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Three-Dimensional Numerical Simulation of Field-Emission-Electric-Propulsion Neutralization

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A three-dimensional full-particle-simulation model is developed for simulation of a field-emission-electric-propulsion (FEEP) thruster operation in an ambient plasma. Simulations are performed with ion-to-electron mass ratios close to actual values (m_i/m_e = 80,000) to resolve the basic characteristics of the propellant ions emitted from a FEEP thruster and their neutralization in an ambient plasma environment or by a thermionic neutralizer. The slit geometry allows a FEEP emitter to transmit reasonable values of emission current, even when no neutralization mechanism is present. However, to neutralize the FEEP beam, one must either operate the FEEP in an ambient plasma with a density comparable with the density of the FEEP beam ions and/or place a neutralizer at a location sufficiently far from the FEEP emitter. Because the electric field from the exposed high-voltage accelerator dominates the neighboring region of FEEP thrusters, a neutralizer placed on the spacecraft surface beside the FEEP emitter will not provide effective neutralization.

Nomenclature

A_e, A_i	= exit area of the electron and ion beam, m^2
a	= emitter–accelerator distance, m
b	= half of accelerator aperature, m
c	= cathode–accelerator distance, m
d	= emitter slit depth, m
E	= electric field, V · m^{-1}
e	= electric charge constant = 1.602×10^{-19} C
I_e, I_i	= electron and ion current, A
k	= Boltzmann constant = 1.381×10^{-23} J/K
l	= emitter slit length, m
m_e, m_i	= electron and ion mass, kg
n_e, n_i	= electron and ion number density, m^{-3}
$n_{e,a}$, $n_{i,a}$	= ambient electron and ion number density, m^{-3}
q	= electric charge
r	= radius from emitter slit, m
r_c	= radius of neutralizer anode, m
T	= temperature, K
U_A	= neutralizer anode potential, V
U_{ACC}	= accelerator potential, V
U_E	= emitter potential, V
U_{Exit}	= potential in the exit area of the slit emitter, V
U_N	= neutralizer grounding potential, V
v_e, v_i	= electron and ion velocity, m · s^{-1}
$v_{e,a}$, $v_{i,a}$	= ambient electron and ion velocity, m · s^{-1}
w	= emitter slit width, m
β	= neutralizer divergence angle, deg
ϑ_i	= divergence angle perpendicular to the slit direction, deg
λ_D	= Debye length, m
ρ	= charge density, C · m^{-3}
ϕ	= potential, V
φ_i	= divergence angle along the slit direction, deg

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I. Introduction

FIELD-EMISSION-ELECTRIC-PROPULSION (FEEP) is an advanced electrostatic propulsion concept[1] that uses liquid metal (usually cesium) as a propellant. A FEEP device consists of an emitter and an accelerator electrode (Fig. 1). The emitter consists of two metal plates that form a slit with a width of ~1 μm. A potential difference typically of the order of 10 kV is applied between the slit emitter and the accelerator electrode, which generates a strong electric field at the tip of the liquid metal surface (Taylor cones) of the emitter. This electric field extracts cesium ions from the tip of the emitter and accelerates them through the accelerator. Because of the high emitter-accelerator potential difference, the propellant ions are accelerated to a very high velocity, typically $>10^5$ m/s. Hence a FEEP device can produce specific impulses of the order of 10^4 s.

One of the prerequisites in the application of any electric propulsion device is that the propellant ions must be adequately neutralized in a space environment. During FEEP emission, the ion density near the FEEP is $\sim 10^{15}$ m^{-3}, whereas typical space plasma densities range from 10^{12} m^{-3} at low Earth orbit (LEO) to $\sim 10^6$ m^{-3} in the solar wind. Because of the small dimensions of the FEEP exit and the slit geometry, the propellant ions emitted by a FEEP will form a very localized, high-density ion beam with properties that differ considerably from the ion beam emitted by conventional ion thrusters. High plasma densities create considerable space-charge effects, which raises the issue of neutralization for a FEEP thruster. Few plasma measurements have been carried out to characterize the FEEP ion beam and its neutralization. The only relevant measurement was a Langmuir probe measurement by Andrenucci et al.,[2] performed for a laboratory FEEP thruster. The measurement was carried out in a vacuum chamber with a relatively high background pressure (10^{-6} mbar). The ambient plasma density inside the vacuum chamber is of the same order of magnitude as the density observed for the FEEP ion beam (10^{14} m^{-3}) and is several orders of magnitude higher than typical space plasma densities. Moreover, the neutralizer used in this experiment was a plasma-bridge neutralizer that emits an electron current of up to 150 mA, a current much higher than the 0.9-mA ion current emitted by the FEEP thruster. Not surprisingly, the ion beam from the FEEP was observed to be fully neutralized under this condition of high background pressure and high electron emission.

Recently, a hot-filament neutralizer (Fig. 2) has been proposed to be used with the FEEP thruster.[3] The hot-filament neutralizer

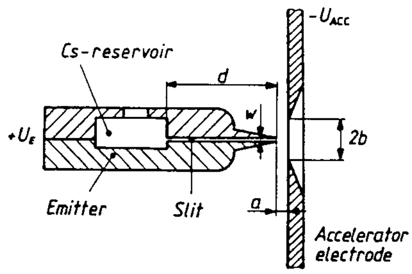

Fig. 1 Sectional view of the emitter–accelerator electrode configuration.[1]

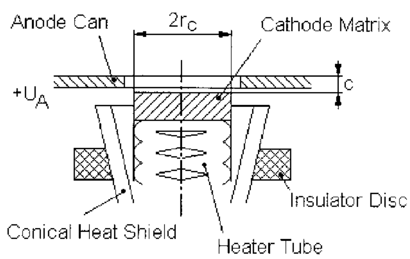

Fig. 2 Sectional view of the neutralizer.

is more attractive than a plasma-bridge neutralizer because of its much lower power consumption. The hot-filament neutralizer uses a low acceleration voltage (100 V relative to the grounding potential of the neutralizer) to accelerate an electron beam into the cesium ion beam. No plasma measurement has been performed for this type of thermionic neutralizer. A few studies, both experimental or theoretical, have been published to characterize the properties and neutralization of the FEEP ion beam. However, there is no general consensus on the basic properties of a FEEP ion beam in a typical low-density space environment and the optimal way to neutralize a FEEP ion beam in space.

Our objective in this paper is to understand the basic characteristics of the propellant ions emitted from a FEEP thruster and their neutralization under laboratory and typical space environments. Because of the difficulty of matching the conditions of space environments in a vacuum chamber, computer particle simulations provide the best means to address this problem. The emphasis of this paper is on the interactions between the three different plasma sources, the beam ions, the neutralizer electrons, and the ambient plasma and the resulting neutralization of the propellant ions. The neutral plume emitted from the FEEP emitter and the resulting charge-exchange collisions will not be considered here because the charge-exchange ions will only have a very minor impact on the neutralization issue. Under typical FEEP operating conditions, it has been measured[1] that the neutral flux from a FEEP emitter is $\sim 1\%$ of the beam ion current, and the maximum charge-exchange density is estimated to be more than 1 order of magnitude below the beam ion density. Hence, neglecting the charge-exchange ions in the simulation will not affect the results. The charge-exchange ion environments will be discussed in a subsequent publication.

We present a three-dimensional full-particle-simulation model for FEEP neutralization. The simulation model is similar to that of Wang and Lai,[4] which is used to simulate ion beam emissions in space plasma, but includes a thermionic neutralizer and the details of the slit FEEP geometry. In general, most full-particle simulations use artificial ion-to-electron mass ratios because of computational constraints. In this paper, however, we perform simulations with a very realistic heavy ion-to-electron mass ratio. We find that the use of realistic ion-to-electron mass ratios and the resulting more expensive computations are needed to resolve the details of the neutralization process. We apply three-dimensional full-particle simulations to predict the beam density and the potential near a FEEP emitter under various FEEP operation modes and ambient plasma environments. We study beam ion neutralization and suggest neutralization examples for reducing the space charge of the FEEP ion beam.

II. Formulation

We consider a FEEP emitter and a thermionic neutralizer in an ambient plasma environment. The FEEP thruster considered (Fig. 1) is similar to that tested at CENTROSPAZIO[2] and other FEEP emitter experiments.[1] Basic parameters for this thruster are summarized in Table 1. The neutralizer considered is a thermionic cathode, which consists of a hot filament underneath a small accelerator cathode (Fig. 2). Basic parameters for the neutralizer are summarized in Table 2.

In a FEEP emitter, ion emission originates from the emitter surface located at a distance a (emitter–accelerator distance) behind the accelerator electrode (Fig. 1). Typically the accelerator electrode of the FEEP emitter is placed on the spacecraft surface. The emitter electrode has a positive potential U_E with respect to the spacecraft potential, and the accelerator electrode has a negative potential U_{ACC} with respect to the spacecraft potential. The geometry of the electrodes creates a focused ion beam that is accelerated through the accelerator. The velocity of the beam ions at the FEEP's exit, v_i, is given by

$$v_i = \sqrt{\frac{2(U_E - U_{\mathrm{Exit}})e}{m_i}} \tag{1}$$

where U_E is the emitter potential and U_{Exit} is the potential within the ion beam at the level of the accelerator electrode. Note that U_{Exit} is a function of U_E, U_{ACC}, and the beam ion density, and needs to be determined self-consistently by taking the space charge into account. At a FEEP's exit, to a good approximation, the propellant ions are focused into a cosine distribution[1] squeezed to the divergence angles ϑ_i perpendicular to the slit direction and φ_i along the slit direction because of the FEEP's geometry (the ion density distribution according to this squeezed cosine distribution is shown in Fig. 3 for a

Table 1 FEEP thruster parameters

Parameters	FEEP thruster
Slit length, cm	3
Slit width, μm	1.5
Accelerator length, cm	4
Accelerator width, cm	1
Emitter–accelerator distance, mm	0.6
Accelerator voltage, kV	−3
Ion divergence perpendicular to slit, deg	30
Ion divergence in slit direction, deg	15

Table 2 Neutralizer parameters

Parameters	Thermionic neutralizer
Inner cathode diameter, mm	3
Cathode–anode distance, mm	0.3
Electron divergence in all directions, deg	30

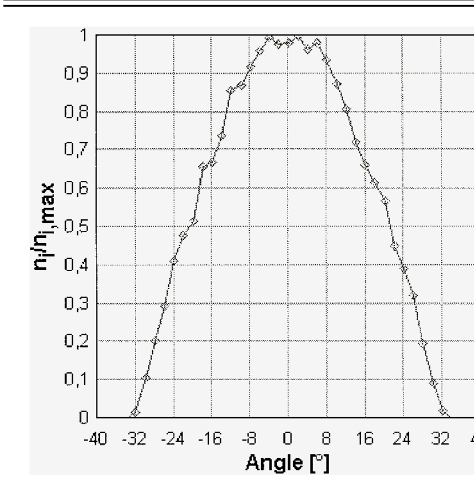

Fig. 3 Ion beam divergence perpendicular to the slit direction at radius $r = 0.06$ m (case 1).

typical case). If the ions were perfectly neutralized and there were no space-charge effects, they would form a beam according to this divergence angles. Under this condition, the cross section of the ion beam near the FEEP exit would be

$$A_i = (l + 2a \tan \varphi_i)(w + 2a \tan \vartheta_i) \tag{2}$$

With the ion current I_i, the ion density n_i at the FEEP's exit can be expressed by

$$n_i = I_i / e A_i v_i \tag{3}$$

In a thermionic cathode neutralizer, electron emission can be considered to originate from a point source in the middle of the accelerator cathode where the electrons are then accelerated by the anode potential U_A (Fig. 2). The exit electron velocity v_e is a combination of the thermal velocity of the hot-filament-generated Maxwellian velocity distribution with the cathode at temperature T and the acceleration that is due to the anode:

$$v_e = \sqrt{8kT/m_e\pi} + \sqrt{2eU_A/m_e} \tag{4}$$

The neutralizer is grounded to the neutralizer grounding potential U_N that is usually negative with respect to the spacecraft surface to enable the electrons to interact with the ion beam. In the absence of space-charge effects, the spatial distribution of the emitted electrons at the exit can be modeled by a simple cosine distribution squeezed in all directions by a divergence angle β. For a given cathode radius r_c, the cross-section area of the electron beam at the neutralizer's exit, A_e, is given by

$$A_e = (r_c + c \tan \beta)^2 \pi \tag{5}$$

where c is the neutralizer cathode–accelerator distance. The electron density at the neutralizer's exit can be expressed similarly to the expression for the ion density in Eq. (3).

In this paper, we study two different FEEP operation modes: FEEP emission without a neutralizer and FEEP emission in connection with a neutralizer, and three very different ambient conditions. The ambient environments considered are 1) the laboratory plasma environment, 2) the LEO plasma environment, and 3) no ambient plasma. When a FEEP thruster is tested in a vacuum tank, the typical background plasma density inside a vacuum tank is approximately 1% of the neutral density inside the tank.[5] Under a typical vacuum tank pressure of 10^{-6} mbar, the ambient plasma density inside the tank would be 2.4×10^{14} m^{-3}. The typical electron temperature in the vacuum chamber was measured[2] to be 4.2 eV, and the ion temperature corresponded to the ambient room temperature. At LEO, typical values of plasma parameters[6] are: density 10^{12} m^{-3}, and electron and ion temperature 0.1 eV. These parameters, summarized in Table 3, will be used for a laboratory or LEO plasma in our model. In this study, both the facility ambient plasma and the LEO ambient plasma are assumed to follow a Maxwellian distribution. In addition, we also consider different neutralizer operating conditions, including two different neutralizer positions. As shown in Fig. 4, the neutralizer can be either mounted on the spacecraft surface or mounted above the spacecraft surface with a look angle into the FEEP beam. The different simulation cases are summarized in Table 4.

A full-particle three-dimensional electrostatic particle-in-cell (PIC) code[7] has been developed to study FEEP-induced plasma interactions. In this code, all plasma particles (beam ions, neutralizer electrons, ambient ions, and ambient electrons) are treated as computational test particles. The trajectories of each test particle, the space charge and the self-consistent electric field, are obtained from Newton's second law and Poisson's equation, respectively:

$$F = m \frac{\mathrm{d}v}{\mathrm{d}t} = Eq \tag{6}$$

$$-\nabla^2 \phi = \rho / \varepsilon_0 \tag{7}$$

The simulation setup is shown in Fig. 5. Part of the spacecraft is modeled as a box in the middle of the bottom area of the simulation

Table 3 Background plasma parameters[2,6]

Background plasma	Density, m^{-3}	Electron temperature, eV	Ion temperature, eV
Laboratory plasma, 10^{-6} mbar	2.4×10^{14}	4.2	0.05
LEO orbit	1×10^{12}	0.1	0.1

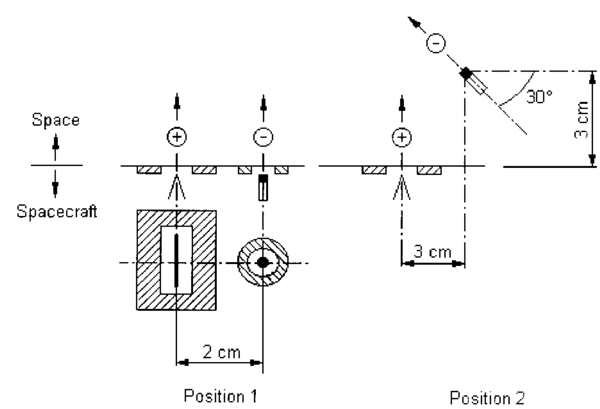

Fig. 4 Neutralizer position.

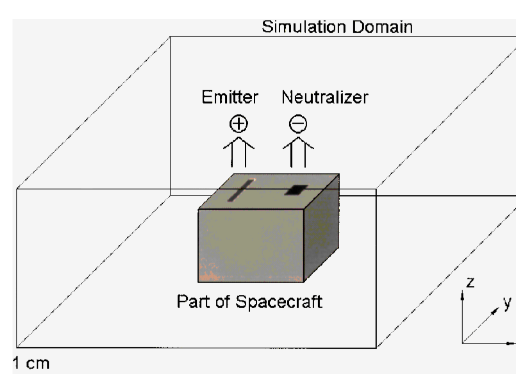

Fig. 5 Simulation domain.

Table 4 Simulation parameters

Case	Emitter current, mA	Emitter voltage, kV	Neutralizer voltage, V	Neutralizer current, mA	Neutralizer grounding potential, kV	Background plasma	Neutralizer (position)
1	0.9	6	——	——	——	——	No
2	1.4	7	——	——	——	——	No
3	0.9	6	——	——	——	LEO	No
4	0.9	6	——	——	——	Laboratory	No
5	0.9	6	100	1	0	——	Yes (1)
6	0.9	6	100	1	0	——	Yes (2)
7	0.9	6	100	1	−3	——	Yes (1)
8	0.9	6	100	1	−10	——	Yes (1)

domain. Test particles representing the FEEP ions are injected into the simulation domain along the FEEP slit on the spacecraft surface with the velocity v_i [Eq. (1)] and with a spatial distribution given by Eq. (2). Test particles representing the neutralizer electrons are injected into the simulation domain from the neutralizer exit with the velocity v_e [Eq. (4)] that follow the spatial distribution given by Eq. (5).

For simulations with an ambient plasma, test particles representing the ambient plasma are loaded uniformly into the domain with a Maxwellian velocity distribution at the start of the simulation. All domain boundaries except the spacecraft box are considered to be open boundaries. At the open boundaries, ambient plasma particles can flow into the simulation domain with a thermal flux

$$\Gamma = n/4\sqrt{8kT/m\pi} \tag{8}$$

A Neumann boundary condition for Poisson's equation is applied on all open boundaries; the potentials at the surfaces of the spacecraft box, the emitter, accelerator, and neutralizer are specified.

In most full-particle simulations, an artificial ion-to-electron mass ratio of ~100 is typically used because of computational constraints. However, to simulate the neutralization process accurately, we find it necessary to use an ion-to-electron mass ratio close to the real value. This is because the neutralization process studied here is for a mesothermal plasma, i.e., the beam ion velocity is much larger than the ion thermal velocity but much smaller than the electron thermal velocity. Under the mesothermal condition, the ion beam is neutralized by thermal electrons. However, an artificial ion-to-electron mass ratio of ~100 would destroy this mesothermal velocity order and lead to a beam ion velocity larger than the electron thermal velocity in the simulation. Hence a small ion-to-electron mass ratio would change the problem into a completely different one, i.e., the interactions of an ion beam with an electron beam. In the simulations presented here, we use an ion-to-electron mass ratio of 80,000. This mass ratio ensures the mesothermal velocity order and is necessary for correctly simulating the problem.

The size of the simulation domain was $0.1 \times 0.1 \times 0.2$ m. In the simulations related to FEEP operations with a neutralizer and FEEP operations in a laboratory environment, the number of grid cells used was $20 \times 20 \times 40$ with a cell size of 5 mm. Incidently, this size corresponds to the Debye length generally corresponding to the plasma condition in the middle of the simulation domain during neutralizer operation. The simulation results show that in the domain center, the electron density is $\sim 1 \times 10^{13}$ m^{-3} (Fig. 6) and the electron temperature is ~5 eV (Fig. 7). In the simulations of FEEP operations in LEO plasma, the number of grid cells used is $20 \times 20 \times 80$ and the cell size corresponds to the Debye length of $\lambda_{D,\mathrm{LEO}} \approx 2.5$ mm. We have performed extensive numerical tests to ensure that our grid resolution does not affect the steady-state solution. As an example, Fig. 8 compares the results from simulations with different grid resolutions. The number of grid cells compared are $20 \times 20 \times 40$, $20 \times 20 \times 80$, and $40 \times 40 \times 40$. We find that the results are not sensitive to the grid size used.

The number of ions emitted from the FEEP thruster varied from case to case but the number of particles per cell was always larger than 100 to minimize the effects of numerical noise. Numerical tests were also performed to ensure that the number of particles we used is sufficient so it does not affect the steady-state situation. The time step was based on the electron plasma frequency. The simulation was performed until a steady state was reached, i.e., the number of particles in the simulation domain remained constant. In a typical case, the number of particles at equilibrium was 80,000 and the number of time steps to reach equilibrium was 30,000. A typical run takes ~3–4 days on a Silicon Graphics Power Challange XL computer.

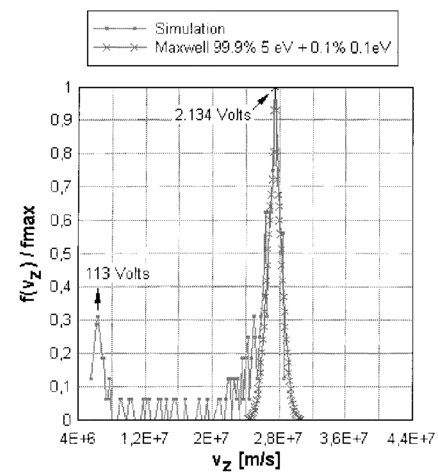

Fig. 7 Velocity distribution $f(v_z)$ of neutralizer electrons in simulation domain (case 7).

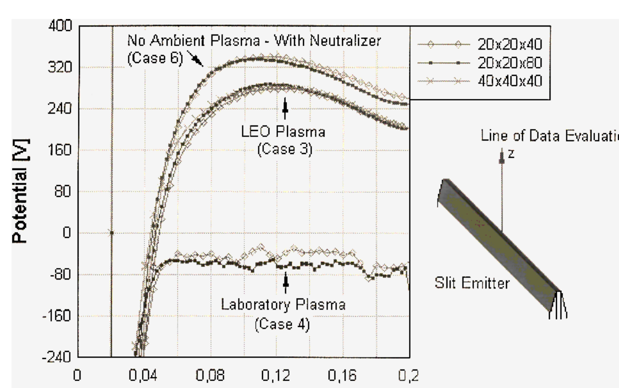

Fig. 8 Grid resolution variation of potential from middle of slit.

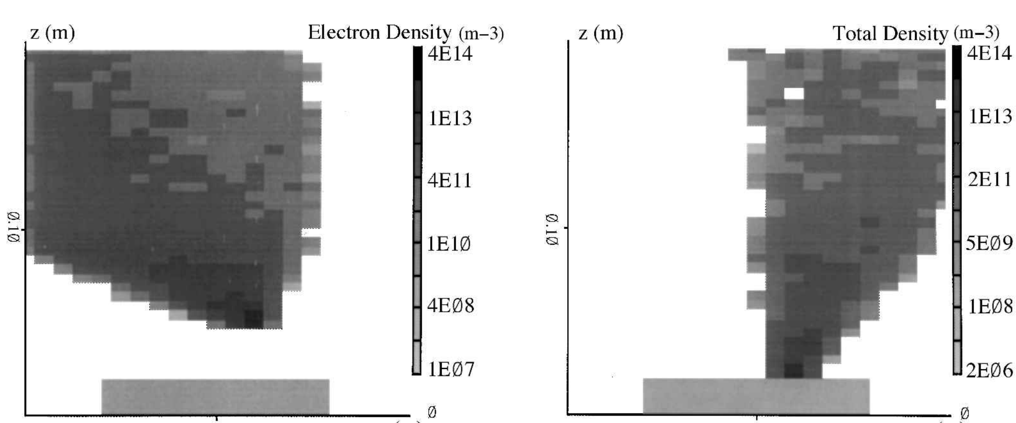

Fig. 6 The x–z plot of neutralizer electron density (cases 6 and 7).

The three-dimensional simulation code has been tested against the ion density measurements obtained for a FEEP emitter at CENTROSPAZIO.[2] The results show a very good agreement between simulations and measurements.[8]

III. Results and Discussions

A. FEEP Emission Without Neutralizer

Our first set of simulations (cases 1–4) concern the operation of a FEEP emitter without a neutralizer. In cases 1 and 2, the emission occurs in a vacuum environment. Because there is no neutralization mechanism in these cases, it is expected that the emission will be dominated by space-charge effects from the beam. Figure 9 shows the beam ion positions for case 1 on a y–z plane along the FEEP emitter slit and on an x–z plane across the center of the slit, Fig. 10 shows the ion beam density and the electric-field distribution on an x–z plane, and Fig. 11 shows the associated beam ion flux vectors. The ions emitted from the FEEP emitter form a divergent beam. The asymptotic divergence is 15.9 deg along the slit and 32.1 deg perpendicular to the slit. Figure 3 shows the divergence perpendicular to the slit at a radius of $r = 0.06$ m. The potential along the z axis is also shown in Fig. 12, which exhibits a nonmonotonic profile with a maximum of 373 V at a distance of 9.5 cm from the FEEP emitter. The buildup of a substantial positive potential inside the beam is obviously due to space charge effects. However, because the potential hump is 1 order of magnitude below the emitter and accelerator potential and the location of the potential hump is 9.5 cm above the FEEP slit, the ion beam divergence does not increase significantly

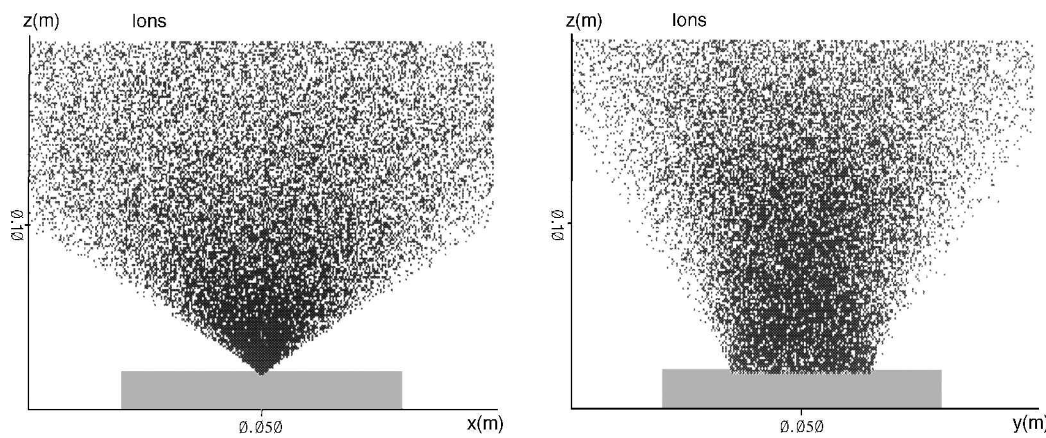

Fig. 9 The x–z and y–z plots of FEEP ion positions (case 1).

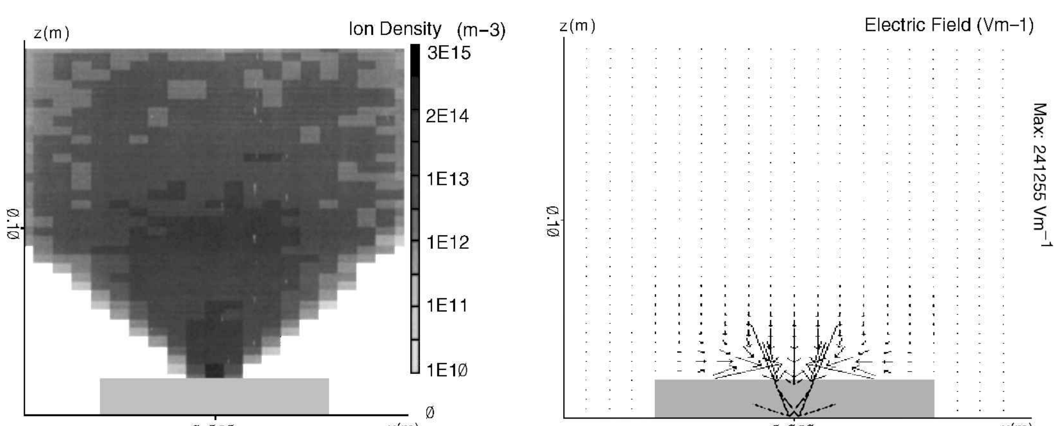

Fig. 10 The x–z plot of FEEP ion density and electric field (case 1).

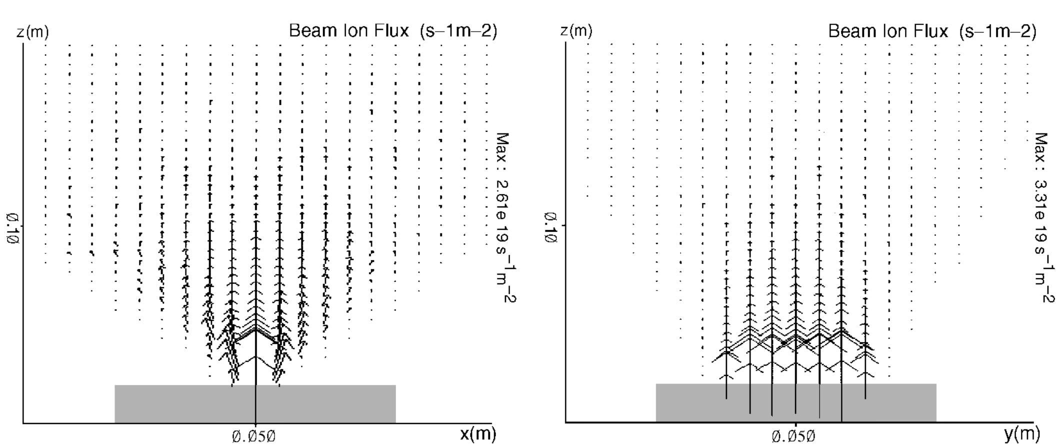

Fig. 11 Beam ion flux $n_i v_i$ plot x–z at plane y = 0.05 m and plot y–z at plane x = 0.05 m (case 1).

(recall that the initial beam divergence is 15 deg along the slit and 30 deg perpendicular to the slit).

Space-charge effects associated with one-dimensional ion beam flows in a diode is a classical problem.[9] In a diode, the maximum current that can be transmitted between the electrodes is limited by the well-known Child's law. If the current emitted exceeds this limit, a virtual anode (with a potential equal to the beam kinetic energy) will form in between the electrodes to block part of the emitting current. Recently, Wang and Lai[4] studied space-charge effects associated with ion beam emissions in space by using three-dimensional full-particle simulations. They found that a nonmonotonic potential profile, or even a virtual anode, can also form for beam emissions in space if the emitted current is sufficiently large. However, compared with the one-dimensional diode problem, beam divergence that is due to space charge and neutralization by the ambient electrons make the conditions for virtual anode formation much less favorable. In particular, the effects from beam divergence and ambient neutralization are more prominent for beams with a smaller beam radius because of higher beam densities.

The beam divergence will greatly relax the condition for virtual anode formation. We have run simulations for various emission current values. For instance, in case 2, we increase the emission current and the acceleration voltage by following the current–voltage emission characteristics of the CENTROSPAZIO thruster.[2] Even though the emission current in case 2 has been increased from 0.9 to 1.4 mA, we find that the FEEP emitter is still able to transmit out all the current. However, in this case, the maximum potential inside the beam also increases to 573 V (see potential profile in Fig. 12) because of the higher emission current. This potential hump is still small compared with the emitter potential of 6000 V and hence does not significantly affect ion emission or increase the beam divergence to a great extent. We find that, in general, the slit geometry allows a FEEP to transmit any reasonable values of emission current, even when no neutralization mechanisms are present, although its performance will suffer because of the reduced beam velocity and increased beam divergence.

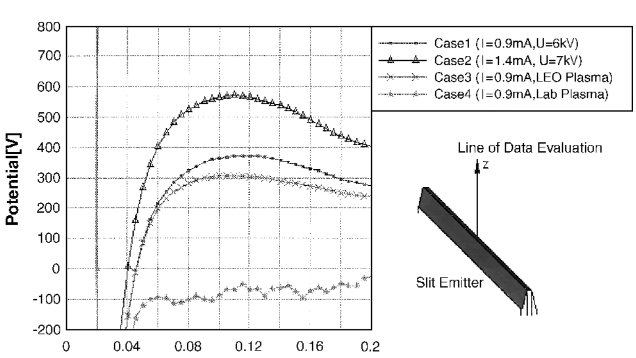

Fig. 12 Comparison of potentials from middle of slit emitter among cases 1, 2, 3, and 4.

We next consider FEEP emission in an ambient plasma environment (Table 3). In case 3, we consider FEEP operation in a typical LEO environment in which the plasma density is $\sim 1 \times 10^{12}$ m^{-3} (the Debye length is $\lambda_{D,\mathrm{LEO}} = 2.5$ mm). This density is more than 3 orders of magnitudes below the maximum ion beam density (Fig. 10). In case 4, we consider FEEP operation in a vacuum chamber. Particle collisions, ion sputtering, and secondary electron emissions inside a vacuum chamber will create a laboratory plasma. Under typical vacuum chamber operating conditions, the density of the laboratory plasma is only ~ 1 order of magnitude below the maximum density of FEEP ions ($\lambda_{D,\mathrm{Laboratory}} \approx 1$ mm).

The potential profiles are compared in Fig. 12. The ambient plasma provides a neutralization mechanism to the space charge generated by FEEP emission. In both cases, the ambient electrons are attracted into the ion beam region by the positive potential from the ion beam's space charge, whereas the ambient ions are attracted to the FEEP accelerator region by FEEP's high negative potential. We find that a LEO plasma with an electron density of 10^{12} m^{-3} is not sufficient to neutralize the space charge of the FEEP beam. In case 3, the FEEP beam becomes an electrostatic trap for the ambient electrons. The ambient electron flux vectors are concentrated in the space-charge region whereas the ambient ion flux vectors are directed to the FEEP accelerator region (Fig. 13). On the other hand, case 4 shows that the high-density laboratory plasma will completely neutralize the beam's space charge. In this case, the FEEP potential is shielded by the plasma. The potential inside the beam also monotonically increases from the negative potential at the accelerator surfaces to the ambient potential.

Both the beam divergence and the beam potential will have significant implications for the performance of a FEEP. For instance, the maximum flux vectors (measured at $z = 0.1$ m) along the thrust direction for cases 1, 3, and 4 are 2.45×10^{18}, 2.88×10^{18}, and 3.13×10^{18} s^{-1}m^{-2}, respectively. This difference is a direct reflection of the effects of the beam potential on the beam ion velocity. Using the potential at $z = 0.1$ m from the simulations and Eq. (1), we find that the maximum beam velocities among these three cases are 90,525, 92,449, and 93,754 ms^{-1}, respectively. Not surprisingly, case 4, i.e. the case with complete neutralization, provides the maximum thrust for FEEP.

B. FEEP Emission with Neutralizer

Our second set of simulations (cases 5–8) concerns the operation of a FEEP emitter in connection with the operation of a neutralizer. In space, a spacecraft's potential with respect to the ambient plasma is a floating variable controlled by the net current received by the entire spacecraft. Under nominal operating condition, the electron current from a neutralizer equals the FEEP ion current

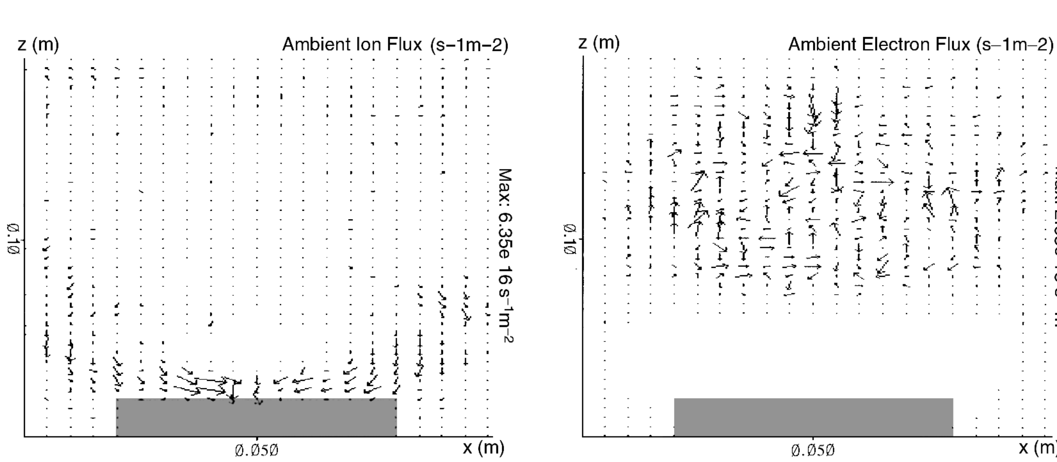

Fig. 13 The x–z plot of ambient ion flux $n_{i,a}v_{i,a}$ and ambient electron flux $n_{i,a}v_{i,a}$ at plane y = 0.05 m (case 3).

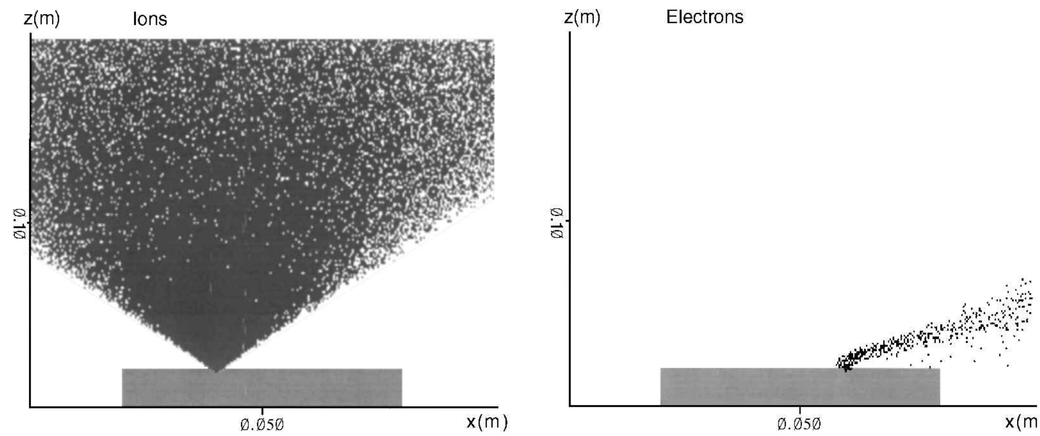

Fig. 14 The x–z plot of beam ion and neutralizer electron positions (case 5).

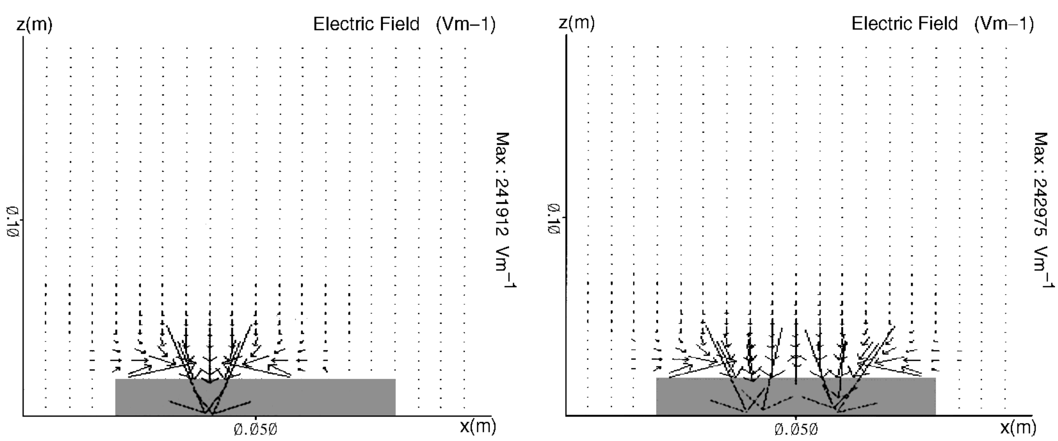

Fig. 15 The x–z plot of the electric field (cases 5 and 7).

and the net current collected by the spacecraft from the ambient plasma to prevent spacecraft charging. To concentrate on the effects from the neutralizer, here we consider a FEEP thruster operating in a vacuum environment. Furthermore, because our interest here is to study local ion beam neutralization, we assume that the potential at the spacecraft surface is held at the ambient potential in all the simulation cases presented here. However, in reality a variation of neutralizer conditions may lead to changes of the spacecraft potential.

Parameters that will affect the neutralization include the neutralizer grounding potential (with respect to the spacecraft potential), the neutralizer voltage, and the neutralizer position. Simulation cases 5 and 7 concern the effect of the neutralizer grounding potential. In these cases, a neutralizer is taken to be mounted on the spacecraft surface beside the FEEP thruster. In case 5, we assume that the neutralizer grounding potential is the same as the spacecraft surface potential (0 V). Figure 14 shows the positions of the beam ions and the neutralizer electrons, and Fig. 15 shows the vector plots of the electric field. In the absence of plasma shielding provided by a dense ambient plasma, the high negative FEEP accelerator potential will dominate a very large neighboring space of the FEEP. Hence the electrons will immediately fall into the electric field produced by the FEEP accelerator potential. As this field is much stronger than the electron kinetic energy, all electrons are pulled away from the beam ion region by the FEEP emitter. Hence there is no interaction among the neutralizing electrons and FEEP ions, and no neutralization of the FEEP beam. The potential profile along the z axis for case 5 is compared with the no-neutralizer case (case 1) in Fig. 16. These two potential profiles are almost identical.

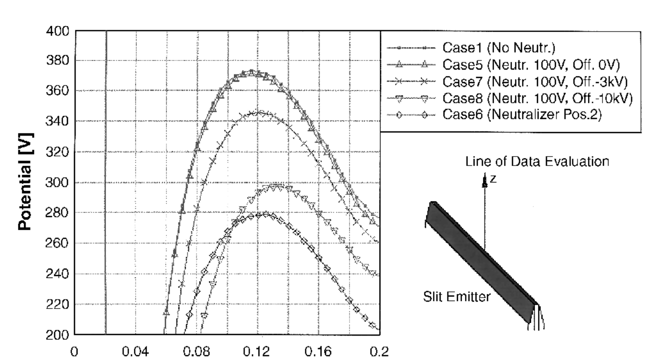

Fig. 16 Comparison of potentials from middle of slit emitter among cases 1, 5, 6, 7, and 8.

For the neutralizing electrons to interact with the FEEP ions, an initial energy sufficient to overcome the electric field produced by the FEEP accelerator must be provided to the neutralizing electrons. In case 7, we take the neutralizer grounding potential to be equal to the negative FEEP accelerator potential ($U_N = -3$ kV). Figure 6 shows the electron density for this case, which indicates that the electrons start to interact with the FEEP ions. As a result, the maximum positive potential in the beam is reduced to 345 V. In case 8, we further increase the neutralizer grounding potential to -10 kV, and the maximum positive potential in the beam is further reduced to 297 V.

In Fig. 7, we show the electron velocity distribution for case 7. The distribution indicates two peaks, one at 113 V, corresponding

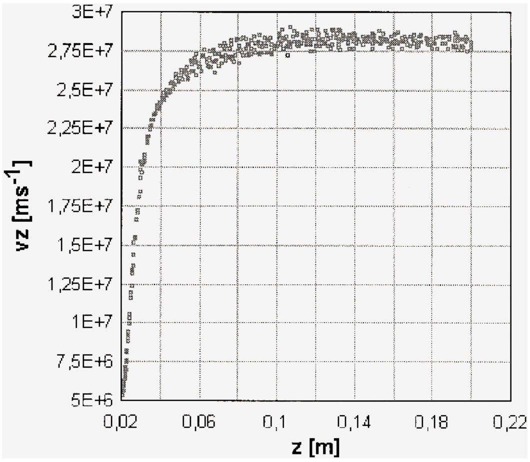

Fig. 17 The v_z vs z phase space plot (case 7).

to the initial neutralizer anode potential acceleration, and the other one at 2143 V, which corresponds to the energy gained from the potential difference between the neutralizer's exit to the middle of the ion beam where the neutralization process is at its maximum. A curve fit of the velocity distribution at this peak obtained from the simulation shows that it is composed of two Maxwellian distributions, one with a temperature of 5 eV and the other one with a temperature of 0.1 eV. As the composition ratio from the curve fit is (99.9% 5 eV) + (0.1% 0.1 eV) the total distribution is dominated by the 5 eV electron component. Recall that the initial temperature of the emitted electrons is 0.1 eV; this result indicates that electron heating has taken place during the neutralization process. The positive space charge of the FEEP beam forms an electrostatic trap for the neutralizing electrons. Interactions between the electrons and this potential further randomize the electron velocity, leading to an increased electron temperature. This can also be seen from the v_z vs v phase space plot in Fig. 17, showing the increase of the electron velocity from the neutralizer's exit toward the ion beam where the initially sharp line broadens because of heating. The 5 eV temperature is also consistent with laboratory measurements of the electron temperature for a similar FEEP emitter and neutralizer configuration.[2] Considering this behavior, the electron dynamics associated with the neutralization process and their effects on the macroscopic potential distribution can be resolved only by a full-particle model.

We have also run simulations with a different neutralizer anode potential U_A. This potential is necessary to accelerate the electrons out of the thermal cathode. Typically, the variation of U_A is within 100 V. Such a small variation will have only a very minor effect on the total electron accelerating potential, $U_N - U_A$. For instance, we have run case 7 with an anode potential of $U_A = 10$ V instead of 100 V, and the results are essentially the same.

Our results suggest that, if a neutralizer is placed besides a FEEP emitter on the spacecraft surface, increasing the total neutralizer accelerating potential ($U_N - U_A$) by even several kilovolts will not have a very significant effect on the beam neutralization in a low-density ambient plasma. Hence, for the electrons emitted from the neutralizer to interact with the beam ions, one must carefully choose the neutralizer location so that the emitted electrons can avoid the region of high negative potential produced by the FEEP accelerator. We have tested various neutralizer locations with simulations. We find that placing a neutralizer above the spacecraft surface and pointing the neutralizer emitter toward the FEEP beam will significantly improve the FEEP beam neutralization. Such a configuration is used in case 6. Here, we take $U_A = 100$ V and $U_N = 0$ V. Figure 6 shows the electron density and Fig. 7 compares the potential for this case against the other simulation cases discussed. The results show that the electrons are attracted toward the beam region, and the positive space charge is the lowest among the no-ambient-plasma cases with the maximum positive potential inside the beam reduced to 278 V. Hence the second neutralization position facilitates a much better FEEP neutralization.

IV. Conclusion

We have developed a three-dimensional full-particle-simulation model for a field-emission-electric-propulsion (FEEP) thruster. Our focus in this paper is to understand the basic characteristics of the propellantions emitted from a FEEP thruster and their neutralization in an ambient plasma environment or from a thermionic neutralizer. The simulation model includes ion emission from a FEEP, electron emission from a thermionic neutralizer, as well as ambient ions and electrons. Simulations are performed with ion-to-electron mass ratios close to actual values ($m_i / m_e = 80{,}000$) so that the neutralization processes are resolved accurately.

The slit geometry and the small dimensions of a FEEP emitter allow the emission of almost any reasonable values of ion current even when no neutralization mechanisms are present. However, the space charge of the beam will produce a substantial positive potential inside the beam. The increased beam divergence and the reduced emission velocity that are due to the beam potential compromise FEEP's thrust performance.

When a FEEP emitter is operated by itself in an ambient plasma, the beam ion characteristics and neutralization are strongly influenced by the ambient plasma density. Our simulation results suggest that only ambient plasmas with a density comparable with the ion density near the FEEP emitter provide a complete neutralization of the FEEP ions. Situations of such a high-density ambient plasma are only relevant to laboratory tests. As the density of typical space plasmas is always orders of magnitude smaller than the FEEP density, laboratory measurements of the FEEP beam must be interpreted with care as they cannot be easily extrapolated to space conditions. For a FEEP operating without a neutralizer in space, the emitted beam ions can never be completely neutralized.

We have investigated the effectiveness of neutralization by a thermionic neutralizer. We find that this effectiveness is primarily controlled by the neutralizer position because of the exposed high-voltage surface of the FEEP. Our results show that, if a neutralizer is placed next to the FEEP emitter on the spacecraft surface, it will have only a very marginal effect on the FEEP beam ions even when the neutralizer is grounded several kilovolts negative with respect to the spacecraft. This is because the electric field surrounding a FEEP emitter is dominated by the field produced by the FEEP's accelerator. Hence, rather than being attracted by the beam's space charge, the electrons emitted by the neutralizer will be pulled away from the FEEP beam. For the same reason, changing the neutralizer accelerator voltage will not help the neutralization. The only way to facilitate interactions among the neutralizer electrons and the FEEP ions is to place the neutralizer outside of the region dominated by the FEEP's accelerator potential. We suggest that a neutralizer should be placed above the spacecraft surface and pointed toward the FEEP beam region. Simulation results suggest that such a configuration provides the best beam neutralization for FEEP operation in a near-vacuum environment.

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References

[1]Mitterauer, J., "Field Emission Electric Propulsion: Mass and Optical Spectroscopy of Beam Components," Final Rept. on ESTEC Contract 6545/85/NL/PH, Vienna Univ. of Technology, Austria, 1989.

[2]Andrenucci, M., Marcuccio, S., and Genovese, A., "FEEP Thruster

Plume Investigation with Langmuir Probes," *Proceedings of the International Electric Propulsion Conference*, IEPC-95-98, Moscow Aviation Inst., Moscow, 1995, pp. 649–664.

[3]Mitterauer, J., "Computer Simulation and Optimization of a Thermionic Neutralizer for a Cesium Liquid Metal Ion Thruster," Internal Rept., Vienna Univ. of Technology, Vienna, Austria, 1997.

[4]Wang, J., and Lai, S. T., "Virtual Anode in Ion Beam Emissions in Space: Numerical Simulations," *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, 1997, pp. 829–836.

[5]Kaufman, H. R., "Technology of Electron-Bombardment Ion Thruster," *Advances in Electronics and Electron Physics*, Vol. 36, Academic, New York, 1974, pp. 266–368.

[6]Hastings, D., and Garrett, H., *Spacecraft—Environment Interactions*, Cambridge Univ. Press, New York, 1996.

[7]Birdsall, C. K., and Langdon, A. B., *Plasma Physics via Computer Simulation*, Adam Hilger, 1991.

[8]Tajmar, M., Mitterauer, J., and Wang, J., "Field-Emission-Electric-Propulsion (FEEP) Plasma Modeling: 3-D Full Particle Simulations," *AIAA Joint Propulsion Conference*, AIAA, Reston, VA, 1999.

[9]Fay, C. E., Samuel, A. L., and Shockley, W., "On the Theory of Space Charge Between Parallel Electrodes," *Bell System Technical Journal*, Vol. 17, No. 49, 1938, pp. 49–79.