Optimization of the Operating Parameters for a 20 mN Class Ion Thruster

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Abstract: A 20 mN class xenon ion thruster, which was developed by Japan Aerospace Exploration Agency (JAXA) and Mitsubishi Electric Corporation (MELCO), was used on Kiku-6, Kakehashi, and Kiku-8, despite small design changes for each satellite. Presently, it is going to be used on the Super Low Altitude Test Satellite (SLATS) to compensate for atmospheric drag. As system requirements of super low altitude satellites for the ion thruster are different from those of geosynchronous satellites, thruster performance measurements by changing operational parameters such as beam voltage and discharge current, were conducted and optimal parameters were found, allowing a thrust/power ratio below 25 w/mN or a lifetime around 25,000 hours. The measurement results were evaluated with ion trajectory analyses.

Nomenclature

Vb	=	beam voltage
Ib	=	beam current
Va	=	accelerator grid voltage
Ia	=	accelerator grid current
Vd	=	discharge voltage
Id	=	discharge current
L	=	grid gap
MPF	=	main propellant feed
mMPF	=	mass flow rate of MPF
MHC	=	main hollow cathode
mMHC	=	mass flow rate of MHC
NHC	=	neutralizer hollow cathode

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mNHC = mass flow rate of NHC
F = thrust
Isp = specific impulse
P = power consumption
Ci = ion production cost

I. Introduction

A 20 mN class xenon ion thruster was developed by the Japan Aerospace Exploration Agency (JAXA) and Mitsubishi Electric Corporation (MELCO). It was used on Kiku-6, Kakehashi, and Kiku-8, despite small design changes for each satellite.[1-3] Presently, it is going to be used on the Super Low Altitude Test Satellite (SLATS) to compensate for atmospheric drag.[4] An ion engine system is being developed for the SLATS.[5-8] The atmospheric drag on a cross-sectional area of 1 m^2 at an altitude of 200 kilometers is about 30 mN on average, making a 20 mN class ion thruster appropriate for drag compensation of a small super low altitude satellite whose cross-sectional area is around 0.5 m^2. Atmospheric drag largely depends on altitude, satellite location on an orbit, and solar activity. Understanding the thrust performance of the 20 mN class xenon ion thruster is necessary for the SLATS and future super low altitude satellites.[9,10] Those satellites require a low power/thrust ratio and long lifetime for the ion engine system. So, the performance measurements were conducted, changing the beam voltage, accelerator grid voltage, discharge current, propellant flow rate and grid gap subject to ion extraction and discharge stability restriction. Also, the measurement results are evaluated by using ion trajectory analyses.

II. The Ion Thruster and Test Cofiguration

A. Ion Thruster

The ion thruster used in the SLATS is almost the same as that used in the Kiku-8 except a few slight dimensional changes. Since these changes have no effects on the thrust performance, an EM ion thruster of the Kiku-8 was used in this study. Only a grid assembly was replaced by a new one. Figure 1 shows the photo of the thruster and the grid assembly, and Fig. 2 shows a schematic of the thruster. The ion thruster is a DC discharge thruster of Kaufman type and many permanent magnets generate divergent magnetic field in the discharge chamber. Two hollow cathodes, a main hollow cathode (MHC) and a neutralizer hollow cathode (NHC), are used in this thruster. The propellant, xenon, is fed to the MHC, NHC, and MPF. The propellant that pass through the MPF is fed to the main discharge chamber. Three grids, a screen grid, an accelerator grid and a decelerator grid, are used to extract the ion beam from the discharge chamber. Three grids are made of molybdenum. The grid diameter is 12 cm. This ion thruster requires seven power supplies. The beam power supply and the accelerator grid power supply supplies high voltage power to the screen grid and accelerator grid respectively, while the discharge power supply supplies power to the anode in the discharge chamber. There are also power supplies to heat up the hollow cathodes and maintain hollow cathode

(a) Ion Thruster **(b) Grid Assembly**

Figure 1. The 20mN class Ion thruster

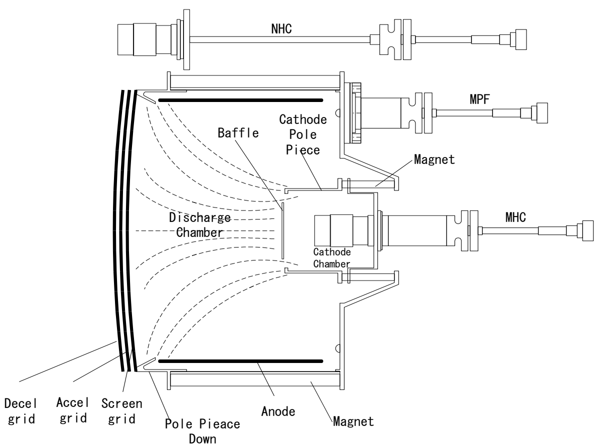


Figure 2. Schematic diagram of the thruster

keeper discharge for the MHC and NHC.

The Kiku-8 is a geostationary satellite, of which the ion thruster was used for north-south station keeping. The operating parameters are shown in Table 1. The beam voltage and the accelerator grid voltage are fixed at 1,000 and -500 V respectively. As shown in Table 1, the three mass flow rates are also constant. Only the discharge current can be modified slightly. This function is provided to maintain thrust against the degradation of thrust in orbit caused by the erosion of the grids. Basically, the required delta V is realized by adjusting the operation time of ion beam generation. Hence, the operating parameters of the thruster on the Kiku-8 are limited to a narrow range. The lifetime of the thruster is 16,000 hours within those operating parameters.

Table 1. The Operating parameters of the Kiku-8 ion thruster

parameter	unit	case1	case2	case3	case4
Vb *1	V	1,000	1,000	1,000	1,000
Va *1	V	-500	-500	-500	-500
Id *1	A	3.25	3.50	3.75	4.00
mMPF *1	sccm	6.5	6.5	6.5	6.5
mMHC *1	sccm	2.0	2.0	2.0	2.0
mNHC *1	sccm	0.6	0.6	0.6	0.6
Ib	mA	>400	>424	>445	>455
F *2	mN	>19.4	>20.5	>21.5	>22.0
Isp *2	sec	>2233	>2360	>2475	>2533
P	W	<648	<677	<701	<725

*1 assigned *2 calculated

B. Test Configuration and Operating Parameters

The ion thruster was attached to a boom with a flange, as shown in Fig. 3, and then, placed into a vacuum chamber of 3 meters diameter and 5 meters long. The vacuum chamber uses a turbo-molecular pump and a cryopump, with ultimate pressure of about 4×10^{-4} Pa at 30 sccm of xenon. Figure 4 shows a photo of the chamber in thruster operation. The operating parameters are shown in Table 2. The variable electrical parameters are beam voltage, accelerator grid voltage and discharge current. Mass flow rate also affects thrust performance. Grid gap is changed by using insert between grids. In the kiku-8 thruster, grid gap was 0.8 mm. A larger grid gap of 1.0 mm was tested here. The spatial beam current was measured using a orificed Faraday probe whose orifice sectional area is 5.3 mm^2 set at the tip of an arm of 1 m long shown in Fig.5. The Faraday probe is moved across the ion beam in front of the thruster by swinging the arm. The distance between the thruster and Faraday probe is adjusted at 70 cm, 140 cm and 210 cm respectively by moving the arm and the thruster. The beam divergence angles at distances of 70 cm, 140 cm, and 210 cm are calculated from the measurement data.

Figure 3. The thruster attached to a boom with a flange.

Figure 4. The 3 m diameter vacuum chamber for the ion engine test.

Table 2. Operating Parameters

Parameter	Unit	Value
Vb/Va	V	800/-400, 800/-300 900/-450 1000/-500, 1000/-400, 1000/-300 1,100/-550 1,200/-600
Id	A	1.0-5.0
mMPF/mMHC	sccm	4.0/2.5, 4.5/2.0, 5.0/1.5 5.0/2.5, 5.5/2.0, 6.0/1.5 6.0/2.5, 6.5/2.0, 7.0/1.5 7.0/2.5, 7.5/2.0, 8.0/1.5 9.0/1.5
mNHC	sccm	2.0
Grid Gap	mm	0.8, 1.0

Figure 5. Faraday probe for ion beam measurement

III. Measurement Results and Evaluation

A lower power/ thrust ratio, rather than higher Isp, is desirable for super low altitude satellites, although a high Isp is preferred for geostationary satellites or space probes to reduce propellant mass. The reason is that a solar array paddle can't be continually oriented toward the sun to minimize air drag and as a result, it is difficult to generate significant electrical power. Considering that the spacecraft lifetime is extended longer to 5-7 years and the duty cycle of an ion thruster may be 50%, the required lifetime for an ion thruster is more than 25,000 hours. The grids in ion thrusters have high voltage applied across a small grid gap, which can lead to high-voltage breakdown. High-voltage breakdown is usually described in terms of the electric field applied to the surface that causes an arc to start. Since super low altitude satellites have low visibility and autonomous thruster on/off control is conducted, few high-voltage break down is required. Enlarging the grid gap is very effective for reducing the occurrence of high-voltage breakdown. Hence, after measuring thrust range, the operating parameters for low power/thrust ratio, long lifetime and larger grid gap were studied.

A. Thrust Range

The typical operational parameters of 8 mN, 10 mN, 15 mN, and 36 mN in thrust level are shown in Table 3. The thruster can be operated in a wide range of thrust. The beam voltage, discharge current and xenon flow rate were changed. The accelerator grid voltage was adjusted at minus half the beam voltage. As shown in Table 3, when a proper grid configuration and operating parameters are selected, the discharge voltages are lower than 35 V. One of the factors that restrict thruster lifetime is the screen grid erosion by the discharge plasma. The erosion rate depends on discharge voltage. The lifetime of a screen grid was demonstrated to be beyond 10,000 hours when the discharge voltage is lower than 35 V in the endurance test of Kiku-8 ion thrusters. Hence, it is expected that the lifetime of the thruster will be greater than 10,000 hours in the thrust range of 8 mN to 36 mN.

Table 3. Thrust range

Parameter	unit	8mN	10mN	15mN	36mN
mMPF	sccm	6.5	6.5	6.5	9
mMHC	sccm	2	2	2	1.5
mNHC	sccm	2	2	2	2
Vb	V	800	800	900	1,200
Ib	mA	186	263	347	678
Va	V	-400	-400	-449	-600
Ia	mA	3.4	3.7	3.7	4.3
Vd	V	31.1	31.9	31	34.2
Id	A	1	1.5	2	5
F	mN	8.1	11.4	16	36
Isp	sec	803	1,135	1,589	2951
Ci	W/A	195	199	188	255
P	W	199	270	394	996
P/F	W/mN	24.7	23.7	24.7	27.7

Note: grid gap is 0.8mm for 8-15mN and 1.0mm for 36mN

B. Parameters for Low power/Thrust Ratio

The measurement results of thrust versus power/thrust ratio are shown in Figs. 6(a)-(c). The beam voltage was changed from 900 to 1,100 V. The accelerator grid voltage is set at minus half the beam voltage. The discharge current was changed from 2 to 5 A to alter the plasma density in the discharge chamber. The xenon mass flow rate for the MPF was changed from 4.5 to 6.5 sccm to determine its effects on the power/thrust ratio. When the thrust is relatively low, the lower the beam voltage, the lower the power/thrust ratio. However, when the thrust is high, the higher the beam voltage, the lower the power/thrust ratio. The reason for this is evaluated theoretically. The power consumption of the ion thruster is given as

$$P = V_b I_b + V_d I_d + \left| V_a I_a \right| + P_{ck} + P_{nk} \cong V_b I_b + V_d I_d , \qquad (1)$$

where *Pck* and *Pnk* represent the power consumption of the main hollow cathode and the neutralizer hollow cathode respectively. Conversly, the thrust is expressed as

$$F = I_b \left(\frac{2m_i}{e} V_b \right)^{1/2} . \qquad (2)$$

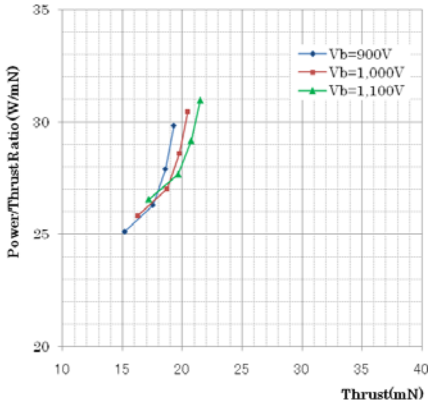
Therefore, the power/thrust ratio is expressed as

$$\frac{P}{F} = \frac{V_b I_b + V_d I_d}{K V_b^{1/2} I_b} = \frac{V_b^{1/2}}{K} + \frac{V_d I_d}{F}, \qquad (3)$$

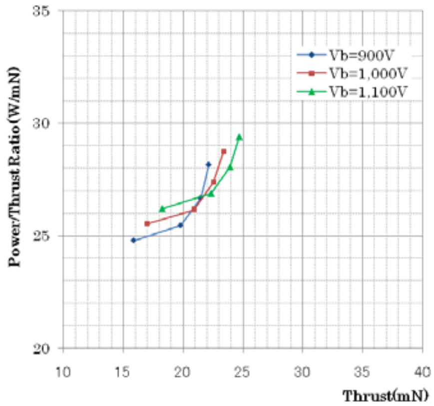
where K is a constant value shown by

$$K = \left(2m_i / e\right)^{1/2} \cong 1.53 \times 10^{-3}.$$

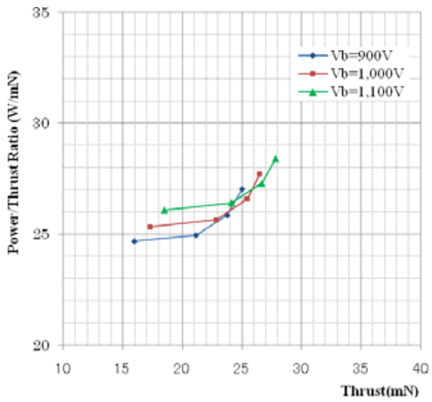
Hence, to make the power/thrust ratio low under constant thrust, it is effective to keep the beam voltage and the discharge current low because the discharge voltage cannot be easily changed and remains nearly constant. However, to maintain constant thrust, the discharge current has to be higher when the beam voltage is made lower. The value of the power/thrust ratio depends on which of the beam voltage and the discharge current is more effective in reducing the power/thrust ratio. The test results shown in Figs. 6(a)-(c) show that when the thrust is relatively low, lowering the beam voltage is advantageous to reduce the power/thrust ratio and when the thrust is relatively high, increasing the discharge current is advantageous. This means that *Vb* is dominant at relatively low thrust and *Id* at relatively high thrust in Eq. (3). Besides, when the mass flow rate of the MPF is increased, the thrust range, where *Vb* is dominant, becomes larger. It is because the value of *Id/F* declines. These might be true qualitatively for any ion thruster, but it depends quantitatively on the individual characteristics of each ion thruster. As the test results, operating parameters under 25 W/mN exist in the thrust range of 16 to 21 mN as shown in Fig. 6(c).



(a) mMPF/mMHC=4.5/2.0 sccm



(b) mMPF/mMHC=5.5/2.0 sccm



(c) mMPF/mMHC=6.5/2.0 sccm

Figure 6. Thrust versus power/thrust ratio

C. Parameters for Long Lifetime

Presently, the lifetime of a ion thruster is restricted by the erosion of the accelerator grid caused by the spattering of the charge exchange ion. The spattering rate depends on the accelerator grid voltage. For molybdenum and ceramic coatings, which are the materials used for the accelerator grid, the spattering yield was measured beforehand with the result showing that the spattering yield at energy of 300 eV is about two thirds of that at energy of 500 eV. This means the lifetime can potentially be extended by 50% if the accelerator grid voltage of -300 V can be chosen as a operating parameters. Hence, the measurements shown in Tables 4 were conducted. The beam enlargement angle is calculated as the angle of 95% ion beam contained at a distance of 210 cm. The accelerator grid voltage was changed from -500 to -300 V. Table 4 shows operating data at a discharge current of 4.00 A and 3.25 A. The accelerator grid current and the beam divergence angle remain low when the absolute value of the accelerator grid voltage is reduced. This means that the operating point of the accelerator grid voltage of -300 V is feasible and promising for a longer lifetime. There is a possibility of the lifetime being extended 50% to 25,000 hours. The plasma density is higher when the discharge current is higher. Since the plasma density at 4 A of discharge current is higher than that at 3.25 A, the possibility of beam divergence is raised at 4 A. However, as shown in Table 4, the accelerator grid current and beam enlargement angle at 4 A are low enough at -300 V of the accelerator grid voltage. These data demonstrate the potential to use an operating point of -300 V of the accelerator grid voltage. However, electron backstreaming after the erosion of the accelerator grid must be carefully considered.

Table 4. The thruster operation in lowered *Va*

parameter	unit	Id=4A			Id=3.25A		
Vb *1	V	1,000	1,000	1,000	1,000	1,000	1,000
Ib	mA	523	521	514	488	485	481
Va *1	V	-500	-400	-300	-500	-400	-300
Ia	mA	1.5	1.5	1.5	1.7	1.7	1.6
Vd	V	34.3	34.3	34.0	34.2	34.2	34.1
Id *1	A	4.0	4.0	4.0	3.25	3.25	3.25
mMPF *1	sccm	6.5	6.5	6.5	6.5	6.5	6.5
mMHC *1	sccm	2.0	2.0	2.0	2.0	2.0	2.0
mNHC *1	sccm	2.0	2.0	2.0	2.0	2.0	2.0
F *2	mN	25.4	25.3	24.9	23.7	23.5	23.3
Isp *2	sec	2532	2522	2482	2362	2342	2323
beam divergence angle	deg	16.3	16.1	15.7	15.4	15.2	14.9

*1 assigned *2 calcurated

D. Effect of Change in the Grid Gap

In Kiku-8, a grid gap of 0.8 mm was applied. For the super low altitude satellite, a grid gap of 1.0 mm was tried to determine the performance. The power versus thrust, measured with a grid gap of 0.8 mm and 1.0 mm, is shown in Fig. 7. Here, the beam voltage and the accelerator grid voltage are the same as those of the Kiku-8 ion thruster shown in Table 1. Figure 7 shows that when the grid gap is 1.0 mm, the thrust is reduced at the same power consumption compared with the case of 0.8 mm. This might be understood as showing reduced ability of extracting ion beam due to the lower electric field. Nevertheless, the extraction of the ion beam is normal at the grid gap of 1.0 mm. The accelerator grid current is low, around 3.8 mA. Hence, The operation point may be useful to prevent the occurrence of high-voltage breakdown. However, when the accelerator grid voltage is reduced, the ion beam diverges and the accelerator grid current increases. So, the operation point of *Va*/*Vb*=1,000/-500 V at the grid gap of 1.0 mm is marginal.

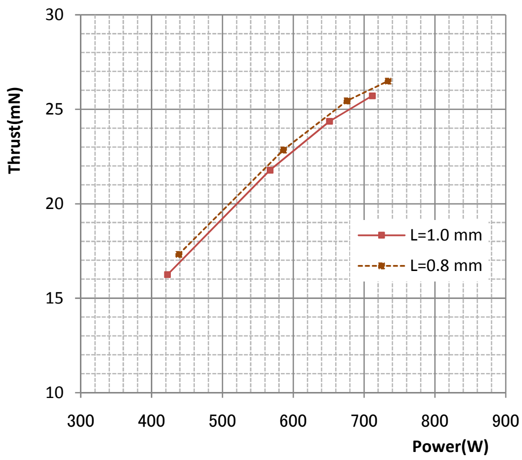


Figure 7. The performance of power versus thrust. Vb/Va=1,000/-500 V

IV. Evaluation by using Beam Trajectory Analyses

A three-dimensional ion beam trajectory analysis code was applied to the measurement results and evaluated theoretically.

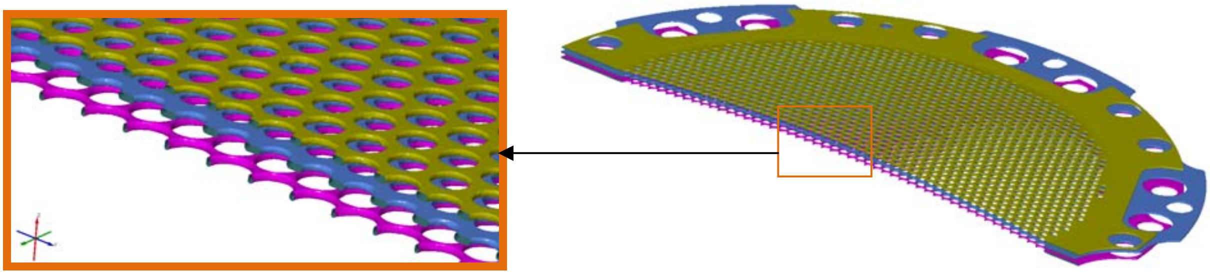
A. Grid Structure and Ion Extraction

The grid assembly consists of three grids, a screen grid (Sc grid), an accelerator grid (Ac grid) and a decelerator grid (De grid). Figure 8 shows normally located three grids. These pictures are virtually cut along grid central line based on the three dimensional optical measurement results. Three grids are convex toward outside and each hole of the Sc grid, Ac grid and De grid are aligned as shown in Fig. 8(a). The grid gap between each grid can be changed by mechanical handling.

The ions in discharge plasma are extracted through grid holes. From the Child-Langmuir law and the ion saturation current in plasma theory, the thickness of sheath for xenon is given as

$$d_s = 7.85\times10^4 V^{3/4} n_p^{-1/2} T_e^{-1/4}, \qquad (4)$$

where V is the voltage between the Sc grid and Ac grid, n_p is plasma density and T_e is electron temperature. The ion beam trajectory depends on the relation between the grid gap and the thickness of sheath. When the thickness of sheath decreases with no change in the grid gap, the ion beam diverges.



(a) Partial enlarged view (b) Location of three grids

Figure 8. Grid Structure(Sc grid: red, Ac grid: blue, De grid: yellow, Virtual cross section: green)

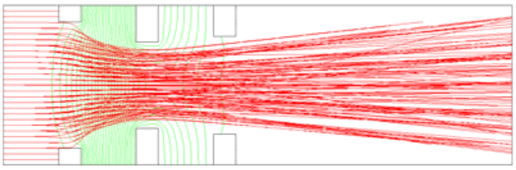
B. Evaluation of Test Results by using Three Dimensional Trajectory Analyses

The test results were evaluated by using three dimensional trajectory analyses. Hayakawa code was utilized for a three dimensional ion beam trajectory analysis.[11] The variable parameters are:

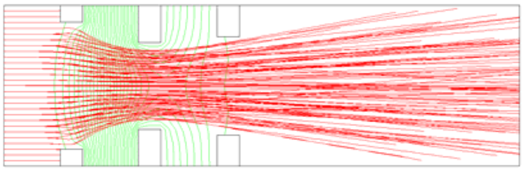
1) dimension of grid holes (diameter, location, distance between holes, grid gap)
2) plasma density in the discharge chamber
3) plasma potential
4) electron temperatures in the discharge chamber and outside
5) voltages of Sc grid, Ac grid and De grid
6) ion velocity at 1.0 mm upstream from the screen grid called "initial ion velocity"

The plasma potential is given as the sum of the beam voltage and discharge voltage as the thruster is a DC discharge typed one. As the values of the electron temperature inside and outside of the discharge chamber are insensitive to the ion trajectory, both temperatures were represented by 3 eV. The initial ion velocity is assumed to be 300 m/s as a typical value using thermal velocity at a temperature of 500 K.

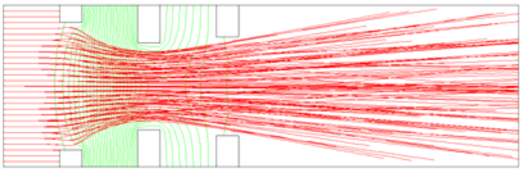
Assuming above parameters, the beam trajectory analyses were conducted as shown in Fig. 9. Vb and Va are 1,000 V and -400 V respectively. The grid gap is 1.0 mm. The plasma density is a unknown parameter and is changed from 1.2×10^{18} m^{-3} to 1.5×10^{18} m^{-3}. As is shown in Fig. 9, a partial beam current enters the deceleration grid. This current, I_{decel}, increases as the plasma density increases. When the plasma density is 1.5×10^{18} m^{-3}, I_{decel} is over 10 percents of the beam current. The discharge plasma density depends on mass flow rates, *mMHC* and *mMPF*, and discharge current. Though it is not proportional to the discharge current in the condition of a fixed mass flow rate, it certainly increases when the discharge current increases. In the measurements, the ion beam diverged excessively to collide with the decelerator grid and I_{decel} increased very much at discharge current of 4 A. Hence, the plasma density might be estimated 1.5×10^{18} m^{-3}, when the discharge current is 4 A. These analyses are applied for only a line of holes. On the other hand, the measurements were performed for a thruster with around 2,100 holes. Hence, the analyses don't correspond strictly to the measurement results and might be rough estimations, assuming a line of holes as the average of many lines of holes of a thruster. Nevertheless, simulation results show a reasonable beam current of about 0.24 A that corresponds well to the measurement result of 505 mA as a thruster. Hence, this estimation might be good as a average. Substituting the estimated plasma density in Eq. (4), the thickness of sheath is 1.07 mm, which is comparatively the same as the grid gap.



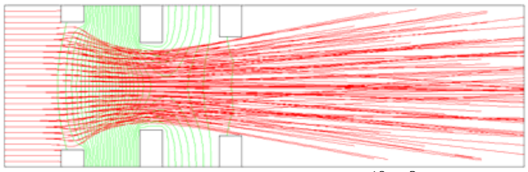
(a) plasma density n_p=1.2×10^{18}m^{-3}
I_b=0.229mA, I_{decel}=0.003mA



(b) plasma density n_p=1.3×10^{18}m^{-3}
I_b=0.236mA, I_{decel}=0.008mA



(c) plasma density n_p=1.4×10^{18}m^{-3}
I_b=0.248mA, I_{decel}=0.014mA



(d) plasma density n_p=1.5×10^{18}m^{-3}
I_b=0.243mA, I_{decel}=0.033mA

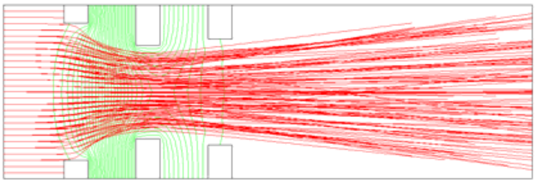
Figure 9. Ion beam trajectory in condition of Vb/Va=1,000/-400 V, L=1.0 mm

C. Discussions for design changes

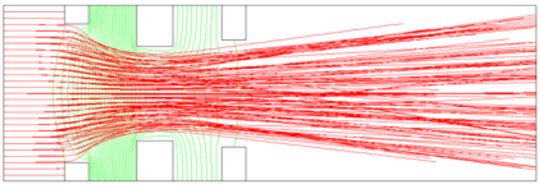
Using the estimated plasma density, two design changes for grid configuration were analyzed. One is the change of thickness of Ac grid from 0.4 mm to 0.6 mm. The purpose of thickening is to extend the thruster lifetime. The other is a two grids system removing De grid, that has advantages of reducing a probable shortage between electrodes and fabrication cost. The simulation results are shown in Fig. 10.

When the thickness of Ac grid is increased, the beam current is the same as that in basic configuration as shown in Fig. 10(a),(b). It means that the performance of ion extraction is the same in both cases even if the Ac grid thickness is changed. Besides, their beam divergence have similar contour. Hence, it seems to have no problem to thicken Ac grid to 0.6 mm. The lifetime of a thruster is restricted by erosion of Ac grid. Hence, when the thickness of Ac grid is increased 50%, the lifetime of a thruster can be expected to extend 50%.

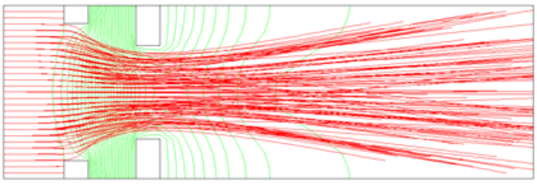
Figure 10(c) shows a beam trajectory in two grid system where De grid is removed. Though the beam current is the same as that in the basic configuration shown in Fig. 10(a), the beam divergence is more than that in the basic configuration. The beam divergence depends on the voltage and the grid gap between Sc grid and Ac grid. In this case, the beam divergence is minimal at the voltages of 1,000/-500V and the grid gap of 0.8 mm. This means the two grid system is worse than the three grid system in the viewpoint of beam divergence. However, as shown in Table 4, beam divergence angle of a thruster defined as a half cone angle in which 95% of ion beam is included is about 16 deg. This angle is larger than the simulation results in Fig. 10. One of the reasons is that the thruster grid is convex and each central axis of the holes diverges. Hence, the beam divergence can't be evaluated only by the simulation.



(a) basic configuration
(Ib: 0.296 mA, beam divergence angle: 9.5deg)



(b) increased thickness of Ac Grid
(Ib: 0.296 mA, beam divergence angle: 9.8 deg)



(c) two grid system configuration
(Ib: 0.296 mA, beam divergence angle: 11.9deg)

Figure 10. Ion beam trajectory in condition of Va/Vb=1,000/-500V, L=0.8 mm

As the feasibility of a thickened Ac Grid and a two grid system was confirmed by the simulation, the measurements using a new grid system are necessary to demonstrate the thruster performance.

V. Conclusion

The 20 mN class ion thruster will be used for the SLATS and future super low altitude satellites to compensate for air drag. Those satellites require low power/thrust ratio, long lifetime and minimal high-voltage breakdown. Hence, efforts were made to determine operation parameters of lower power/thrust ratio, lower accelerator grid voltage and a wider grid gap. The test results shows that operation points exist with a power/thrust ratio under 25 W/mN and that the accelerator grid voltage of -300 V is useful in extending lifetime to 25,000 hours. The grid gap of 1.0 mm to reduce high-voltage breakdown is marginal compared with the grid gap of 0.8 mm. However, the operation point of V_b=1,000 V and V_a=-500 V can be used. Those test data are very useful for selection of the operating parameters in super low altitude satellites. Finally, utilizing a ion beam trajectory analysis code, a rough estimation of plasma parameters in the discharge chamber was conducted. The analysis will be useful to understand the behavior of a thruster and to improve it and develop a new ion thruster such as a thickened grid system or a two grid system.

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