Study on Helicon Plasma Lissajous Acceleration for Electrodeless Electric Propulsion

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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 the Lissajous acceleration. Plasma acceleration experiments have been conducted and plasma acceleration was evaluated using a Mach probe. Although the experiments showed some features of the electromagnetic acceleration, most increment of the plasma velocity is caused by the increment of the electron temperature. The thrust (4.95 μN) did not reach 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 experimental parameters are off from an optimum operational condition which provides the maximum thrust.

Key Words: Electrodeless Plasma Thruster, Rotating Electric Field, Lissajous Acceleration, Helicon Plasma

Nomenclature

\( a \) : magnetic coil radius
\( B \) : magnetic flux density vector
\( C_s \) : acoustic velocity
\( C, D \) : initial position of particle
\( E \) : electric field vector
\( e \) : electron charge
\( F \) : thrust force
\( J \) : ion saturation charge
\( k_B \) : Boltzmann constant
\( M_i \) : ion acoustic Mach number
\( m \) : particle mass
\( n \) : number density
\( L \) : axial length of acceleration area
\( q \) : charge of particle
\( r \) : radial distance
\( r_0 \) : cross sectional radius of thruster
\( R_L \) : Larmor radius
\( R_D \) : ExB drift gyration radius
\( T \) : temperature
\( t \) : time
\( v \) : velocity
\( V \) : amplitude of the REF voltage
\( x, y, z \) : coordinate
\( \alpha \) : initial direction of thermal velocity
\( \beta \) : reduction rate of plasma density
\( \varepsilon \) : angular frequency ratio
\( \kappa \) : coefficient for para-perp type Mach probe
\( \mu \) : dimensionless parameter
\( \omega \) : angular frequency of REF
\( \omega_p \) : angular frequency of cyclotron motion
\( \omega_p \) : plasma frequency

Subscripts

\( e \) : electron particle
\( i \) : ion particle
\( x, y, z \) : component
\( 0 \) : initial

1. 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 which are one of electric propulsion systems, and the mission was successfully accomplished. However, conventional electric propulsion systems have some problems about the lifetime due to electrode erosion and contamination caused by contacts between electrodes and the
plasma.

The electrodeless plasma thruster, in which the electrodes do not contact with the plasma, is one of solutions for these problems. Some of typical examples of electrodeless plasma thruster adopt the electro-thermal plasma acceleration {Variable Specific Impulse Magnetoplasma Rocket (VASIMR)\(^{(3)}\)} or electro-static plasma acceleration {Helicon Double Layer Thruster (HDLT)\(^{(4,5)}\)}. 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 are an electrodeless plasma source. In VASIMR, the plasma is heated by ion cyclotron resonance and subsequently accelerated in a magnetic nozzle. In HDLT, 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 acceleration\(^{(5-7)}\). In this study, we focus on the electrodeless electromagnetic plasma acceleration.

In order to develop the electrodeless electromagnetic plasma thruster, we have initiated the HEAT (Helicon Electrodeless Advanced Thruster) project in Japan and have been investigating various concepts utilizing a helicon plasma source\(^{(8-10)}\). In the HEAT project, three types of electrodeless electromagnetic plasma acceleration concept have been investigated: Lissajous acceleration, rotating magnetic field (RMF) acceleration and ion acceleration by the use of ponderomotive force as shown in Fig. 1.

2. 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 on 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 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 and the plasma.

In our previous works, high density helicon plasma up to \(10^{19} \text{ m}^{-3}\) has been successfully produced in the glass tube of 25 mm inner diameter (I.D.)\(^{(11,12)}\) and some plasma acceleration were observed when the REF was applied to the plasma\(^{(14,15)}\). 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\(^{(15,16)}\) which requires radial profiles of plasma parameters as an input. Therefore, it is important to obtain the detailed spatial distribution of the plasma plume and an evaluation of thrust by use of the plasma parameters obtained in experiments.

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. Thrust force is evaluated from the experimentally observed plasma parameters and is compared with the force estimated by the theoretical thrust model. Some guidelines for improving the thrust performance based on a theoretical thrust model.

In this paper, 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 acceleration area which lies downstream of the helicon plasma source, a rotating electric field (REF) in the radial direction 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 and the plasma.

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electron trajectory analysis and a one-dimensional RF sheath model in the electrostatic field assumption. The induced azimuthal electric current density $j_L$ is given by

$$j_L = \frac{2B_0}{3\pi a^2} \left( \frac{E_0 a}{\omega B_0} + v_0 n_e \right),$$

(7)

$$F = \pi \frac{2e}{4} \frac{E_0}{a} \frac{n_e}{\omega B_0} + \frac{v_0 n_e}{e}.$$

(8)

Here, the amplitude of the REF penetration into a uniform magnetized plasma ($E_0$) is obtained from a 1D analysis and is given by,

$$E_0 = \frac{1 - \frac{\mu}{2\epsilon}}{\epsilon} \left( \epsilon - \sqrt{\epsilon^2 + \mu} \right)^2,$$

(9)

$$\epsilon = 1 - \frac{\alpha^2}{\alpha_c^2} = 1, \mu = \frac{2eV_0 \omega e_0}{m_e r_L^2 \omega_c^2}.$$

(10)

In this theoretical thrust model, collision-less plasma is assumed, and so the Hall parameter is enough large. However, when the collision cannot be negligible, the $E_B$ drift radius $R_D$ becomes smaller than the Eq. (6) because of particle collision. As a result of the $R_D$ reduction, the thrust decreases with increasing the particle collision.

3. Experiment of Lissajous Acceleration

Experiments of Lissajous plasma acceleration are conducted in order to obtain radial profiles of the electron temperature and plasma velocity of the plume for evaluating the plasma acceleration.

3.1. 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. Two power supplies 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 is corresponding to the background pressure of 8.2x$10^{-2}$ Pa. A signal generator and a 500 W RF amplifier with a matching box at the frequency of 27.12 MHz are used for the plasma production. For plasma acceleration, two RF signals, which are fed from a function generator, are sent to a phase shifter in

Tb_19
order to adjust the relative phase ($\delta$) between those two RF signals and subsequently amplified by two 200 W amplifiers. The frequency range of the amplifiers is between 20 and 60 MHz. Each amplified signal is sent 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.

$$\frac{J_{\text{para}}}{J_{\text{perp}}} = \frac{M_i}{\kappa} \quad (M_i > 1), \quad (11)$$

$$\frac{J_{\text{para}}}{J_{\text{perp}}} = \exp[aM_i^{1/a}] \quad a = -\ln \kappa \quad (M_i < 1). \quad (12)$$

Electron temperature and electron density can be also measured by using the Mach probe as a double probe. The plasma velocity is obtained from Eq. (13).

$$v = M_i \cdot C_s = \frac{k_B(T_e + T_i)}{m_i}. \quad (13)$$

Ion temperature is fixed at the 0.3eV, which is a typical temperature of helicon plasma. Since the plasma acoustic velocity is dominated by the electron temperature, the assumption of the constant ion temperature is expected to be validated.

Experiments are conducted by varying the relative phase ($\delta$). 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.

3.3. 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. 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 in 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 $\delta$ in a range except for the vicinity of -90° and shows

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a peak increments of 1,000 m/s at the phase difference of approximately 90° from the base as shown in Fig. 8 (d). Similar increment is observed for the electron temperature as shown in Fig. 8 (b).

When the plasma is accelerated by the Lorentz force between radial magnetic field and azimuthal electric current, the electron temperature should not change in the case of collision-less plasma, or be reduced by the adiabatic expansion. Therefore, if the Lorentz force is only acting on the plasma, the ion Mach number is expected to significantly increase with increasing the plasma velocity. Except in the vicinity of -90°, significant dependence of the Mach number on the phase difference cannot be observed; this result indicates weak electromagnetic acceleration of the plasma. When the phase difference is equal to -90°, the plasma condition does not changed by the REF power, and this result indicates that the electrical power from the power supply is not absorbed by the plasma. In addition, the trend of the change in the plasma velocity with the phase difference is strongly correlated with the change in the electron temperature. Therefore, it is considered that almost of the power for the plasma acceleration is consumed for heating the plasma and the plasma acceleration is mainly due to the thermal effect.

The radial distribution of the plasma parameter is measured 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 and 10, respectively.

Fig. 8. Experimental results varying the phase difference.
The plasma acceleration by applying the REF can be confirmed in these figures. The electron density with the REF is lower than the base due to acceleration of the plasma. Eq. (14) shows the thrust force evaluated from integrating the momentum flux obtained from the experiments, and the evaluated thrust is $4.95 \mu N$.

$$F = \int_0^{\infty} \nabla \cdot \rho v \cdot m_{\infty} \cdot 2\pi r \cdot dr.$$ (14)

Contribution from neutral flow is not included thus the thrust is underestimated compared with actual thrust. The fitted curve to the density distribution shown in Fig. 10 reveals that the reduction rate of the plasma density $\beta$ (in Eqs. (7) and (8)) is 0.685. The thrust is theoretically estimated to be 14.2 $\mu N$ by substituting the $\beta$ and experimental other geometrical parameters to the theoretical thrust Eq. (7). The experimental thrust is smaller than the theoretical estimation. From previous experiment, the plasma density inside the acceleration area is approximately 50 times denser than the density at the measurement point. Using the density inside of the acceleration area, the estimated thrust is greater than the experimental thrust by a factor of 200. Therefore the validity of the model may not be confirmed by the data shown here. The discrepancy could arise due to lack of key physics such as wall particle loss, collisions and non-uniformity of the parameters in the theoretical thrust model. The experimental uncertainty could also be a reason in particular to the RF voltage applied on the antennae and nun-uniformity of the REF. Voltage of applied REF is taken from values of matching boxes. Experiments are planned to measure the RF voltage.

### 4. Discussions for Enhancing Thrust Force

As it is 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 maximum electromagnetic force. The theoretical thrust distributions in the parameter planes of the axial magnetic field – REF frequency, the axial magnetic field – the plasma density and the plasma density – amplitude of the applied REF voltage are shown in Figs. 11, 12 and 13, respectively. Here, $\beta$ and other geometrical parameters are taken from the experimental condition and are shown in Table 2.

<table>
<thead>
<tr>
<th>Fixed parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>0.685</td>
</tr>
<tr>
<td>$n_0$</td>
<td>$3.72 \times 10^{16}$ m$^{-3}$</td>
</tr>
<tr>
<td>$L$</td>
<td>0.05 m</td>
</tr>
<tr>
<td>$r_0$</td>
<td>0.013 m</td>
</tr>
<tr>
<td>$a$</td>
<td>0.1 m</td>
</tr>
</tbody>
</table>

Figures 11 and 12 show that the theoretical thrust has a peak when the axial magnetic field is equal to 0.025 T. And 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.

### 5. Summary

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 accelerator and experiments were conducted. In the experiment, the radial profiles of plasma parameters in the plume were measured by a Mach probe. Although some features of the Lissajous acceleration were measured, most
increment of the plasma velocity is considered to be caused by
the increment of the plasma temperature. A theoretical thrust
model was surveyed at some parameter planes and it was
implied by the survey that the thrust has a peak at an optimum
axial magnetic field for the prototype. In addition, it was also
implied that the thrust increases either by reducing the REF
frequency, or increasing plasma density, or increasing the
REF voltage from the experimental point reported in this
paper.

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