BEAM INTENSITY DISTRIBUTION OF A RING-CUSP ION THRUSTER

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Abstract

A new method of an ion beam trajectory design is proposed for a ring-cusp ion thruster. The newly introduced simple models give three profiles: 1. an ion saturation current density in the neighborhood of a screen grid, 2. a separation distance between screen and accelerator grids, and 3. a multibeam intensity. The calculated result of the multibeam intensity profile is compared with the measured results of a beam profile test for a 35-cm diameter ring-cusp xenon ion thruster. The both results agree well, and the foregoing models are proved effective. This indicates that the ion beam trajectory design is possible for the ring-cusp ion thruster.

Introduction

Application of ion thrusters in space has started in Japan. Ion engine systems perform north-south stationkeeping with Kaufman-type xenon ion thrusters at a nominal thrust of 25 mN. They were onboard the Engineering Test Satellite-VI (ETS-VI) in 1994, and the Communications and Broadcasting Engineering Test Satellite (COMETS) in 1998.1,2

Primary propulsion is the next target of ion thruster application. We are investigating ring-cusp ion thrusters with a nominal thrust of 150 mN. The objective is to develop basic technology for future application to primary propulsion systems of orbit transfer vehicles (OTV). The development of two laboratory models (LM-1, 2) was started in 1987 and finished in 1993.3,4 The latest thruster is the first breadboard model (BBM-1), which was fabricated in 1994.5,6

In this paper, we will describe a new method of an ion beam trajectory design for the ring-cusp ion thruster. The ion beam trajectory design has five analyses: a cusped magnetic field analysis, a plasma particle trajectory analysis, a grid separation analysis, a beamlet trajectory analysis, and a multibeam trajectory analysis. The newly introduced simple models will give three profiles: an ion saturation current density in the neighborhood of a screen grid for the plasma particle trajectory analysis, a separation distance between screen and accelerator grids for the grid separation analysis, and a multibeam intensity for the multibeam trajectory analysis. We will compare the designed result with the measured results of a beam profile test for the multibeam intensity profile of the BBM-1 thruster.

Ion Beam Trajectory Design

Thrustor Specifications

The BBM-1 thruster is the ring-cusp ion thruster with a beam exhausting diameter of 35 cm, and works with xenon as a propellant. It produces a thrust of 150 mN and a specific impulse of 3,500 s at a xenon flow rate of 3.27 A equivalent in the nominal operating condition. Figure 1 shows a cross section of the BBM-1 thruster. It has a cylindrical form of 45 cm in diameter and 29 cm in length, and weighs 12 kg. Hollow cathodes are used for main and neutralizer cathodes. Table 1 shows the main specifications and target performance of the BBM-1 thruster.

The BBM-1 thruster uses a three-grid ion accelerating system. The screen grid is made of a 0.4-mm thick molybdenum plate, and the accelerator and decelerator grids are made of 0.6-mm thick molybdenum plates. Each grid is dished outward, and the screen grid has 18,241 holes of 2.2 mm in diameter for ion extraction arranged in hexagonal arrays. The screen, accelerator and decelerator grids have open area fractions of 70%, 26% and 50%, respectively. Each grid is mounted on the thruster body with 12 grid supports which are flexible, using piano wire springs.

The discharge chamber has an iron anode consisting of a 1-mm thick sidewall and a 1-mm thick dished endwall. The sidewall is 17.4 cm long and its cross section is a regular polygon of 24 sides with an inner osculating circle of 37 cm in diameter. The endwall has a radius of curvature of 2 m and a dish depth of 6 mm. The anode surfaces are coated with molybdenum on the inside and white alumina on the outside.

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Cusped Magnetic Field Analysis

Ring-cusp magnetic field is formed in the discharge chamber by four rings of samarium cobalt (Sm2-Co17) magnets as shown in Fig. 1: two magnet rings M1 and M2 are attached on the sidewall, and the others M3 and M4 on the endwall. The magnet ring M1 has 24 pieces of small straight magnets with cross section of 3 mm in width and 6 mm in height, and 2-mm width iron plates to absorb the excessive magnetic field. The magnet rings M2 and M3 have 24 pieces of small straight magnets with cross section of 5 mm in width and 6 mm in height. The magnet ring M4 has 12 pieces of small straight magnets with cross section of 5 mm in width and 6 mm in height, and a molybdenum magnet cover to prevent the discharge current from flowing directly into the magnets.

The cusped magnetic field analysis is based on a three-dimensional computation code (MAGNA/IEM) for magnetic fields. The objective is to obtain a magnetic-field-free region from scalar magnetic field contours. The discharge chamber plasma is confined within this region. Figure 2 shows the scalar magnetic field contours in the discharge chamber. In the contour calculation, we assume that the discharge chamber has a 1-mm thick cylindrical iron anode of 37.2 cm in diameter and 18.1 cm in length. This figure indicates that the 4-mT contour does not intersect the chamber walls. The inner part of this contour surface is the magnetic-field-free region. The 4-mT contour shape approximates to a circular truncated cone which has an upper radius of 12.1 cm, a lower radius of 15.6 cm and a height of 11.1 cm as shown by a broken line in Fig.2.

Plasma Particle Trajectory Analysis

The plasma particle trajectory analysis is based on a newly introduced simple model (circular truncated cone approximation model) for the discharge chamber plasma. This model is obtained using the two-dimensional free-fall model. The objective is to obtain the ion saturation current profile in the neighborhood.

### Table 1: Target and test values of thruster parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
<th>Test</th>
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<tr>
<td>Thrust, mN</td>
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<td>150</td>
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<tr>
<td>Specific impulse, s</td>
<td>3500</td>
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<td>Total electric power, kW</td>
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<td>Propellant utilization</td>
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<td>efficiency, %</td>
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<td>Ion production cost</td>
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<td>Acceleration System</td>
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<td>Beam voltage, V</td>
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<td>Accel. grid current, mA</td>
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<td>Decel. grid current, mA</td>
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<td>Discharge chamber</td>
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<td>Xenon flow rate, Aeq</td>
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<td>Discharge voltage, V</td>
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<td>Discharge current, A</td>
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<td>Main cathode</td>
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<td>Neutralizer cathode</td>
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<td>Neutralization current, A</td>
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<td>Keeper current, A</td>
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of the screen grid from the magnetic-field-free region which has a circular truncated cone form defined by
an upper radius of \( r_u \), a lower radius of \( r_{a} \) and a
height of \( l_{h} \). The ion saturation current density in the
neighborhood of the screen grid is expressed by

\[
J_{ia} = e\sqrt{2} I_{o} C_{i} n_{e} \alpha_{i}[r; \kappa],
\]

(1)

where \( n_{e} \) is the electron density in the neutral plasma
region of the discharge chamber plasma,

\[
C_{i} = \frac{eT_{e}^{M}}{m_{i}}
\]

is the sound velocity, \( T_{e}^{M} \) is the electron
temperature, \( m_{i} \) is the ion mass and \( e \) is the elementary
charge. Assuming that an ion particle does not collide
with other particles for the discharge chamber plasma,
a normalized cross section for the ion particle flux is
expressed by

\[
\alpha_{i}[r; \kappa] = \exp(-\rho)(1+\kappa \rho) \quad (0 \leq \rho \leq 1)
\]

\[
= \exp(-\rho)(\rho_{c} - \rho)\frac{\kappa + 1}{\rho_{c} - 1} \quad (1 < \rho \leq \rho_{c})
\]

(2)

where \( \rho = \left( \frac{r}{r_{a}} \right)^{2}, \rho_{c} = \left( \frac{r_{c}}{r_{a}} \right)^{2} \)
and \( r_{c} \) is a lower
radius of the discharge chamber. Assuming that the
discharge chamber plasma is confined firmly by the
cusped magnetic field when the magnetic-field-free
region has a cylindrical form, a distributed constant
for the ion particle flux is expressed by

\[
\kappa = \frac{1}{\Omega + 2 - \exp(1)} - 1,
\]

(3)

where

\[
\Omega = \frac{2\{G_{1}[x] + (1 - \xi_{m})G_{2}[x]\}}{\exp(-\eta_{o}) + \exp(-\eta_{m}[x])\xi_{m}^{2}}
\]

(4)

and \( \xi_{m} = \frac{r_m}{r_a} \). An electron scattering coefficient is
expressed by

\[
R[x] = \frac{G_{2}[x]}{G_{1}[x]} + \frac{2}{1 + \exp(\eta_{m}[x] - \eta_{o})},
\]

(5)

where

\[
\xi_{m} = \frac{r_{m}}{r_{a}}.
\]

(6)

Fig. 2 Scalar magnetic field contours in the discharge chamber.

Fig. 3 Ion saturation current density profile in the
neighborhood of the screen grid.

\[
\eta_{o}[x] = \left( 1 - \sqrt{1 - (1 - x)^{2}} \right) U[1 - x],
\]

where

\[
x = \frac{l_{h}}{L_{S_o}} , \quad L = \sqrt{2} C_{i}, \quad n_{o} \text{ is the neutral atom}
density, \langle \sigma_{10} \rangle \text{ is the ionization rate and } U[\tau] \text{ is}
the unit function. } G_{1}[x] \text{ and } G_{2}[x] \text{ are given by}
\[ G_i[x] = \frac{1}{x} \int_{-\tau}^{\tau} \exp(-\eta_2 \tau) \, d\tau, \quad (7) \]
and
\[ G_2[x] = \frac{1}{x^2} \int_{-\tau}^{\tau} \exp(-\eta_2 \tau)(\tau - 1) \, d\tau, \quad (8) \]

where
\[ \eta_2 = \left\{ 1 - \sqrt{1 - \tau^2} \right\} U[\tau]. \quad (9) \]

\[ G_i[x] \text{ and } G_2[x] \text{ can be approximated the following equations:} \]
\[ G_i[x] = \frac{1}{x} \left( \frac{L_o}{s_o} - 1 + x \right) \quad (x > 1) \]
\[ = \exp(-\eta_o) + \left\{ \frac{L_o}{s_o} - \exp(-\eta_o) \right\} \sqrt{x} \quad (x \leq 1) \quad (10) \]
and
\[ G_2[x] = \frac{1}{x^2} \left\{ \Gamma_o + \frac{1}{2}(1 - x^2) \right\} \quad (x > 1) \]
\[ = -\frac{1}{2} \exp(-\eta_o) + \left\{ \Gamma_o + \frac{1}{2} \exp(-\eta_o) \right\} \sqrt{x} \quad \]
\[ (x \leq 1) \quad (11) \]

The plasma-sheath constants are given by
\[ L_o = \frac{2}{\pi} \exp(-\eta_o) D[\sqrt{\eta_o}] = 0.3444, \quad (12) \]
and
\[ \Gamma_o = \frac{\exp(-\eta_o) + \eta_o - 1}{\eta_o^2} - \frac{L_o}{s_o} = -0.4677, \quad (13) \]
where \( \eta_o = 0.8539 \), \( s_o = 0.4046 \) and \( D[x] \) is the Dawson function.

Figure 3 shows the ion saturation current profile in the neighborhood of the screen grid. This figure indicates that the discharge chamber plasma is confined fully within the magnetic-field-free region.

**Grid Separation Analysis**

The grids are fabricated using press-welding and press-forming techniques after the holes and outer shapes were formed by photo-chemical etching. The screen, accelerator and decelerator grids have convex curvatures of 1.6 m, 1.5 m and 1.4 m at room temperature, respectively. The cold separation distance between the screen and accelerator grids is 1.5 mm at the grid center and 0.8 mm in the periphery region. The cold separation distance between the accelerator and decelerator grids is 1.3 mm at the grid center and 0.5 mm in the periphery region. Because each grid is mounted on the thruster body with 12 axial springs to absorb radial thermal expansion of the grid, the change of the grid separation is caused by a difference of the average and periphery grid temperatures at the nominal operation.

The grid separation analysis is based on a two-dimensional thermal analyzing code and a newly introduced simple model for the grid separations. The objective is to obtain three profiles for the ion accelerating system from the ion saturation current in the neighborhood of the screen grid: the screen grid temperature, the separation distance between the screen and accelerator grids, and the beamlet focal length for the ion optics. Figure 4 shows the temperature profiles of the screen and accelerator grids at the nominal operation. The average and periphery grid temperatures of the screen, accelerator and decelerator grids at the nominal operation are 266 °C and 178 °C, 124 °C and 125 °C, and 51 °C and 59 °C, respectively. This indicates that the screen grid curvature becomes smaller exclusively at the nominal operation.

Assuming that the parameter changed by the difference of the average and periphery grid temperatures is only the grid curvature, the screen grid curvature at the nominal operation is expressed by
\[ R_s = \frac{1}{2\sqrt{6}} \sqrt[3]{\frac{L_s^3}{L_s - D_s}}, \quad (14) \]
and the screen grid diameter at the nominal operation is given by
\[ D_s = D_{s0} \left\{ 1 + \alpha_s \left( T_s - T_0 \right) \right\}, \quad (15) \]
where \( \alpha_s \) is the linear expansion coefficient at the nominal operation, \( D_{s0} \) is the cold screen grid diameter, \( T_s \) is the periphery screen grid temperature at the nominal operation, and \( T_0 \) is the room temperature. The arc length of the screen grid at the nominal operation is given by
\[ L_s = L_{s0} \left\{ 1 + \alpha_s \left( T_s^* - T_0 \right) \right\}, \quad (16) \]
and the cold arc length of the screen grid is given by
\[ L_{\alpha 0} = 2 R_{\alpha 0} \sin^{-1} \frac{D_{\alpha 0}}{2 R_{\alpha 0}} \], \quad (17) \]

where \( R_{\alpha 0} \) is the cold screen grid curvature and \( \langle T_{s} \rangle \) is the average screen grid temperature at the nominal operation. The other grid curvatures at the nominal operation can be calculated in much the same way as that of the screen grid.

The separation distance between the screen and accelerator grids for the \( \mu \)th beamlet at the nominal operation is expressed by

\[ d_{sa}^{\mu} = d_{sa}^{e} - z_{s}^{\mu} + z_{a}^{\mu} \]. \quad (18) \]

where \( d_{sa}^{e} \) is the cold separation distance between the screen and accelerator grids in the periphery region. The screen grid depth at the nominal operation is given by

\[ z_{s}^{\mu} = \sqrt{R_{s}^{2} - (x_{se}^{\mu})^{2} - (y_{se}^{\mu})^{2}} - \sqrt{R_{s}^{2} - \left( \frac{D_{s}}{2} \right)^{2}} \], \quad (19) \]

and the accelerator grid depth at the nominal operation is given by

\[ z_{a}^{\mu} = \sqrt{R_{a}^{2} - (x_{ae}^{\mu})^{2} - (y_{ae}^{\mu})^{2}} - \sqrt{R_{a}^{2} - \left( \frac{D_{a}}{2} \right)^{2}} \], \quad (20) \]

where \( (x_{se}^{\mu}, y_{se}^{\mu}) \) and \( (x_{ae}^{\mu}, y_{ae}^{\mu}) \) are the center coordinates of the etched plates for the screen and accelerator grids.

The focal length profile for the \( \mu \)th beamlet at the nominal operation is expressed by

\[ f_{\mu} = f_{s} + f_{a}^{\mu} \]. \quad (21) \]

Where the focal length of the screen grid at the nominal operation is given by

\[ f_{s} = \sqrt{R_{s}^{2} - \left( \frac{D_{s}}{2} \right)^{2}} \]. \quad (22) \]

The displacement correction of the accelerator grid is given by

---

**Fig. 4** Temperature profiles of the grids.

**Fig. 5** Separation distance profile between the screen and accelerator grids.

**Fig. 6** Beamlet focal length profile for the ion optics.
\[ f_\mu = \frac{R_s}{1 - \frac{1}{\beta_\mu}}, \quad (23) \]

where
\[ \beta_\mu = 0.321 \frac{R_s}{d_{\mu}^\mu} \left( \frac{P_{s0}}{P_s} - \left( 1 + \frac{d_{\mu}^\mu}{R_s} \left( \frac{t_s + t_a}{2R_s} \right) \right) \right), \quad (24) \]

\( t_s \) is the screen grid thickness and \( t_a \) is the accelerator grid thickness. The hole pitch of the screen grid at the nominal operation is given by
\[ P_s = P_{s0} \left\{ 1 + \alpha_s \left( \langle T_s \rangle - T_0 \right) \right\}, \quad (25) \]

and the cold hole pitch of the screen grid is given by
\[ P_{s0} = P_{se} \frac{2 R_{s0}}{D_{s0}} \sin^{-1} \frac{D_{s0}}{2 R_{s0}}, \quad (26) \]

where \( P_{se} \) is the hole pitch of the etched plate for the screen grid. The hole pitch of the accelerator grid at the nominal operation \( P_{a0} \) can be calculated in much the same way as that of the screen grid.

Figure 5 shows the separation distance profile between the screen and accelerator grids at the nominal operation. This figure indicates that the separation distance between the screen and accelerator grids at the nominal operation is about 0.4 mm at the grid center and 0.8 mm in the periphery region. Figure 6 shows the beamlet focal length profile for the ion optics at the nominal operation. The curvature and focal length are 1.457 m and 1.445 m for the screen grid at the nominal operation.

**Beamlet Trajectory Analysis**

The beamlet trajectory analysis is based on a two-dimensional ion beam optics code for the ion beamlet. This computation code is made the optics model of the sheath approximation in which the ion extraction surface is self-consistently determined. The objective is to obtain three profiles for the ion beamlets from the separation distance between the screen and accelerator grids; the beamlet divergence angle, the transmission factor, and the ion current density. Figure 7 shows the beamlet divergence angle profile for the ion optics. The beamlet divergence angle is defined by a 1/e-folding peak current half angle. Figure 8 shows the transmission factor profile for the ion beamlets. The ion production cost of the BBM-1 thruster decreases with larger transmission factors. The ion
current density can be obtained as the product of the transmission factor and the ion saturation current density in the neighborhood of the screen grid. Figure 9 shows the ion current density profile for the ion beamlets.

**Multibeam Trajectory Analysis**

The multibeam trajectory analysis is based on a newly introduced simple model for the convex multibeam optics. The objective is to obtain the multibeam intensity profile from three profiles: the beamlet focal length, the beamlet divergence angle, and the ion current density. Assuming that an ion beam divergence of all beamlets has a Gaussian intensity profile, the multibeam intensity profile is expressed by

\[ J_b = \sum_{\mu=1}^{N} I_{\mu} \frac{l_{\mu}}{\pi a_{\mu}^2} \exp\left(-\frac{\rho_{\mu}^2}{a_{\mu}^2}\right), \]  

(27)

where

\[ a_{\mu} = \tau_{\mu} \tan \theta^i_{\mu}, \]  

(28)

\[ I_{\mu} = \frac{\pi}{4} \left( \Lambda_{\mu}^s \right)^2 J^i_{\mu}, \]  

(29)

\( \theta^i_{\mu} \) is the beamlet divergence angle, \( J^i_{\mu} \) is the ion current density, and \( \Lambda_{\mu}^s \) is the screen grid hole diameter for the \( \mu \)th beamlet. The axial distance from the ion accelerating system is given by

\[ \tau_{\mu} = l^x_{\mu} (x-x^*_{\mu}) + l^y_{\mu} (y-y^*_{\mu}) + l^z_{\mu} (z-z^*_{\mu}), \]  

(30)

and the radial distance from the center of the \( \mu \)th beamlet is given by

\[ \rho_{\mu} = \sqrt{(x-x^*_{\mu})^2 + (y-y^*_{\mu})^2 + (z-z^*_{\mu})^2 - \tau_{\mu}^2}, \]  

(31)

where \( z^*_{\mu} \) is the screen grid depth at the nominal operation. The direction cosines at the nominal operation are given by

\[ l^x_{\mu} = x^*_{\mu} R_f, \quad l^y_{\mu} = y^*_{\mu} R_f, \quad l^z_{\mu} = z^*_{\mu} + f_{\mu} R_f, \]  

(32)

where

\[ R_f = \sqrt{(x^*_{\mu})^2 + (y^*_{\mu})^2 + (z^*_{\mu} + f_{\mu})^2}, \]  

(33)

and \( f_{\mu} \) is the \( \mu \)th beamlet focal length.

The thrust of the BBM-1 thruster decreases with larger beam divergences. This thrust drop is given by

\[ \Delta F = 1 - \frac{1}{I_b} \sum_{\mu=1}^{N} I_{\mu} f(\tan \theta^i_{\mu}), \]  

(34)

where

\[ I_b = \sum_{\mu=1}^{N} I_{\mu}, \]  

(35)

and

\[ f(x) = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{(2n)!}{n!} \left(\frac{x}{2}\right)^{2n}. \]  

(36)

The thrust drop due to the beam divergence can be divided into two components due to the beamlet divergence angle as given by

\[ \Delta F_d = \Delta F_{f_{\mu = \infty}}. \]  

(37)

and the beamlet focal length as given by

\[ \Delta F_f = \Delta F_{f_{\mu = \infty}} - \Delta F_{f_{\mu = \infty}}. \]  

(38)

Figure 10 shows the multibeam current density versus the cone angle on the horizontal plane. The thrust drops are 1.60% due to the beam divergence, 1.11% due to the beamlet divergence angle, and 0.49% due to the beamlet focal length.

![Multibeam intensity profile of the thruster.](image)
Beam Profile Test

The beam profile test was conducted to evaluate the new method of the ion beam trajectory design. The multibeam intensity profiles were measured with a Faraday probe facing the BBM-1 thruster after it reached the thermally steady state. The probe was moved to five different distances from the thruster of 80 cm, 110 cm, 140 cm, 170 cm and 200 cm. Half-cone angles could be obtained from the measured profiles at 80-cm, 110-cm and 140-cm downstreams. The BBM-1 thruster was operated under the conditions summarized in Table 1.

We are interested in a multibeam radius defined as the 1/e-folding peak current radius, and a beam divergence angle defined as the half-cone angle at an integrated probe current ratio of 95%. Figure 11 shows the comparisons of the measured and calculated multibeam radiiues. This figure indicates that the measured results agree well with the calculated result obtained by the ion beam trajectory design. The measured beam divergence angle was 13.1°.

The thrust drop due to the measured beam divergence is evaluated using the following relationship,

\[ \Delta F \leq 1 - \cos \theta_b, \]

(39)

where \( \theta_b \) is the measured beam divergence angle. The thrust drop due to the measured beam divergence is under 2.6%, and about 1% larger than that due to the calculated beam divergence.

Conclusions

The new method of the ion beam trajectory design was applied to the first breadboard model thruster (BBM-1) for primary propulsion. This newly introduced design method gave the thrust drop and profiles as follows: the scalar magnetic field contour in the discharge chamber, the ion saturation current density in the neighborhood of the screen grid, the temperatures and separation distance for the screen and accelerator grids, the divergence angle and focal length for the ion optics, the transmission factor and ion current density of the ion beamlets, and the multibeam intensity. The calculated result of the multibeam intensity profile agreed well with the measured results of the beam profile test. This indicates that the ion beam trajectory design is possible for the ring-cusp ion thruster. The thrust drop due to the calculated beam divergence is about 1% smaller than that due to the measured beam divergence.

References