma density, and plasma velocity plotted against the phase difference, respectively. The plasma parameter is measured 20 mm downstream from the end of the acceleration antennae and at $r = 0$ mm (the center of the plasma plume). Results before applying the acceleration power are shown with the dashed line and this level is refereed as the base in this paper. A weak dependency on the phase difference can be observed as to the Mach number by the slight increase in the range of the phase difference from 0 degree to 90 degrees as shown in Fig. 8 (a). The increase of the plasma velocity is observed in a wide range of δ in a range except for the vicinity of -90° and shows a peak (increments of 1,000 m/s at the phase difference of approximately 90° from the base line) as shown in Fig. 8 (d). Similar increment is observed for the electron temperature as shown in Fig. 8 (b). If the electromagnetic effect exceeds the thermal effect, the acoustic Mach number should be significantly varies responding to the phase difference. As shown in Fig. 8, most increment of the plasma velocity is accompanied by the increment of the electron temperature, i.e. it is considered that the observed plasma acceleration is mainly from thermal effect.

The radial distribution of the plasma parameter is measured at 50 mm downstream from the end of the acceleration antennae for the case of the phase difference of 120° , at which the maximum velocity is achieved. The radial distribution of the plasma velocity and the plasma density are shown in Figs. 9 (a) and 9 (b), respectively. The plasma acceleration by applying the REF can be confirmed in these figures. The electron density with the REF is lower than the base line due to acceleration of the plasma. Equation (11) shows the thrust force evaluated from integrating the momentum flux obtained from the experiments, and the evaluated thrust is $4.95 \mu\text{N}$.

$$F = \int_0^r n(r) v(r)^2 m_{ion} \cdot 2\pi r \cdot dr . \quad (11)$$

Here, contribution from neutral flow is not included thus the thrust is underestimated compared with actual thrust.

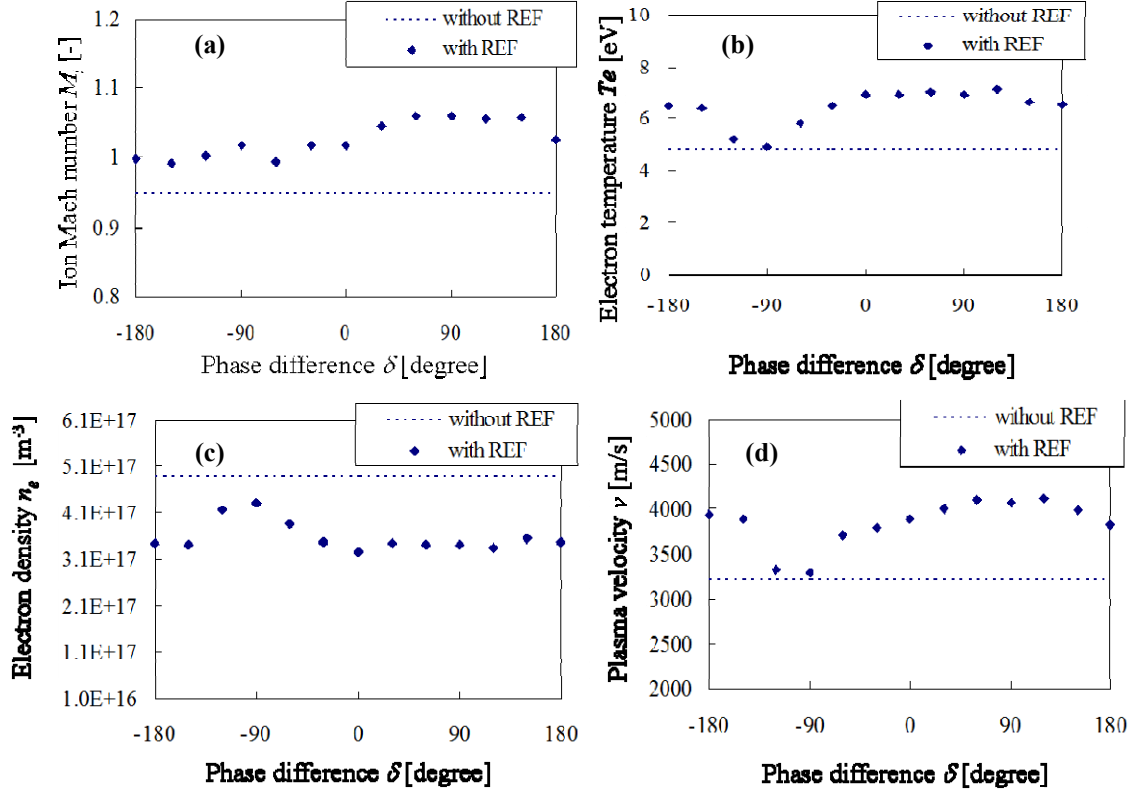


Figure 8. Experimental results varying the phase difference. (a) Mach number, (b) Electron temperature, (c) Electron density, (d) Plasma velocity.

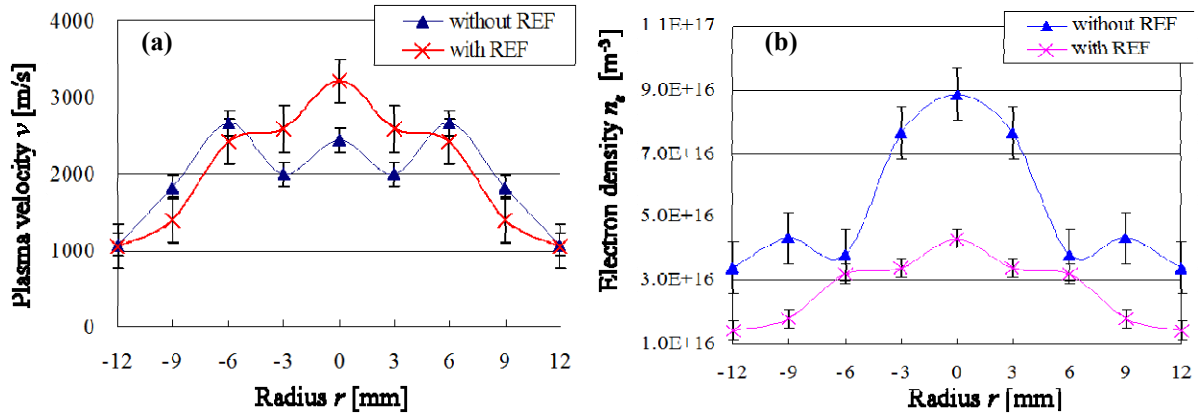


Figure 9. (a) Plasma velocity distribution. (b) Plasma density distribution. Phase difference $\delta = 120^\circ$ and measurement position $z = 50$ mm downstream from the end of the acceleration antennae.

D. Experimental Issues

As described above, the significant electromagnetic effect was not observed in the experiment. One of the issues of the weak electromagnetic effect is that the experimental parameters are not optimized. The guidelines for optimizing the experimental parameters will be discussed in the later section. In addition to non-optimized experimental parameters, there are experimental uncertainties in the applied REF due to our experimental settings and procedures.

The REF conditions are controlled by a function generator and the RF power amplifiers; the phase difference is varied by the function generator, and the REF strength (the strength of electric field) is changed by the output electric power from the amplifier. However, the conditions of the amplified RF signal might be changed between

antennae and the matching box. The REF conditions (applied voltage to the antenna and the phase difference) should be monitored at the acceleration antennas. Monitoring the REF conditions at the acceleration antennas is also for important keeping the repeatability of the experiment.

In the present experiment, the REF signals are fed by two RF power suppliers, and so two plates of the acceleration antennas are grounded through the experiment. In this condition, the applied REF might be distorted inside of the thruster. Non-uniformity of the REF inside of the thruster is evaluated by solving Poisson's equation for electric field using SOR method. Figure 10 shows the simulation domain and Tables 2 (a) and (b) show the simulation conditions; Case 1 denotes the present experimental setting (V3 and V4 plates are grounded), and in the Case 2, three power supplies are used for two-pairs of the deflection plates (i.e. only one plate of V4 is grounded).

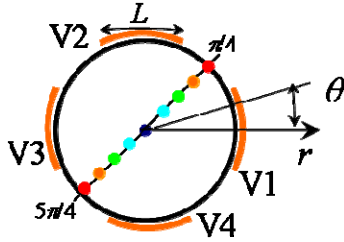


Figure 10. Simulation domain of REF analysis.

Table 2. REF simulation conditions.

(a) Antennae voltages		
Antenna position	Case 1 (two power supplies)	Case 2 (three power supplies)
V1 [V]	$1000\sin(t)$	$500\sin(t)$
V2 [V]	$1000\cos(t)$	$1000\cos(t)$
V3 [V]	0	$-500\sin(t)$
V4 [V]	0	0

(b) Geometrical condition	
Radius : R	0.015 m
Grid point : $I(\text{radius}) \times J(\theta)$	100 x 100
Antenna width : L	0.02 m (0.42π)

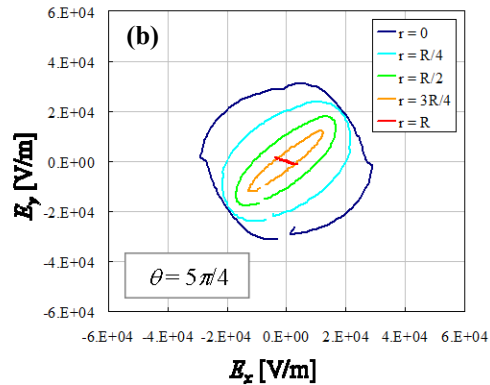
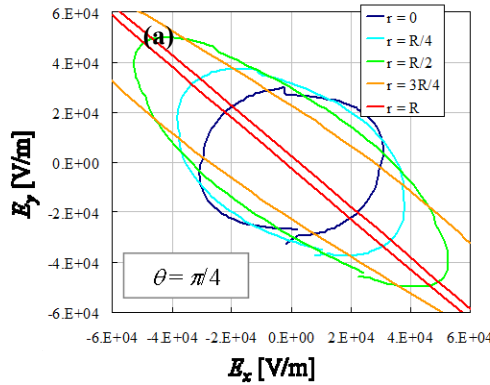


Figure 11. REF analysis in Case1 (two power supplies). Lissajous diagram of the electric field at the radial line (a) at $\theta = \pi/4$, (b) at $\theta = 5\pi/4$. Blue: $r = 0$, Cyan: $r = R/4$, Green: $r = R/2$, Orange: $r = 3R/4$, Red: $r = R$.

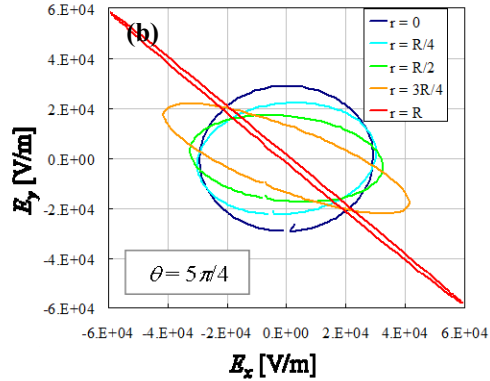
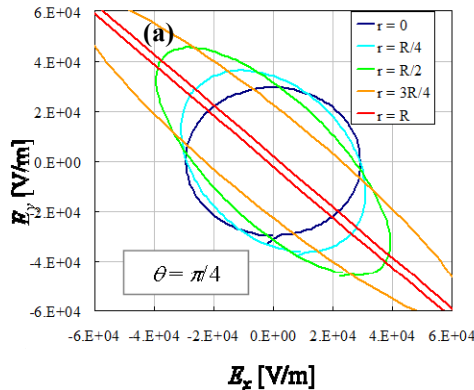


Figure 12. REF analysis Case2 (three power supplies). (a) $\theta = \pi/4$, (b) $\theta = 5\pi/4$. Blue: $r = 0$, Cyan: $r = R/4$, Green: $r = R/2$, Orange: $r = 3R/4$, Red: $r = R$.

Figure 11 shows $E_x - E_y$ Lissajous diagrams at the each point along the radial line (shown in Fig. 10) in the Case 1. From Fig. 11, the Lissajous diagram is deformed from a complete circle at the distant point from the center, and in addition, the Lissajous diagrams in Fig. 11 (a) are totally different from those in Fig. 11 (b); the electric field strength rapidly decays with the distance from the center near the grounded plates (along $\theta = 5\pi/4$ radial line). That is, symmetrical REF is obtained only near the center region. To reform the distortion of the REF, three power suppliers or more need to be used. Figure 12 shows the Lissajous diagrams in the Case 2. As shown in Fig. 12, the symmetry of the REF is apparently improved; the Lissajous diagrams at the radial line of $\theta = 5\pi/4$ become nearly equal to those at the line at $\theta = \pi/4$.

Now, we undertake experiments solving above-mentioned issues; the experimental conditions are set by monitoring the REF condition at the acceleration antennas using a high voltage probe and acceleration power supply system using three power suppliers is constructed.

IV. Discussions for Enhancing Thrust Force

A. Discussion of Theoretical Thrust Model Using Experimental Conditions

As discussed in the previous section, the theoretical thrust model is under development. We plan to benchmark the model by selecting parameter sets for future experiments such that the thrust model shows the maximum electromagnetic force. For the input parameters of the theoretical thrust model, the plasma density and the density distribution factor β are taken from the experimental measurement data at the end of electromagnetic coil; the measured helicon plasma density is shown in Fig. 13. Other geometrical parameters are taken from the experimental condition and are shown in Table 3.

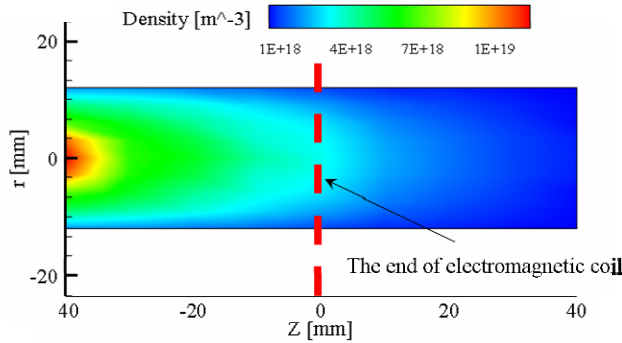


Figure 13. Helicon plasma density distribution.

Table 3. Input Parameters for the Theoretical Thrust Model.

β	0.80
n_0	$3.33 \times 10^{18} \text{ m}^{-3}$
L	0.05 m
r_0	0.013 m
a	0.069 m

The theoretical thrust distributions in the parameter planes of (the axial magnetic field – REF frequency), (the axial magnetic field – the plasma density), (the plasma density – amplitude of the applied REF voltage) and (REF frequency – amplitude of the REF voltage) are shown in Fig. 14, 15, 16 and 17, respectively.

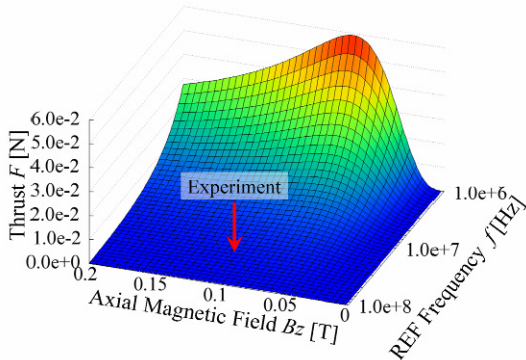


Figure 14. Theoretical thrust in B_z - f plane. Parameters plasma density $n_0 = 3.33 \times 10^{18} \text{ m}^{-3}$ and REF voltage $V_0 = 757.8 \text{ V}$ are fixed.

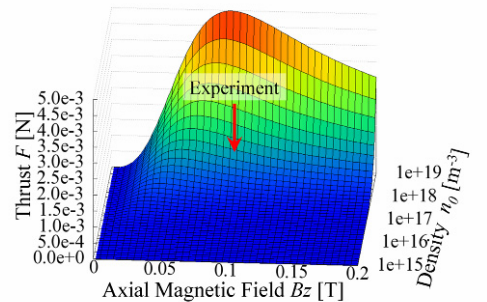


Figure 15. Theoretical thrust in B_z - n_0 plane. Parameters REF frequency $f = 27.12 \text{ MHz}$ and REF voltage $V_0 = 757.8 \text{ V}$ are fixed.

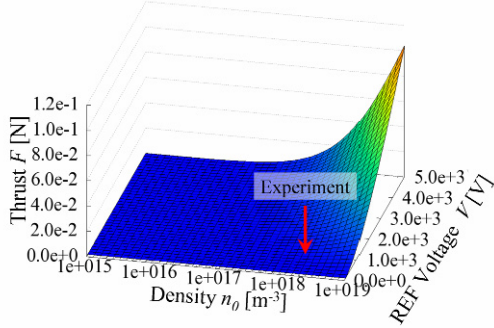


Figure 16. Theoretical thrust in n_0 - V plane. Parameters axial magnetic field $B_z = 0.0950$ T and REF frequency $f = 27.12$ MHz are fixed.

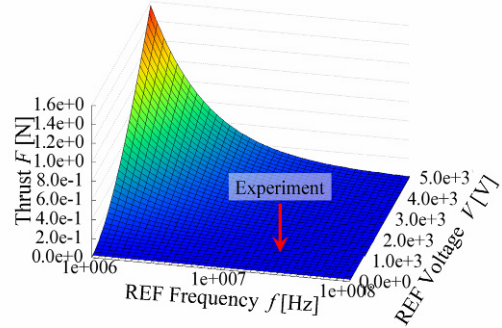


Figure 17. Theoretical thrust in f - V plane. Parameters axial magnetic field $B_z = 0.0950$ T and plasma density $n_0 = 3.33 \times 10^{18} \text{ m}^{-3}$ are fixed.

Figures 14 and 15 show that the theoretical thrust has a peak depending on the axial magnetic field. The strength of the optimum axial magnetic field increases with increasing the plasma density. In addition, the thrust increases either by reducing REF frequency, by increasing plasma density or increasing the REF voltage as shown in Fig. 16 and 17.

B. Constraint on the R_D/r_0

Some guidelines for enhancing the electromagnetic thrust have been obtained from the theoretical thrust model; the electromagnetic thrust increases with lower REF frequency and higher antenna voltage (stronger electric field), and there is an optimum value in the axial magnetic field strength. This discussion is conducted under the condition that the REF frequency, antenna voltage and axial magnetic field strength are free independent parameters. However, when the plasma-loss at the thruster wall is taken into account, there is a constraint on the ratio of the $\mathbf{ExB}$ drift gyration radius R_D to the radius of the thruster (bulk plasma) r_0 ; two-dimensional PIC simulation conducted in our previous work¹⁵ showed that the maximum azimuthal electron current was obtained at $R_D/r_0 = 0.4$.

The theoretical thrust model indicates that larger R_D produces larger electromagnetic thrust force. However, when R_D/r_0 is larger than 0.4, the plasma loss to the wall due to the large gyration motion exceeds the thrust increment. In this way, the REF frequency, the antenna voltage and the axial magnetic field strength are related with each other through the parameter R_D/r_0 . When R_D/r_0 is fixed as 0.4, the relation among the REF frequency, antenna voltage and the axial magnetic field strength is expressed as following;

$$V = 1.6\pi B_z r_0^2 f \quad (12)$$

The relation line between V and f obtained from Eq. (12) is plotted in Fig. 16 assuming $B_z = 0.095$ T, and we can obtain Fig. 18. Figure 19 plots the thrust force against the REF frequency along the relation line in Fig. 18. From Figs. 18 and 19, it is concluded that the REF frequency needs to be increased with increasing antenna voltage.

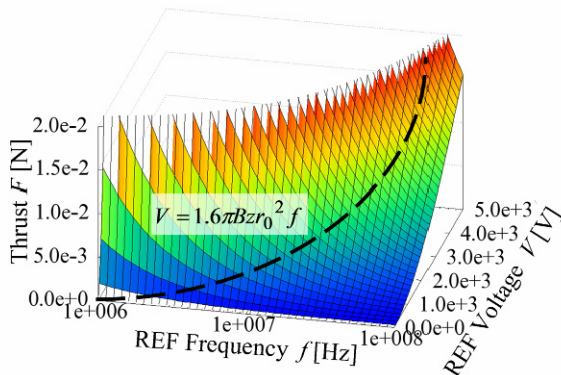


Figure 18. Theoretical thrust in f - V plane. Parameters axial magnetic field $B_z = 0.0950$ T and plasma density $n_0 = 3.33 \times 10^{18} \text{ m}^{-3}$ are fixed. Dashed line shows the relation of Eq. (12).

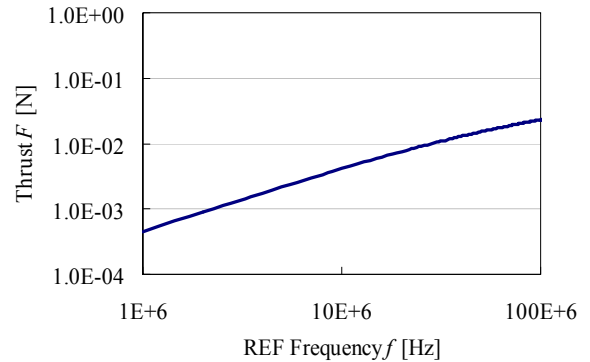


Figure 19. Theoretical thrust vs REF frequency considering the R_D/r_0 limit.

V. Conclusion

In order to realize a long-lived electric propulsion system, we have been investigating the electrodeless electromagnetic plasma thruster concept utilizing a helicon plasma source and the Lissajous plasma acceleration. We developed a laboratory model Lissajous acceleration thruster and relating experiments were conducted. In the experiment, the spatial distributions of plasma parameters in the plume were measured by a Mach probe. Although some plasma acceleration was measured, most increment of the plasma velocity is considered to be caused by the increment of the electron temperature. We still have several issues to be solved have still remained in the experiments, and we undertake experiments solving these issues. A theoretical thrust model was checked in some parameter planes and it was implied that the thrust has a peak at an optimum axial magnetic field for the laboratory model thruster. In addition, the discussion including the constraint of R_D/r_0 was also conducted and it was concluded that the REF frequency needed to be increased with increasing the antenna voltage.

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