

Investigation of Electron Extraction from a Microwave Discharge Neutralizer for a Miniature Ion Propulsion System

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Abstract: To investigate electron extraction from the orifices of a microwave discharge neutralizer, three-dimensional particle simulations have been conducted. The numerical model is composed of a particle-in-cell simulation with a Monte Carlo collision algorithm for the kinetics of charged particles, a finite-difference time-domain method for the electromagnetic fields of 4.2-GHz microwaves, and a finite element analysis for the magnetostatic fields of permanent magnets. The distribution of the current density on the orifice plate obtained from the numerical model is in a reasonable agreement with the measurement result in an experiment. Moreover, the numerical results have indicated that the electrostatic field of the plasma has a dominant influence on the electron extraction.

Nomenclature

B_{st}	=	magnetostatic field of permanent magnets
E_{ES}	=	electrostatic field
E_{EM}	=	electromagnetic field of microwaves
f	=	microwave frequency
I	=	current
j_p	=	plasma current density
m	=	mass
n	=	number density
p	=	pressure
P_{abs}	=	power absorbed in the plasma
q	=	charge
T	=	temperature
$\mathbf{v}$	=	velocity
ϵ_0	=	vacuum permittivity

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ϵ_r	=	relative permittivity
μ_0	=	vacuum permeability
ρ	=	charge density
ϕ	=	electrostatic potential
ω	=	microwave angular frequency

I. Introduction

LOW costs and short development periods have enabled even small companies and universities to launch and operate microspacecraft, which brings a good opportunity for education and a new business. However, most microspacecraft do not have any propulsion systems, and thus they rely on passive control systems, such as gravity gradient stabilization and magnetic torquers. If a microspacecraft had microthrusters mounted on it, the microspacecraft could be controlled more effectively and inserted into a specific orbit by itself. To realize a microthruster installable to microspacecraft, high specific impulses, high-thrust efficiencies and low-power consumptions are required in addition to small size and light weight because of the limited power generation and propellant storage.¹

To satisfy such requirements, a miniature ion propulsion system (MIPS) was developed by the University of Tokyo,^{2,3} as shown in Fig. 1. The MIPS employs electron cyclotron resonance (ECR) discharges with ring-shaped permanent magnets for its ion source and neutralizer.^{4,5} The FM specifications of the MIPS are evaluated at the weight of 8.1–8.6 kg (dry: 7.2 kg), volume of $34 \times 26 \times 16$ cm³, power consumption of 27–34 W and thrust of 210–300 μ N with specific impulse of 740–1100 s.^{6,7} The MIPS was installed on a 50 kg-class spacecraft, HODOYOSHI-4, which was launched on June 19, 2014, and was successfully operated in space on October 28.

Although the MIPS has already been utilized in space, there are still some physical phenomena to be elucidated especially in the mechanism of electron extraction from its neutralizer. In order to clarify the mechanism, numerical simulations could represent a powerful tool to compensate for lack of information obtained from experiments. Hence, we have developed a three-dimensional numerical model,⁸ which consists of a particle-in-cell simulation with a Monte Carlo collision algorithm (PIC-MCC) for the kinetics of charged particles,⁹ a finite-difference time-domain (FDTD) algorithm for the electromagnetic fields of microwaves,¹⁰ and a finite element analysis for the magnetostatic fields of permanent magnets.

In the present work, to investigate electron extraction from the microwave discharge neutralizer of the MIPS, we have conducted PIC-MCC simulations. The simulation results are compared with experimental results to validate the model. The validated numerical simulation would be useful to design better performance neutralizers. In the next section, we briefly describe the numerical model, followed by the experimental procedure for validation. The characteristics of the microwave discharge plasma are indicated and compared with the experimental results. We have also investigated what causes electron extraction, and have found that the electrostatic field is the most important factor. Finally, conclusions are drawn of this paper.

II. Numerical Model

The three-dimensional PIC-MCC calculations described in the previous papers^{8,11-13} were carried out under the following assumptions. (i) Only singly-ionized xenon and electrons are treated as particles, where the reactions taken into account are elastic scattering, excitation, and ionization for electrons,¹⁴⁻¹⁶ and elastic scattering and charge exchange for ions.¹⁷ (ii) The magnetic fields of microwaves are neglected compared with the magnetostatic fields of the permanent magnets. (iii) The effect of the plasma current is not taken into account owing to the low power of microwaves in this study.

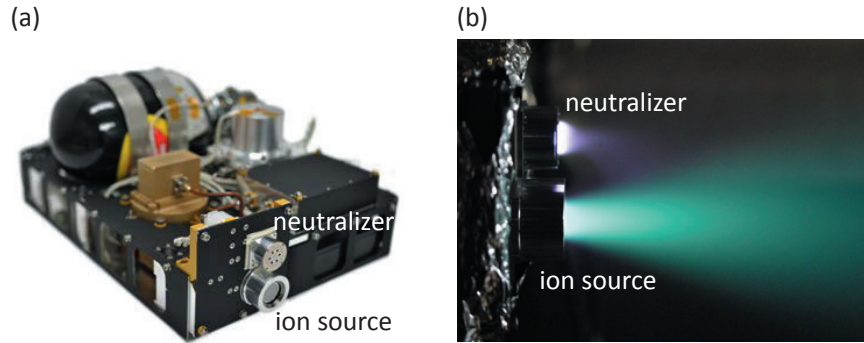


Figure 1. Photograph images of (a) MIPS-FM and (b) MIPS-FM in operation.

Figure 2 shows the flow chart for the numerical model employed. First, we set initial conditions and then we solve Maxwell's equations by FDTD for the electromagnetic fields of microwaves with a time increment $\Delta t_{EM} = 2.98 \times 10^{-13}$ s (1/800 of a microwave cycle for 4.2 GHz) to obtain a steady state without plasma. We use the amplitude of the electric fields of microwaves E_0 at steady state. Second, electrostatic PIC-MCC calculations are performed with a time step $\Delta t_e = 5.95 \times 10^{-12}$ s (1/40 of a microwave cycle) by using the electrostatic field E_{ES} of the plasma, the time-varying electric field of microwaves $E_{EM} = E_0 \cos(\omega t)$, and the magnetostatic fields B_{st} produced by the permanent magnets, which is determined with ANSYS software. Here, in order to speed up the simulation, the motion of ions is updated with a time step $\Delta t_i = 2.38 \times 10^{-10}$ s (one microwave cycle) by neglecting E_{EM} and using the time-averaged E_{ES} over one microwave cycle because the frequency of 4.2 GHz is much higher than the ion plasma frequency. In the simulation, the power absorbed in the plasma P_{abs} is used as an input parameter, where P_{abs} is obtained by calculating the change in kinetic energy of electrons and ions before and after the calculation of the equation of motion.¹⁸ Last, we rescale the amplitude E_0 to yield the specified power absorbed in the plasma P_0 and iterate the above procedure until the steady state solution is obtained. For example, if the obtained power P_{abs} is below the specified power P_0 , then we increase the amplitude of the electric field E_0 . The details are described in the previous paper and references therein.⁸

III. Experimental

To validate our numerical model, the current distribution on the orifice plate was measured in the experiment and its result was compared with the numerical result. Figure 3 shows schematics of the circuit and photograph images of the current probes for the measurement. The closed circles in red represent the measurement points of the current, where the diameter is all 1.5 mm. In Fig. 3(a), measurement points are arrayed on the x/y axis, where the points are set at 1, 2, 3, 4, 5, 6, 7, 8, 9 mm from the center of the

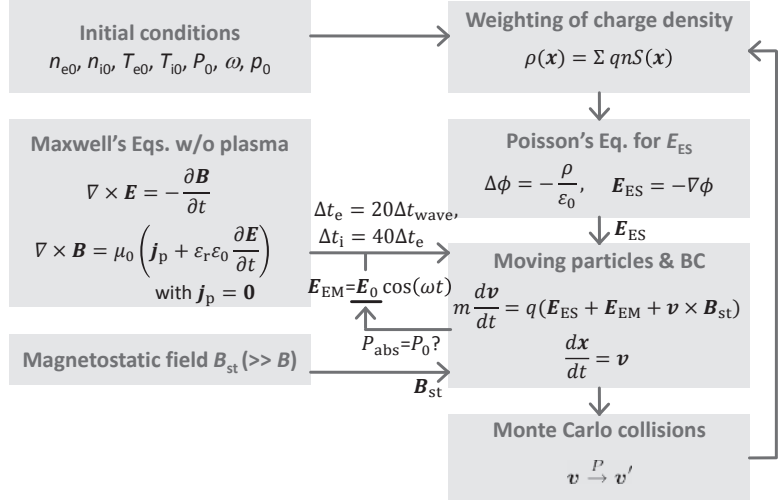


Figure 2. Flow chart for the numerical model presented. First, we set initial conditions and then we solve Maxwell's equations by FDTD for the electromagnetic fields of microwaves to obtain a steady state without plasma. We use the amplitude of the electric fields of microwaves E_0 at steady state. Second, electrostatic PIC-MCC calculations are performed by using the electrostatic field E_{ES} , the time-varying electric field of microwaves E_{EM} , and the magnetostatic fields B_{st} , which is determined with ANSYS software. In the simulation, the power absorbed in the plasma is used as an input parameter.

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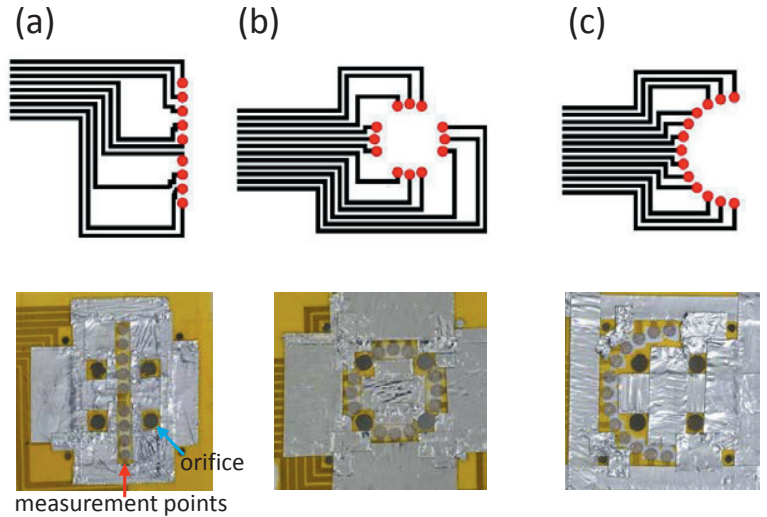


Figure 3. Schematics of the circuit (top) and photograph images (bottom) of the current probes. The closed circles in red represent the measurement points of the current. The measurement points are set at (a) $r = 1, 2, 3, 4, 5, 6, 7, 8, 9$ mm, (b) $r = 5$ mm, and (c) $r = 7.5$ mm.

orifice plate. There are 12 measurement points at the radius of 5 mm in Fig. 3(b) and 13 points at the radius of 7.5 mm in Fig. 3(c).

The current measurement was conducted in the vacuum chamber at the pressure of less than 1×10^{-3} Pa after the orifice plate with the current probe was mounted on the microwave discharge neutralizer. The voltage of the current probes was set at 0 V to prevent the probe from sputtering of the plasma and to reduce the perturbation of the plasma discharge. However, setting the voltage at 0 V causes us to measure the total current, i.e., the sum of the ion and electron currents and thus we cannot measure electron and ion currents separately in the experiment. At the current measurement, we set the neutralizer at 0 V and placed an electron-collector plate with the positive potential of 20 V downstream of the neutralizer to extract electrons. The measurement was conducted at a xenon gas mass flow rate of 10.5 $\mu\text{g/s}$ and the microwave input power of 0.5 W.

IV. Results and Discussion

A. Loss Region in the Plasma Source

Figure 4 shows the computational domain and dimension of the microwave discharge neutralizer in the present study. The Cartesian coordinate system is used and its origin is placed on the center of the antenna at the interface between the metal wall and the plasma in the z direction. The lengths in the x , y , and z directions are set at 20, 20, and 4 mm, respectively. The transverse electromagnetic waves are injected into the system at the excitation plane ($z = -1.2$ mm) of the coaxial waveguide, where its inside is filled with the dielectric of boron nitride (BN). The microwave power is fed into the ring-shaped antenna through the four spokes as shown in Fig. 4(a). It should be noted that the BN region is also included in the electromagnetic-field calculation of microwaves, although the simulation area for charged particles is only the plasma region (yellow area in Fig. 4). The grid spacing is set at 0.2 mm at regular intervals, and the space between inner and outer ring magnets is neglected and filled with metal for simplicity.

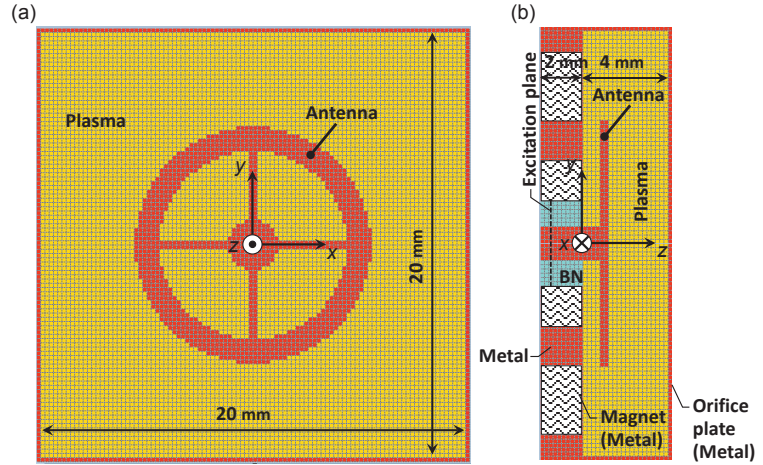


Figure 4. Computational area and grids for calculations of the microwave discharge neutralizer without extraction of electrons: (a) x - y plane ($z = 1$ mm) and (b) y - z plane ($x = 0$ mm).

A xenon plasma discharge was calculated for the microwave discharge neutralizer under the base case condition, where the xenon gas pressure is $p = 1$ mTorr, the microwave frequency is $f = 4.2$ GHz, and the absorbed power is $P_{\text{abs}} = 0.3$ W. The initial densities of both electrons and ions are set at $1.0 \times 10^{16} \text{ m}^{-3}$ and are distributed uniformly in the simulation area. The initial electron and ion temperatures are 2.0 eV and 0.05 eV, respectively. The macroscopic parameters, such as the electron density and electron temperature were determined by averaging over 50000 microwave cycles (11.9 μs) after the steady state was reached.

The peak plasma density is located in the ECR layer on the right side of the antenna, where the maximal value of the electron density is $1.6 \times 10^{17} \text{ m}^{-3}$, and their distributions spread along the magnetic field lines, producing the ring-shaped profile of the plasma density. This result indicates that the plasma is well confined because of the mirror magnetic fields. The distribution of the electron temperature is almost the same as that of the plasma density, where the peak electron temperature obtained is 16 eV. The electron temperature in front of the ring antenna is much larger than the ionization energy of xenon. The details of the other results are described in our previous paper.⁸

Tables 1 and 2 summarize the ion and electron currents flowing into each boundary of the microwave discharge neutralizer. Here, I_{antenna} , I_{endwall} , I_{sidewall} , and I_{orifice} represent the currents flowing into the ring-shaped antenna, the wall at $z = 0$ mm, the side walls (in the x and y directions), and the wall at $z = 4$ mm, where orifices are placed for electron extraction, respectively. Since the plasma chamber is much shorter in the z direction than in the x and y directions, the

Table 1. Ion currents flowing into each boundary for $P_{\text{abs}} = 0.3$ W.

$I_{i,\text{antenna}}$ (mA)	$I_{i,\text{endwall}}$ (mA)	$I_{i,\text{sidewall}}$ (mA)	$I_{i,\text{orifice}}$ (mA)
1.85	1.11	0.25	2.07

Table 2. Electron currents flowing into each boundary for $P_{\text{abs}} = 0.3$ W.

$I_{e,\text{antenna}}$ (mA)	$I_{e,\text{endwall}}$ (mA)	$I_{e,\text{sidewall}}$ (mA)	$I_{e,\text{orifice}}$ (mA)
0.71	1.95	0.02	2.72

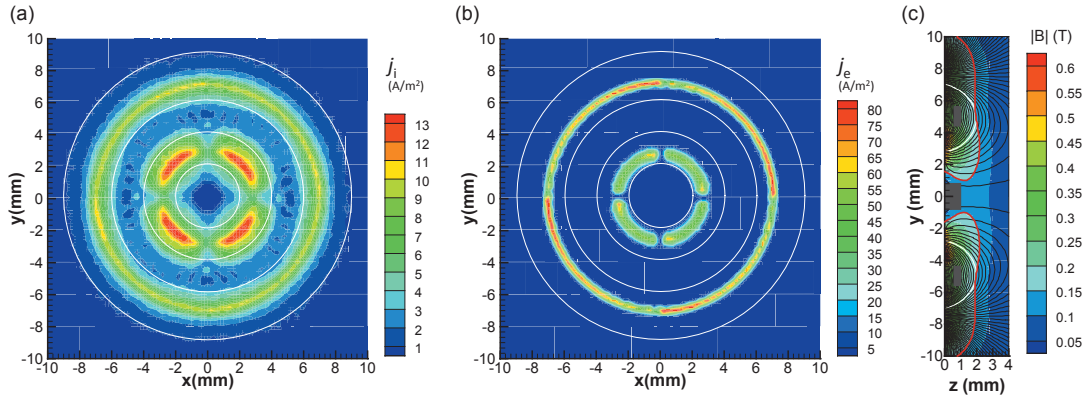


Figure 5. Two-dimensional distributions of the (a) ion and (b) electron current densities flowing into the end wall ($z = 0$ mm), together with circles in white representing the boundaries of the ring-shaped permanent magnets. (c) Contour plots at the z-y plane ($x = 0$ mm) of the strength of the magnetic field of the ring-shaped permanent magnets and the magnetic field lines in black, together with the lines in red representing the resonant magnetic field of 0.15 T for 4.2-GHz microwave.

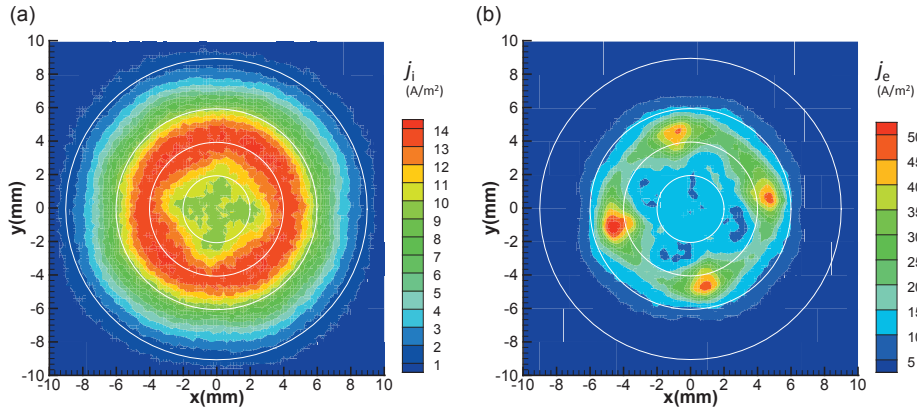


Figure 6. Two-dimensional distributions of the (a) ion and (b) electron current densities flowing into the orifice plate ($z = 4$ mm), together with circles in white representing the boundaries of the ring-shaped permanent magnets.

current flowing into the side walls are much lower than into the other boundaries. The peak plasma density is obtained downstream of the ring-shaped antenna and ions are not magnetized, so that the ion current flowing into the antenna is larger than into the end wall. On the other hand, electrons are well confined because of the mirror magnetic fields, and thus the opposite trend is obtained. The confinement also results in the largest value of the current flowing into the wall at $z = 4$ mm.

Figure 5 shows the two-dimensional distributions of the ion and electron current densities flowing into the end wall ($z = 0$ mm), together with the contour plots at the z-y plane ($x = 0$ mm) of the strength of the magnetic field of

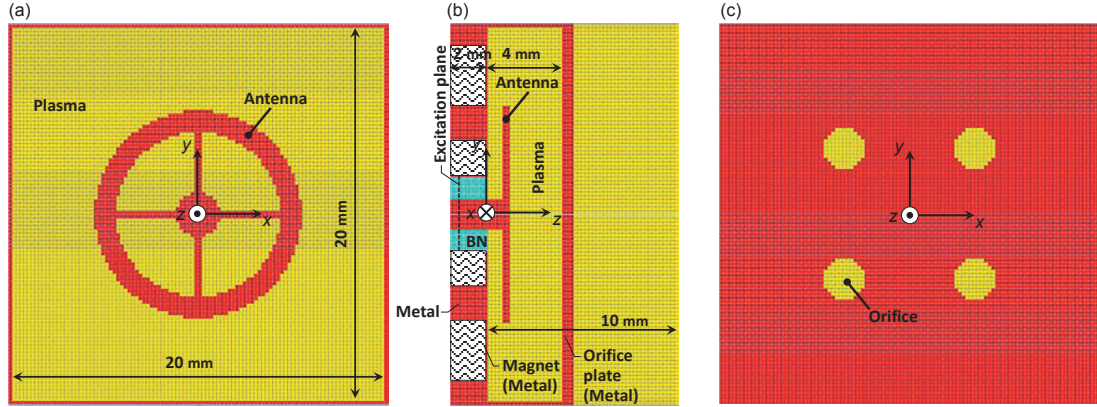


Figure 7. Computational area and grids for calculations of the microwave discharge neutralizer with extraction of electrons: (a) x - y plane ($z = 1$ mm) at the antenna, (b) y - z plane ($x = 0$ mm), and (c) x - y plane ($z = 4$ mm) at the orifice plate.

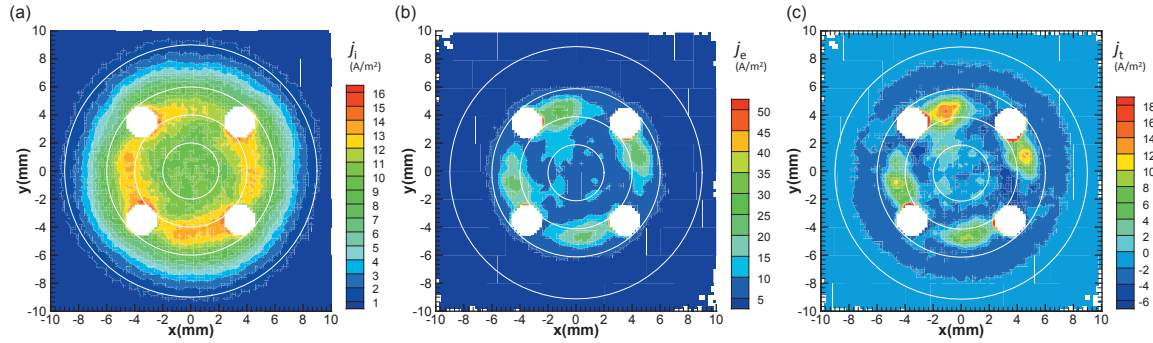


Figure 8. Two-dimensional distributions of the (a) ion, (b) electron, and (c) total current densities flowing into the orifice plate ($z = 4$ mm), together with circles in white representing the boundaries of the ring-shaped permanent magnets. Note that the contour plots are not shown in the four orifice regions.

the ring-shaped permanent magnets and the magnetic field lines in black. While the distribution of the ion current density is broad, where the motion of ions is interrupted by the ring-shaped antenna, the distribution of the electron current density is very narrow. As shown in Fig. 5(c), most electrons are found to be lost through the loss cones of the mirror magnetic field. Electrons are heated in the ECR layer (the thick line in red on the right side of the antenna), and move along the magnetic field line, traveling back and forth owing to the confinement. Some energetic electrons are lost through the loss cones along the thick magnetic field line in white in Fig. 5(c). Moreover, the grad-B and/or curvature drift probably causes the clockwise increase in electron current density. The sudden decrease in current density would be due to the abrupt change in the electric field of microwaves caused by the spokes to feed the microwave power into the ring-shaped antenna. The similar tendency can be seen in the distribution of the current density on the wall at $z = 4$ mm as shown in Fig. 6, although the

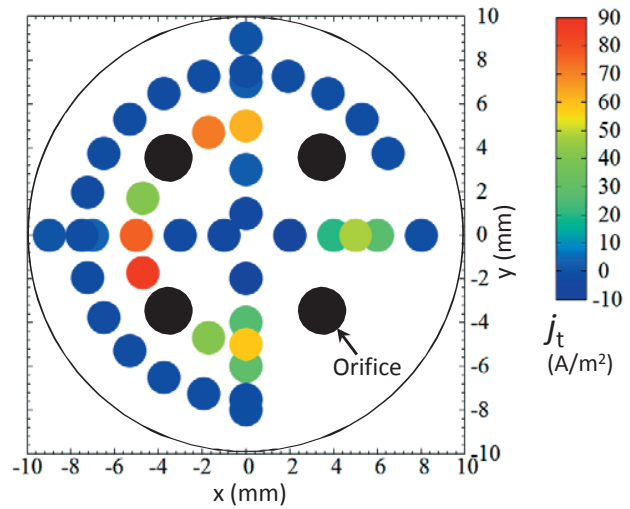


Figure 9. Two-dimensional distributions of the total current densities flowing into the current probes in the experiment, where the input power of microwaves is 0.5 W and the xenon gas flow rate of 10.5 $\mu\text{g/s}$.

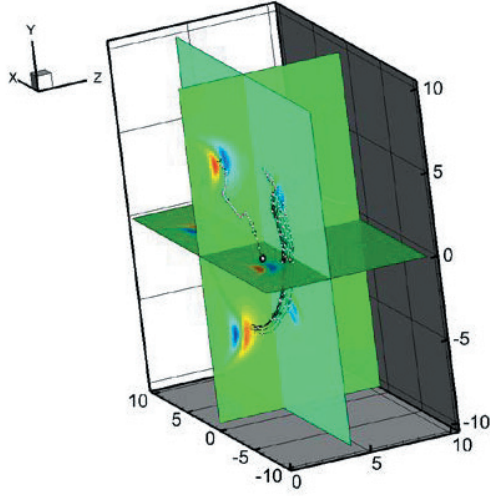


Figure 10. Cross-sectional views of the time-averaged electron current density and a few example of its streamlines.

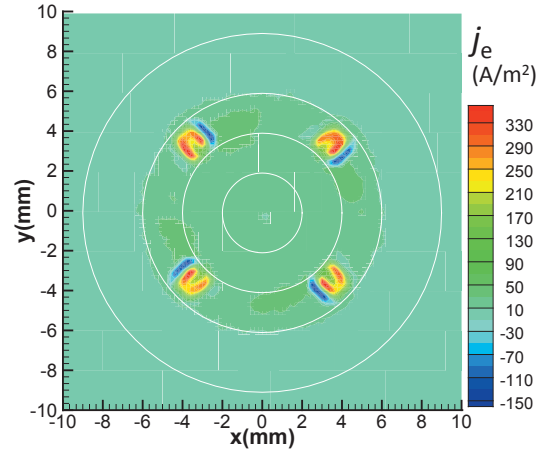


Figure 11. Two-dimensional distributions of the electron current density at $z = 4$ mm, together with circles in white representing the boundaries of the ring-shaped permanent magnets.

distribution is along the ring-shaped antenna, where the peak plasma density is obtained. Slow ions moves along the time-averaged electric field, so that the distribution of the ion current density is relatively uniform compared with that of the electron current density.

B. Validation: Comparison with Experiments

Figure 7 shows the computational domain and dimension for electron extraction in the present study. The dimension is the same in Fig. 4 except the length in the z direction and the orifice plate. We set 0.6-mm thick orifice plate at $z = 4$ mm and extraction region in z direction as shown in Fig. 7(b), where four orifices are employed in this study. The potential on all the metal area is set at zero, and we set 20 V at $z = 10$ mm for electron extraction, representing the electron-collector plate as described in Section III.

Figure 8 shows two-dimensional distributions of the ion, electron, and total current densities flowing into the orifice plate. Note that the contour plots are not shown in the four orifice regions. Extraction of electrons causes a little different distribution of the electron current density from that in Fig. 6. There are no significant peaks on the orifice plate although the current density in the clockwise direction with respect to the orifice is higher than that in the anti-clockwise direction. The similar tendency can also be seen in the distribution of the ion current density. Since the broad distribution of the ion current, the

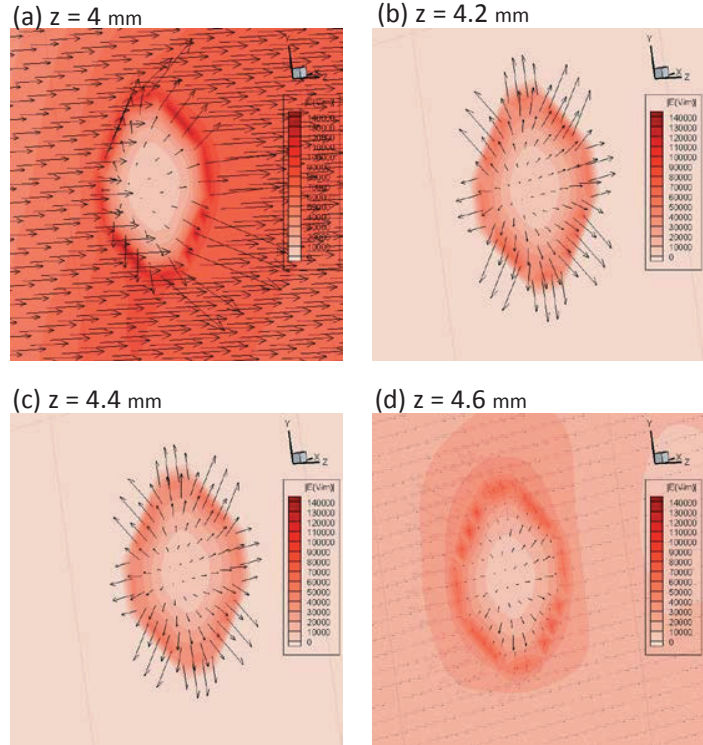


Figure 12. Contour plots of the time-averaged magnitude and vectors of the electric field around the orifice.

distribution of the total current density (the sum of the ion and electron current densities) displays the negative values inside and outside of the ring-shaped antenna.

Figure 9 shows the two-dimensional distributions of the total current densities flowing into the current probes in the experiment. As shown in the figure, the similar tendency can be seen: the peak current density is obtained at around $r = 5$ mm (the position of the ring-shaped antenna), where the electron current is dominant over the ion current, and the current density in the clockwise direction with respect to the orifice is higher than that in the anti-clockwise direction. Even though the current density obtained in the experiment is about five times larger than that obtained in the simulation, the distribution of the current density is quite similar with each other.

C. Analysis of Electron Extraction

To investigate the mechanism of electron extraction from the orifices, we have obtained the time-averaged

electron current streamlines as shown in Fig. 10, where the distributions of electron current are also plotted as cross-sectional views. The figure clearly indicates the grad-B and/or curvature drift of electrons due to the magnetostatic field of the permanent magnets. Although the circulation of the electrons can be explained by the drift motion, the mechanism of electron motion in the z direction is not fully understood yet. Moreover, the drift direction is changed to the opposite at around $z < 2$ mm.

Figure 11 shows the two-dimensional distributions of the electron current density at $z = 4$ mm, where the current density inside the orifice regions is also displayed. As shown in the figure, some electrons flow back into the plasma source from the outside and the extraction regions of electrons are in a horseshoe shape. Figure 12 shows the time-averaged magnitude and vectors of the electric field around the orifice. Since the potential is set at zero on the orifice plate and positive plasma potential with respect to the orifice plate, the electric field vectors represent normal sheath structure and there are no unnatural distribution that might cause the distribution of the electron current density as shown in Fig. 11. One of the possible mechanism of the distribution around the orifice edge is the $\mathbf{E} \times \mathbf{B}$ drift because of the strong magnetic field of the permanent magnets. However, extraction mechanism from the center of the orifice is still unclear.

As indicated in Fig. 2 of the flow chart, the electrons are moved by the sum of the electrostatic electric field $\mathbf{E}_{ES}$, the microwave electromagnetic field $\mathbf{E}_{EM}$, and the magnetostatic field of the permanent magnets $\mathbf{B}_{st}$. Although electron-neutral collisions also have an influence on the electron motion, the effect would be relatively small because of few collisions at the low pressure of 1 mTorr. To investigate what effect plays a dominant role to extract electrons from the orifice, we have conducted the PIC calculations with deleting some effects artificially after the steady state

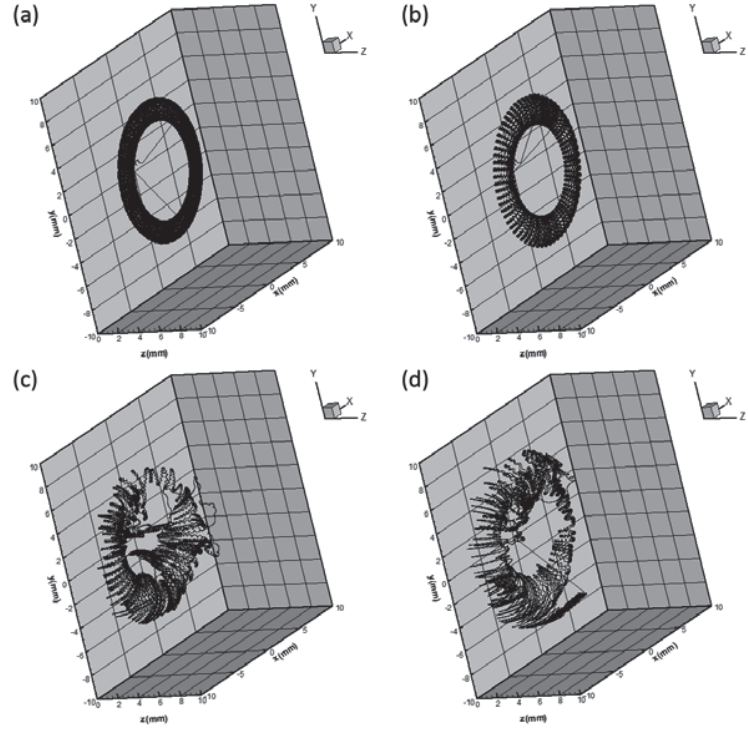


Figure 13. Typical examples of an electron trajectory under the effect of (a) B_{st} only; (b) B_{st} and E_{EM} ; (c) B_{st} and E_{ES} ; and (d) B_{st} , E_{EM} and E_{ES} with MCC.

Table 3. The number of electrons extracted from the orifice out of 100 samples chosen at random.

	B_{st}	$B_{st} + E_{EM}$	$B_{st} + E_{ES}$	$B_{st} + E_{EM} + E_{ES}$
W/o MCC	0	0	35	35
With MCC	0	0	31	47

solution is obtained. Figure 13 shows typical examples of an electron trajectory under the effect of (a) $\mathbf{B}_{st}$ only; (b) $\mathbf{B}_{st}$ and $\mathbf{E}_{EM}$; (c) $\mathbf{B}_{st}$ and $\mathbf{E}_{ES}$; and (d) $\mathbf{B}_{st}$, $\mathbf{E}_{EM}$ and $\mathbf{E}_{ES}$ with collisions. The magnetostatic field causes only the mirror confinement and grad-B and/or curvature drift, so that the electron trajectory shows just a circulation. The addition of $\mathbf{E}_{EM}$ gives only a slight change. However, the addition of $\mathbf{E}_{ES}$ clearly has a strong effect on electron trajectory and the electron is extracted from the orifice. Table 3 summarizes the number of electrons extracted from the orifice out of 100 samples chosen at random, which indicates that electrons are not extracted unless the effect of $\mathbf{E}_{ES}$ is taken into account in the PIC calculation.

Finally, the electron current extracted from the orifice was calculated to be 1 mA, while the electron current lost to the wall was 4 mA. This result shows that 20% of electrons produced in the discharge chamber are extracted from the orifice as electron beams for a neutralizer.

V. Conclusions

In the present work, we have conducted three-dimensional PIC-MCC simulations to investigate the electron extraction from the microwave discharge neutralizer. The PIC-MCC model includes an FDTD for the electromagnetic fields of 4.2-GHz microwaves and an FEM analysis for the magnetostatic fields of permanent magnets. The PIC-MCC results have shown that the electrons are expected to be extracted effectively through the orifice from the result of the loss region of the electron current. The numerical results have also been compared with the results obtained in the experiment to validate our model, where the distribution of the current density is quite similar with each other. To investigate what causes electron extraction from the orifices, we have calculated the PIC with deleting some effects artificially. As a result, electrons are not extracted unless the effect of $\mathbf{E}_{ES}$ is taken into account in the PIC calculation, and thus the electron extraction is attributed to the electrostatic field of the plasma. Finally, 20% of electrons produced in the discharge chamber are found to be extracted from the orifice.

Acknowledgments

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