Investigation of Plasma Characteristics and Ion Beam Extraction for a Micro RF Ion Thruster

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Two-dimensional axisymmetric particle-in-cell simulations with a Monte Carlo collision algorithm, external circuit analysis, and measurements of plasma densities and ion beam currents have been conducted for a micro RF ion thruster. The plasma source of the thruster is 5.0 mm in radius and 10 mm in length with a five-turn helical coil around a cylindrical quartz chamber, where the plasma is generated at low RF powers (< 10 W). The numerical results have indicated that high RF frequencies (> 100 MHz) lead to a high coupling efficiency between the RF power and the plasma, although too high RF frequencies (> 300 MHz) degrade the efficiency. The optimum gas flow rate for ion beam extraction is determined to be $10^{13}$ g/s. These results are qualitatively in good agreement with the experimental results, which validates our numerical model, and thus the model would be useful to estimate the performance of the micro RF ion thruster.

Key Words: Micro Ion Thruster, RF Plasma, PIC-MCC, Circuit Model, Ion Beam Extraction

Nomenclature

$C$: capacitance
$f$: RF frequency
$I$: current
$L$: self-inductance
$M$: mutual inductance
$n$: number density
$p$: pressure
$P$: power
$R$: resistance
$V$: voltage
$V_{\text{in}}$: momentum transfer collision frequency between electrons and neutrals
$\rho$: plasma resistance
$\phi$: potential
$Z$: plasma reactance
$\omega$: angular frequency

Subscripts

abs: absorption
b: beam
cap: capacitive
e: electron
g: RF generator
in: input
ind: inductive

1. Introduction

In recent years, because of low development and launch costs and short development periods of microspacecraft, the worldwide interest in microspacecraft has grown to such an extent that even universities are currently able to launch and operate microspacecraft. However, most microspacecraft that universities operate do not have any propulsion systems, which is why they rely on passive controls, such as gravity gradient stabilization, and geomagnetic attitude stabilization. If a microspacecraft had microthrusters mounted on it, we could control the microspacecraft more effectively to create a specific flight path. Owing to the limited power generation and propellant storage, high specific impulses, high-thrust efficiencies, and low-power consumptions are required for microthrusters, in addition to small size and light weight.

Several types of microthrusters are proposed and some of them are already developed. Among them, ion thrusters are one of the most promising propulsion systems for microspacecraft.

In order to develop such a micro ion thruster, we have to figure out how to generate plasma in a small space and how to extract ions from it efficiently and effectively. A lot of experimental studies have already been carried out. However, the information obtained from such experiments is always limited because of the small size. The spatial distribution of plasma parameters in small space less than a centimeter is not readily available in experiments. This is why numerical simulations can also be useful to compensate for lack of information, and the combination of experimental and numerical studies would be important. To develop a reasonable numerical model, simplicity is a key factor. The micro RF ion thruster presented in this study is one of the simplest ion thrusters as shown in Fig. 1. The thruster consists of a cylindrical micro inductively coupled plasma source (ICP), which has no magnets or cathodes, and a grid system with a single hole on the central axis. Because of this structure, the ion thruster can be modeled in the two-dimensional cylindrical coordinate system.

Since the calculation results are just a simulation and not real, a numerical model should be validated by comparing the experimental results. The objective of this study is to verify our
developed already 2), we investigate the frequency dependence of a two-dimensional particle model and a circuit model, which we use for ion thruster optimization. In the present study, by using a numerical model so that the model can be used for micro RF plasma source optimization, we found that the ratio of the reflected power to the total power can be less than 1% under most experimental conditions by using the matching network. Working gases of Xe are also used to decrease the reflected power. The power reported in this paper is the net power supplied to the thruster through a mass flow controller, and a filament electron source is employed as a neutralizer. All the experiments are carried out in a stainless-steel vacuum chamber; the chamber is evacuated using a rotary pump and a turbo molecular pump, where the lowest pressure is less than $1 \times 10^{-3}$ Pa without Xe gas flows. Here, the chamber is used as the ground reference for all experiments.

For electrical diagnostics, a cylindrical Langmuir probe is inserted into the plasma source through the grids hole to determine the electron density thereof. The probe tip is made of a tungsten wire of 0.05 mm in diameter and 1.4 mm in length. The probe measurement is carried out by using a semiconductor parameter analyzer (Hewlett Packard, 4145B) with a low-pass filter to prevent the measurement from the RF interference. It should be noticed that the screen grid is biased to the ground potential, which serves as a reference electrode in the probe circuit when the probe measurement is conducted. A detailed explanation is described elsewhere 3). Current measurements of the two grids are also conducted for ion beam diagnostics with a shunt resistance of 1 kΩ. The ion beam current $I_b$ is obtained by subtracting the accelerator current from the screen current.

3. Numerical Model

3.1. Particle simulation

Figure 3 shows the simulation areas for the analysis of the micro ICP source and the ion beam extraction. For the analysis of the frequency dependence of microplasma source, only the plasma source is taken into consideration for simplicity. The simulation area is 5 mm in radius and 10 mm in length, and divided at regular intervals with the grid spacing of 0.1 mm. On the other hand, the screen and accelerator grids, and space are also taken into consideration.
for the analysis of the ion beam extraction. The length of space area is set at 20 mm downstream of the accelerator grid. The length of two-dimensional spatial computational mesh (singly ionized xenon ions and electrons) are loaded into a of charged particles. A number of simulated superparticles due to the space charge, the equation of motion, and collisions electric electromagnetic equation for the RF-induced azimuthal (PIC-MCC). The present PIC-MCC model consists of the simulations with a Monte Carlo collision algorithm (a) the micro ICP source and (b) the ion beam extraction.

To investigate the characteristics of the plasma source, we have conducted two-dimensional axisymmetric particle-in-cell simulations with a Monte Carlo collision algorithm (PIC-MCC). The present PIC-MCC model consists of the electromagnetic equation for the RF-induced azimuthal electric field, the Poisson equation for the electrostatic field due to the space charge, the equation of motion, and collisions of charged particles. A number of simulated superparticles (singly ionized xenon ions and electrons) are loaded into a two-dimensional spatial computational mesh \((r, z)\), along with three velocity components \((v_r, v_z, v)\). The equation of motion for charged particles is solved explicitly by a time-centered leap frog method for time integration and the Buneman-Boris method for the velocity advance with a coordinate rotation for the position advance. The collision of charged particles can be treated separately from the calculation of motion as long as the time step chosen is much smaller than the mean free time. The postcollision velocities of charged particles are determined by the conservation equations of momentum and energy. The reactions to be taken into account are elastic scattering, excitation, and ionization for electrons \(^{46}\); and elastic scattering and charge exchange for ions \(^7\), which are described by the null-collision method to reduce the calculation time. Neutral particles are assumed to be spatially uniform throughout the simulation with a Maxwellian velocity distribution at a gas temperature of 300 K. The motion of excited-state atoms, Coulomb collisions between charged particles and the secondary electrons are not considered in the present study.

Since a high frequency (> 100 MHz) operation is also calculated, the effect of capacitive coupling of the RF antenna coil is taken into account. We assume that the different turns of the coil act like electrodes in capacitive discharge to include the effect of capacitive coupling. The voltage applied to these electrodes decreases linearly from the powered end of the coil \((z = 9 \text{ mm})\) towards the grounded end \((z = 1 \text{ mm})\). The powered end of coil oscillates as \(I(t) = 2\pi L I_{\text{coil}} \cos(\omega t)\) when the time-varying current of the RF coil is taken as \(I(t) = I_{\text{coil}} \sin(\omega t)\). The details of our PIC-MCC model are described in the previous papers and the references therein \(^{8,9}\).

### 3.2. Circuit analysis

Figure 4 shows a schematic of a simplified model of an ICP source with a helical external coil, indicating two current branches: an inductive current \(I_{\text{ind}}\) and a capacitive current \(I_{\text{cap}}\). In this work, the capacitive coupling is also taken into account in the circuit model to investigate the effect of the capacitive coupling on the inductive discharges. The inductive current \(I_{\text{ind}}\) is assumed to flow azimuthally along a concentric plasma ring (H-mode), whereas the capacitive current \(I_{\text{cap}}\) flows from a high voltage coil to a ground electrode through the quartz glass, cylindrical plasma, and sheaths (E-mode). In the present case, the same voltage is assumed to be applied through both the paths.

In order to analyze the electrical properties of an inductive RF discharge, it is convenient to represent the inductive discharge with a capacitive coupling by the equivalent circuit...
as shown in Fig. 5(a). The primary coil of the transformer is the induction coil, which is composed of five turns with inductance $L_0$ and resistance $R_0$. The plasma is assumed to be a one-turn secondary winding of an air-core induction coil with inductance $L_z$ and resistance $R_p$. The plasma inductance consists of two components, the geometrical inductance $L_z$ due to the plasma current path, and the electron inertia inductance $L_e$. The amount of inductive coupling between the primary coil and the secondary plasma coil is measured by their mutual inductance $M$. It should be noted that the inductor and the other transmission lines: absorbed by the plasma is deposited into the resistances of the coil $R_0$ and the other transmission lines: $R_{01}$ due to ohmic heating of the discharge electrons, the electron inertia inductance $L_{02}$, a parallel combination of the plasma-to-ground electrode sheath capacitance $C_{sh1}$, the plasma resistance $R_{02}$ due to Ohmic heating of the plasma, the electron inertia inductance $L_{02}$, and the effective sheath resistance $R_{sh2}$ due to a collisionless stochastic process.

Here, the RF generator has a typical waveform of $V_{RF} = V_0 \sin(\omega t)$ with internal resistance $R_g$. In our study, a $T$-shaped matching network is employed with two variable capacitances of $C_1$ and $C_2$. These expressions for the circuit elements are described in our previous paper.

It should be noted that the inductive and capacitive power absorptions are defined as $P_{ind} = \mu I_{ind}^2$ and $P_{cap} = R_{sh} I_{cap}^2 + R_0 (I_{ind} + I_{cap})^2$, respectively, by using the root mean square of the current. The power which is not absorbed by the plasma is deposited into the resistances of the coil and the other transmission lines: $R_0 (I_{ind} + I_{cap})^2$.

4. Results and Discussion

The circuit element analysis was conducted for the wide range of frequency $f = 2–500$ MHz and pressure $p = 1.3–6.3$ mTorr (i.e., $V_{abs} = 1.0–5.0 \times 10^7$ s$^{-1}$ for Xe) at the fixed electron density of $3.0 \times 10^{16}$ m$^{-3}$, where the electron density was volume averaged value and it was determined from the PIC calculations. It should be noted that the volume averaged electron density is almost independent of the RF frequency at fixed absorbed power of electrons. Here, the coupling coefficient $k_M$ was set to be 0.2 on the basis of the available experimental study.

Figures 6(a) and 6(b) show the inductive and capacitive power absorptions as a function of RF frequency. As shown in the figures, the inductive component of the absorbed power $P_{ind}$ dominates over the rest of components $P_{cap}$ below 10 MHz while the capacitive component dominates over the inductive one over 20 MHz. This is because that the inductive current $I_{ind}$ significantly increases with decreasing RF frequency as shown in Fig. 6(c). On the other hand, the capacitive current $I_{cap}$ increases with increasing RF frequency and then levels off. The capacitive current becomes larger than the inductive current over 100 MHz. Figure 6(d) shows the total power of the RF generator $P_g$ required to deposit 100 mW into the plasma as a function of RF frequency. The RF power $P_g$ significantly increases with decreasing frequency because the larger current at low frequencies leads to a large power loss to the resistances of the coil $R_0$ and the other transmission lines: $R_t$. As the frequency increases, almost all of the RF power is deposited into the plasma, and then $P_g$ slightly increases because of the increase in resistance (the resistances of $R_0$ and $R_t$ are proportional to the square root of the RF frequency). It should be noted that $P_{ind}$ and $I_{ind}$ become minimal at the frequency of 200 MHz because the frequency approaches the resonant frequency of the parallel LC circuit shown in Fig. 5.

Figure 7 shows the minimum RF input power $P_{in}$ to sustain...
the plasma discharge as a function of RF frequency in the experiment. The minimum $P_{in}$ decreases with increasing frequency, and then becomes minimal at the frequency of 300 MHz. The minimum $P_{in}$ again increases with increasing frequency over 300 MHz. This tendency is qualitatively in good agreement with the result of the circuit analysis as shown in Fig. 6(d). It should be noted that as the frequency further decreases, the minimum $P_{in}$ increases significantly (not shown here), and at least 10 W was required to sustain the plasma discharge at around $f = 10$ MHz. This result also implies that a higher RF power is required to sustain the plasma at low frequency because of the high coil current required as shown in Fig. 6(c).

Figure 8 shows the electron density as a function of RF input power at the Xe gas flow rate of 2.0 μg/s (0.2 sccm) for the RF frequencies of 117 and 260 MHz. The electron density increases with increasing RF input power. The electron density at $f = 260$ MHz is larger than that at $f = 117$ MHz under all RF power conditions. As indicated in Fig. 2(b), RF input power was measured before the matching network, so that input power includes the power loss to the resistances of the coil and the other transmission lines. The loss at $f = 260$ MHz is probably lower than that at $f = 117$ MHz and thus more RF power is deposited into the plasma. This tendency is also confirmed in the PIC simulation result as shown in Fig. 9, where the power absorbed in the plasma is fixed at every RF frequency. In our previous paper 8), PIC calculations showed that at lower frequencies more electrons reach the dielectric window during the positive cycle of the potential oscillation, so that the dielectric window is more negatively charged, which results in the negative potential on the dielectric. This large potential difference between the bulk and on the dielectric leads to the large ion heating. Since a larger fraction of RF power deposits into ions through the acceleration in the sheath, which reduces the power deposition into electrons, the electron density decreases with decreasing frequency. In addition to the power loss to the resistances of the coil and transmission lines, the effect mentioned above would also cause the large differences in the electron density between 260 MHz and 117 MHz. However, the physical mechanism causing the differences is still unclear and will be discussed in future work.

Figure 10 shows the ion beam currents $I_b$ as a function of RF input power at $f = 160$ MHz for different Xe gas flow rates of 10, 20, and 50 μg/s, where the screen and accelerator grid voltages were set at 1050 V and −200 V, respectively.

![Fig. 7. Minimal RF input power to sustain the plasma discharge as a function of RF frequency.](image)

![Fig. 8. Electron density as a function of RF input power at the Xe gas flow rate of 2.0 μg/s (0.2 sccm) for the RF frequencies of 117 and 260 MHz.](image)

![Fig. 9. Electron density as a function of RF frequency, calculated at the Xe gas pressure of 5 mTorr.](image)

![Fig. 10. Ion beam currents as a function of RF input power at $f = 160$ MHz for different Xe gas flow rates of 10, 20, and 50 μg/s, where the screen and accelerator grid voltages were set at 1050 V and −200 V, respectively.](image)
plasma density as shown in Fig. 8. Although the beam current at 10 µg/s is almost equal to that at 20 µg/s, the beam current of 50 µg/s decreases significantly. The beam currents show low values because the grids have only a single hole. If the H-mode discharge was obtained, the beam current would increase at least more than double.

The calculation of ion beam extraction was also carried out. Figure 11 shows the distributions of the potential, ion density, and ion beam energy at the gas flow rate of 20 µg/s. Note that only the ion density is expressed as logarithmic scale. Most ion beam trajectories seem to fit the single hole on the central axis, but some ions are found to collide with the accelerator grid. Table 1 summarizes the beam currents for different gas flow rates taken from the calculation. As the flow rate increases, the accelerator current increases because of the increase in collisions between ions and neutrals, and thus the beam current is the lowest at the gas flow rate of 50 µg/s. This tendency is consistent with the experimental result.

5. Conclusions

In this work, we have conducted PIC-MCC simulations, external circuit analysis, and measurements of plasma densities and ion beam currents to investigate plasma characteristics and ion beam extraction for a micro RF ion thruster and to validate our numerical model. The numerical results have indicated that relatively high RF frequencies (> 100 MHz) lead to a high coupling efficiency between the RF power and the plasma at low RF powers. However, too high RF frequencies (> 300 MHz) degrade the efficiency. This tendency is qualitatively in good agreement with the experimental results at low RF powers. Moreover, the optimum gas flow rate for ion beam extraction was determined to be 10–20 µg/s in experiments, and this result was also consistent with the numerical result. These comparisons validate our numerical model, and thus the model would be useful to estimate the performance of the micro RF ion thruster. As a next step, the neutralizer will be incorporated into our model to investigate the interaction between ion beams and electron beams.

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References