

Sensitivity Analysis on Ion Acceleration Grid Erosion in Ion Thrusters

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Abstract: The JIEDI (JAXA's Ion Engine Development Initiative) tool has been developed to assess the ion acceleration grid erosion of an ion thruster. The sensitivity analysis of the input parameters of the JIEDI tool is conducted in this paper. We compare the simulation results of the JIEDI tool and show that it successfully reproduces the full lifetime test of the $\mu 10$ prototype model. Through sensitivity analysis, we found that the sticking factor is the most sensitive input parameter when estimating the accelerator grid erosion and electron backstreaming time. For the worst case scenario of grid erosion (without re-deposition), the uncertainty in the neutral mass flow rate through grid holes is important when estimating the accelerator grid erosion. A 30% change in the neutral mass flow rate caused by a 6% change in the propellant utilization efficiency, corresponds to about a 20% change in the accelerator grid mass loss as well as the increasing rate of minimum potential on the axis of the ion optics. In contrast to the accelerator grid erosion, the uncertainties in the discharge voltage and grid gap (that affect the trajectory of the mainstream ions), are important when estimating decelerator grid erosion. A 40% change in the discharge voltage corresponds to about a 90% change in the decelerator grid mass loss. In addition, a 30% change in the grid gap between the screen grid and the accelerator grid corresponded to about a 40% change in the decelerator grid mass loss.

Nomenclature

I	=	flux-tube current
I_b	=	total ion beam current
$I_{b,average}$	=	average ion beam current per hole
m_i	=	ion mass
$\dot{m}_n$	=	neutral mass flow rate

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N	=	number of beamlets
n_n	=	neutral number density
T_e	=	electron temperature
T_k	=	stay time of the k -th flux tube
V_{element}	=	element volume
v	=	relative velocity between ion and neutral
v_i	=	ion velocity
Γ	=	flux generated by collision
γ	=	doubly charged ion fraction
ϵ_0	=	permittivity of vacuum
η_u	=	propellant utilization efficiency
ρ_e	=	electron charge density
ρ_i	=	ion charge density
σ	=	reaction cross section
ϕ	=	potential
ϕ_0	=	plasma potential

I. Introduction

ION thrusters are frequently used for North-South orbital control of geostationary satellites as well as orbital transfers of space probe, because they greatly contribute to shorter mission trip times and an increase in the payload ratio¹. For example, in Japan, asteroid sample return mission HAYABUSA² and Engineering Test Satellites (ETS-6³ and ETS-8⁴), Communications and Broadcasting Engineering Test Satellite (COMETS⁵) succeeded in on-orbit operation of ion thruster systems, and a variety of future space missions are planned such as super low altitude satellite⁶, Mercury explorer (BepiColombo⁷, in cooperation with ESA), and HAYABUSA follow-on missions⁸. Many commercial applications as well as scientific missions are already done or are in progress in U.S.A. and European countries^{9,10}. The thrust created in ion thrusters is, however, very small compared to conventional chemical rockets. Accordingly, in order to take advantage of the ion thruster's high specific impulse and efficiency, a long continuous operation (of the order of years) is required. The cost for a lifetime qualification of an ion thruster is hence quite high, resulting in a lengthy development and introduction of an optimal ion thruster for a specific mission. If numerical simulations can replace some of the lifetime tests, the cost and time for development of an ion thruster could be drastically reduced. Following this concept, numerical models for the lifetime evaluation of ion thruster's ion optics were studied by researchers. Thanks to these studies, physical model for ion optics was deeply discussed and is now considered well established¹¹⁻²³. Nevertheless, it is still challenging for these numerical codes to serve as a design tool because the accuracy and precision of numerical lifetime estimation are not clearly addressed. The essential requirements for a computer model for design use are assured accuracy, low costs, and fast turnaround. To satisfy these requirements, a numerical tool called JIEDI (JAXA's Ion Engine Development Initiative) was developed in JAXA's Engineering Digital Innovation center to assess the ion acceleration grid erosion of an ion thruster.

In the previous study²⁴, validation of the JIEDI tool was conducted. High numerical precision by the JIEDI code was guaranteed by comparison with a three-dimensional full particle-in-cell (PIC) simulation, in which discrepancies in the grid currents between the JIEDI and the full-PIC codes were found to be less than 1% for the grid configuration of HAYABUSA's microwave ion thruster ($\mu 10$ engineering model (EM)). Some numerical wear tests were also conducted for the carbon/carbon (C/C) ion acceleration grids of $\mu 10$ EM. Compared to experimental results, the JIEDI code showed good agreement with a real-time (18,000-hr) endurance test when the motion of eroded grid materials and low-energy sputtering yields below 300 V were incorporated. These tests demonstrated that the JIEDI tool successfully estimates ion grid acceleration erosion with high precision and accuracy.

Because of uncertainties in the physical model and input conditions (caused by, for example, non-uniform plasmas, and measurement errors), numerical assessment of grid erosion by the JIEDI tool will inevitably include some error. Confirming the sensitivity of the physical model and input conditions is an important step for numerical qualification of ion acceleration grids by the JIEDI tool. The sensitivity of the sputtering model and doubly charged ion fraction on grid erosion was discussed by Nakano *et al*^{25,26}. In this paper, numerical wear tests of the $\mu 10$ Prototype Model (PM) ion thruster from the beginning-of-life (BOL) to 20,000 h were conducted by the JIEDI tool for each parameter. The error of the grid erosion assessment was evaluated by analyzing the sensitivity of the input parameters to grid erosion.

II. Physical and Numerical Model for the JIEDI Tool

A. Physical Process in a Pair of Grid Aperture

Figure 1 shows a schematic representation of the ion thruster and erosion mechanism of ion acceleration grids (grid system). Ionized propellants (ions) are accelerated through an electric field created by charged plate electrodes (grids) that have many holes in them. A grid system, which is schematically plotted in Fig. 1, is designed so that ions being extracted through the grid aperture do not strike the acceleration grids directly and sputter the grid material. Within the grid aperture, there are both fast-moving ions and slow-moving neutral atoms escaping through the grids, and a small fraction of the ions will capture an electron from an adjacent neutral during the brief interval when the ion is being accelerated into the exhaust beam. Typically, as marked as “CEX” in Fig. 1, such a charge exchange event yields a fast-moving neutral that escapes downstream and a slow-moving ion that is drawn into and sputter erodes the acceleration grids. Even though the current of these ions is relatively small, they impact at high energies, hence they can cause it to erode and fail. Accelerator (accel.) grid erosion leads to the primary life-failure mechanism in ion thruster; namely grid aperture enlargement that leads to electron backstreaming. A secondary failure mode results from accelerator or decelerator (decel.) grid erosions due to sputtering, which can lead to structural failure of the grids, and/or electron backstreaming if the erosion penetrates all the way through the grid.

In the JIEDI tool, in order to include all possible particle impingements on the grid surfaces, two processes were considered in addition to the direct impingement of mainstream ions (Beam) and the impingement of charge exchange (CEX) ion or neutral. The first is elastic scattering as shown by “SCAT” in Fig. 1: when a fast ion trajectory is scattered by collision with a neutral atom, it is possible that the fast ion or neutral directly impinges onto the grid surface. The second process is the re-deposition of sputtered grid material: when sputtered grid material emitted from a grid surface reaches another grid surface, since some percentage of the sputtered material will stick onto the arriving grid surface, this “Re-deposition” of grid material will affect the estimation of the grid mass loss rate.

B. Outline of the JIEDI Tool

The JIEDI tool in principle uses a combination of algorithms used in previously reported ion trajectory codes. Its source code is written as an updated version of 2-D ion optics code (OPT) by Arakawa and Ishihara¹¹ and its 3-D versions^{13,16}, but some modifications²⁷ are made to incorporate the outcomes from ion optics studies. The major features of the JIEDI tool are 1) a hybrid fluid-particle approach is employed to model the plasma dynamics: ions and neutrals are treated as particles, and their trajectories are obtained based on flux tube method; in contrast, a fluid approach is employed for the electrons, 2) self-consistent treatment upstream sheath and downstream neutralization in 3-D coordinate, 3) incorporation of latest sputtering models, 4) treating sputtered grid material's motions and their re-deposition onto grid surface, 5) solution-adaptive mesh generation for mesh reconstruction, and 6) improved robustness and convergence of Poisson solver.

To evaluate the lifetime of ion thruster's ion optics, the JIEDI tool performs a “numerical wear test” for a single pair of grid apertures, because the difference of the ion beam current between adjacent grid apertures is quite small. Figure 2 shows the computational region of the ion acceleration grids in the JIEDI tool. The

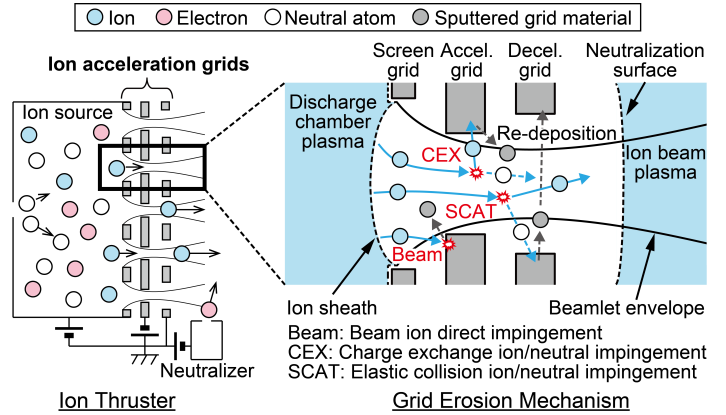


Figure 1. Schematic representation of an ion thruster and the erosion mechanism of ion acceleration grids.

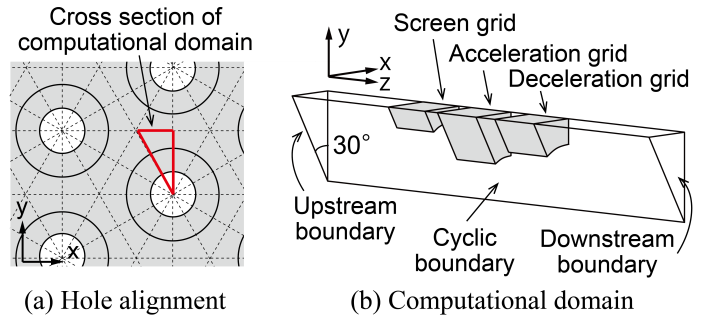


Figure 2. Computational region of the ion acceleration grids.

symmetry of the grid hole distribution permits a reduction of the computational domain size to 1/12 of a grid hole, as shown in Fig. 2. The numerical procedure implemented in the JIEDI tool is summarized in Fig. 3. It consists of a routine that calculates the erosion rate in each grid surface by the OPTJ code and the mesh reconstruction by the solution adoptive method (GRID-SHAPE). To accurately estimate a grid erosion rate, the physics associated with grid erosion by ion impingement should be evaluated. This is possible when ion/neutral flows and their production in a grid aperture are accurately solved. The OPTJ code models ion beamlet trajectories through a single pair of grid apertures with the self-consistent electric potentials found by solving Poisson's equation. Using the OPTJ code, the erosion rate of each grid element is calculated for the initial grid geometry at the beginning of thruster operation (0 hour). After this calculation, the amounts of grid erosion after specified operation time, for example 500 h, are evaluated, and consequently, the shape of each grid after the time is decided by the GRID-SHAPE routine. In the next step, the new mesh is generated, and the erosion rate calculation for the new mesh is repeated to estimate the grid shape at the next time step. This iteration continues until either end-of-life of the ion acceleration grid, or target operation time.

C. Physical Modeling in the OPTJ Code

The flowchart for the OPTJ code is shown in Fig. 4. The electrostatic potential distribution is solved using Poisson's equation, and the mainstream ion beams are tracked using the flux-tube method. In the flux-tube method, the equations for potentials and the equations of motions are not solved time-dependently and simultaneously. Instead, the ion charge density of the operating ion beams is calculated by assuming that the potential distribution is in a steady state. Then, Poisson's equation is solved using the charge density to update the potential distribution. This process is repeated until the ion beam trajectories and potential distributions reach the steady state self-consistently. After the ion beam trajectories and potential distribution are determined self-consistently, the particles generated by the charge exchange and elastic collisions are tracked. The erosion rate of each element is calculated by the trajectories of ions and neutrals. Finally, the sputtered grid materials are tracked and the re-deposition rate of each element is calculated by their trajectory. The net erosion rate of each element equals the subtraction of the re-deposition rate from the erosion rate.

1. Neutral density and velocity

The OPTJ code requires the neutral density and velocity to estimate the reaction rate of the collisions between ions and neutrals. At the start of the OPTJ calculation, the neutral density and velocity are determined by using the Direct Simulation Monte Carlo (DSMC) method for a rarefied flow with a diffuse reflection condition on the grid surface. This DSMC calculation requires the neutral mass flow rate leakage from each grid hole, the neutral gas temperature, and the grid surface temperature. In the OPTJ code, neutral atoms are assumed to flow out uniformly through the ion source, and the uniform mass flow rate is given as

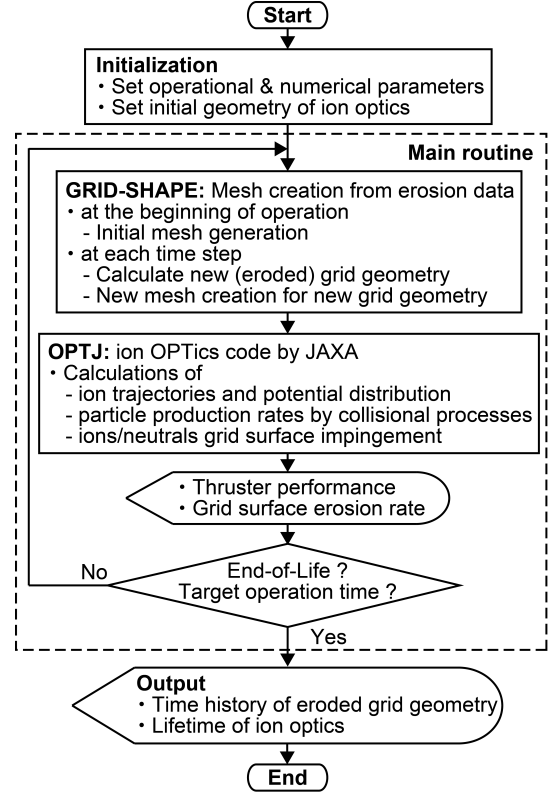


Figure 3. Numerical procedure implemented in the JIEDI tool.

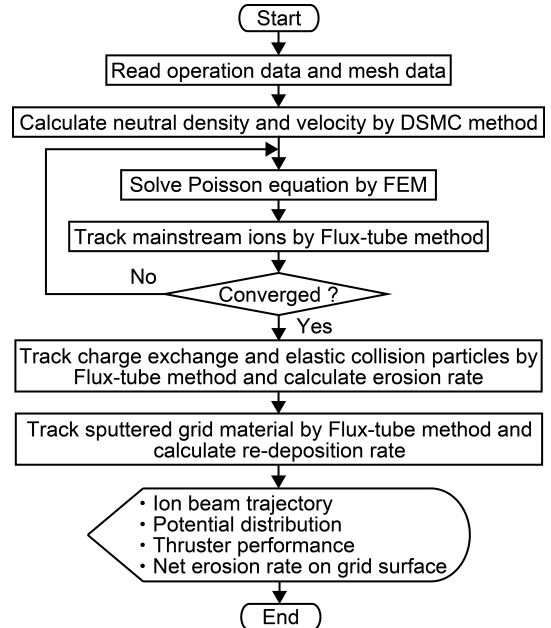


Figure 4. Flowchart of the OPTJ code.

$$\dot{m}_n = \frac{m_i I_{b,average}}{\eta_u e} \left(1 - \frac{1 + \gamma/2}{\gamma} \eta_u \right) \quad (1)$$

where m_i is the ion mass, $I_{b,average}$ is average ion beam current per hole, η_u is propellant utilization efficiency, γ is the doubly charged ion fraction. Using the singly charged ion current I_b^+ , the doubly charged ion current I_b^{2+} , and the doubly charged ion fraction γ , the total ion beam current I_b is expressed by

$$I_b = I_b^+ + I_b^{2+} = I_b^+ (1 + \gamma). \quad (2)$$

2. Ion beam trajectory and potential distribution

Primary ions are released from the upstream boundary of the computational domain, where a plasma condition with a Maxwellian electron distribution is assumed. The primary ions are divided into N beamlets, each with a current that was determined by I_b/N . To obtain the ion trajectories, the location and velocity of each ion beam are updated by solving the equation of motion of charge particle, as described in Eq. (3),

$$m_i v_i \nabla v_i = -e \nabla \phi. \quad (3)$$

The electrostatic field, ϕ , is described by the Poisson's equation:

$$\nabla^2 \phi = -\frac{\rho_i - \rho_e}{\epsilon_0} \quad (4)$$

where v_i is the ion velocity, e is the elementary electric charge, ρ_i is the ion charge density, ρ_e is the electron charge density, and ϵ_0 is the vacuum permittivity.

The ion charge density on the right-hand side of Eq. (4) is given by the following summation,

$$\rho_i = \sum_k \frac{IT_k}{V_{element}} \quad (5)$$

where $I (=I_b/N)$ is the flux-tube current, T_k is the stay time of the k -th flux-tube, and $V_{element}$ is the element volume. In this calculation, the ion charge density is calculated by assuming that all of the mainstream ion are singly charged and then corrected to include the effect of doubly charged ions as

$$\rho_{i,new} = \frac{1 + \gamma/\sqrt{2}}{1 + \gamma} \rho_i. \quad (6)$$

On the other hand, the electron charge density on the right-hand side of Eq. (4) is given by the Boltzmann relation with the uniform electron temperature T_e [eV] as

$$\rho_e = \rho_{e0} \exp\left(\frac{\phi - \phi_0}{T_e}\right) \quad (7)$$

where ϕ_0 is the plasma potential and ρ_{e0} is the electron charge density in discharge chamber plasma.

For higher time accuracy, the 4th-order Runge-Kutta method is employed for the time integration of the equation of motion (Eq. (3)). The Poisson's equation (Eq. (4)) is solved by the finite element method and the resulting simultaneous equations have nonlinear terms from Eq. (7). The nonlinear simultaneous equations are solved by the Newton-Raphson method with the incomplete Cholesky conjugate gradient matrix solver.

3. Erosion and Re-deposition rate

With regards to ion collisions with neutrals, the elastic scattering and charge exchange collisions are incorporated, and their reaction rates evaluate by using the number density of neutral particles, the primary ion beam

current, the ion velocity, and the reaction cross sections. The flux generated by the collisions of singly charged ions in each element is expressed as

$$\Gamma^+ = \sum_k \frac{1}{1+\gamma} n_n \sigma^+ v_k \frac{I}{e} T_k \quad (8)$$

and the flux generate by the collisions of doubly charged ion is given by

$$\Gamma^{2+} = \sum_k \frac{1}{2} \frac{\gamma}{1+\gamma} n_n \sigma^{2+} v_k \frac{I}{e} T_k \quad (9)$$

where n_n is the neutral density, σ is the reaction cross section, and v_k is the relative velocity between ion and neutral of the k -th flux-tube. In Eqs. (8) and (9), the charge exchange collision cross sections are taken from Miller *et al*²⁸, whereas the elastic collision cross sections are taken from the hard sphere model described by Bird²⁹. The ion and neutral beams produced by elastic scattering and charge exchange collisions are moved using the same technique as that employed for the primary ion beams. Similarly, they are tracked until they escaped from the computational domain or collide with one of the grid surfaces. In the OPTJ code, the multiple collisions is neglected, and the error cause by the neglect is less than around 5% based on the full PIC simulation by Miyasaka *et al*²².

When a beam impacts on a grid surface, the sputtered grid mass and the injection directions of the sputtered grid materials are calculated to estimate the erosion rate of each element using the differential sputtering yield. In the JIEDI tool, the differential sputtering yield is taken from the experimental data of Williams *et al*³⁰ or the molecular dynamic (MD) simulation data of Muramoto *et al*³¹.

The former is called the “CSU” model; the latter is called the “MD” model. The MD model employs the data by MD simulation within the range of ion incident energies of 200 to 500 eV; outside of this range, the experimental data of Williams *et al* is used.

Sputtered grid materials are also traced by the flux-tube method to estimate re-deposition rate of each element until they hit a grid surface or escape from the computational domain. When the sputtered grid materials reach a grid surface, some of the materials stick to the grid surface. The ratio of sticking materials to materials hitting a grid surface is called “sticking factor” in this tool.

III. Calculation Conditions

Numerical wear tests of a $\mu 10$ PM ion thruster from 0 h (BOL) to 20,000 h were carried out with the input parameters shown in Table 1. The baseline configuration of the input parameters was the values given in line “2” of Table 1: when one parameter was varied whilst investigating its sensitivity, the others were fixed to their baseline value. In order to evaluate the sensitivity of each input parameter (with the exception of the sticking factor), three values representing a minimum, middle and maximum were selected from the simulation as shown in Table 1.

The $\mu 10$ PM ion thruster employs the C/C composite grids and xenon as a propellant³². During the simulation, the grid voltage, ion beam current per hole, grid hole diameter, and grid thickness

Table 1. Input parameters and their values/types/ranges.

Parameter	Value/Type/Range		
	1	2	3
Propellant		Xenon	
Grid material		C/C	
Sputter model		CSU	
Sticking factor, -	0	0.78	-
Operation conditions			
- Grid voltage, V			
> Screen		1,500	
> Accelerator		-350	
> Decelerator		0	
- Ion beam current per hole, mA/hole			
> Very high		0.23	
> High		0.18	
> Medium		0.13	
> Low		0.08	
> Very low		0.055	
> Average		0.156	
- Doubly charged ion fraction, -	0.05	0.15	0.25
- Propellant utilization efficiency, -	0.75	0.80	0.85
- Discharge voltage, V	15	25	35
- Electron temperature, eV	3	5	7
- Grid surface temperature, K	353	373	393
Grid geometry			
- Grid hole diameter, mm			
> Screen		3.05	
> Accelerator		1.8	
> Decelerator		2.5	
- Grid thickness, mm			
> Screen		0.95	
> Accelerator		1.0	
> Decelerator		1.0	
- Grid gap, mm			
> between screen and accelerator	0.22	0.32	0.42
> between accelerator and decelerator	0.4	0.5	0.6

were not changed. Because ions were extracted non-uniformly from the ion source³³, five currents representing very-high-, high-, medium-, low- and very-low-current regions were selected. The results for each hole were interpolated using a cubic function and integrated over the radius of the beam diameter to yield the total grid value. The CSU model was employed as sputtering model in this simulation.

In Table 1, the sticking factor of 0.78 was taken from the studies of Marker *et al*³⁴ and Muramoto *et al*³⁵. The discharge voltage is the potential difference between the discharge plasma and the screen grid. The range of operation conditions refer to the experimental values³⁶⁻³⁸. The uncertainty in grid gap due to misalignment and thermal expansion was assumed to be 0.1 mm, as shown in Table 1.

IV. Results and Discussion

A. Comparison with simulation and experiment

The possible failure modes in the ion thruster's ion acceleration grids are grid structural failure and electron backstreaming. Electron backstreaming occurs when the negative potential region that separates the discharge and neutralization plasma disappears because of an enlargement in the accelerator grid hole diameter (due to erosion). Thus, the accelerator grid erosion is important when estimating the ion thruster lifetime. The accelerator grid current and the accelerator grid mass change were evaluated to validate the result obtained by the JIEDI tool.

Figure 5 shows the accelerator grid current as a function of the accumulated operation time for different sticking factors. The accelerator grid current is the total current carried into the accelerator grid by mainstream ions, charge exchange ions, and scattered ions. The experimental data of the accelerator grid current used for comparison was 0.5 mA for 0 h to 20,000 h³². The measurement error of the accelerator grid current was not evaluated accurately in the endurance test of $\mu 10\text{PM}$, but was ± 0.05 mA in the endurance test of $\mu 10\text{EM}$ ³⁸. If measurement error is taken into account, the calculated currents showed good agreement with experimental results. This indicates that the JIEDI tool accurately assesses the total amount of ions impinging onto the accelerator grid surface.

Figure 6 shows the accelerator grid mass change as a function of the accumulated operation time for different sticking factors. A negative value of the mass change, as shown in Fig. 6, indicates that the accelerator grid mass was decreased by thruster operation. The experimental data for the accelerator grid mass change was -0.49 g after 20,000 h (of operation)³⁹. The error bar shown in the experimental data in Fig. 6 was also employed in the endurance test of $\mu 10\text{EM}$. The error bar considers the back-sputtering effect from the experimental setup. The accelerator grid mass change for a sticking factor of 0 indicates the case without re-deposition. The case with re-deposition shows the least eroded profile; the case without re-deposition shows the most eroded profile.

At 20,000 h the experimental data (black square) exists somewhere between the data with re-deposition (red circles) and the data without re-deposition (blue triangles) as shown in Fig. 6. Therefore, if the correct sticking factor is selected, the simulation result should agree with the experiment. The data presented in Fig. 6 shows that the full lifetime test of $\mu 10\text{PM}$ was successfully reproduced by the JIEDI tool and that selecting the correct sticking factor is important for the ion acceleration grid erosion. However, because it is difficult to evaluate whether the grid surface

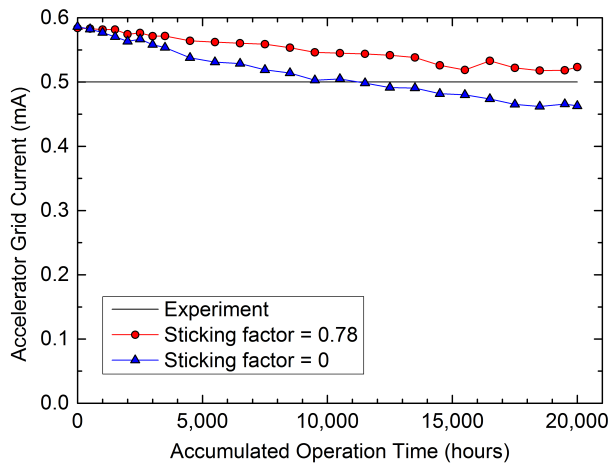


Figure 5. History of the accelerator grid current for different sticking factors at baseline configuration (line “2” of Table 1).

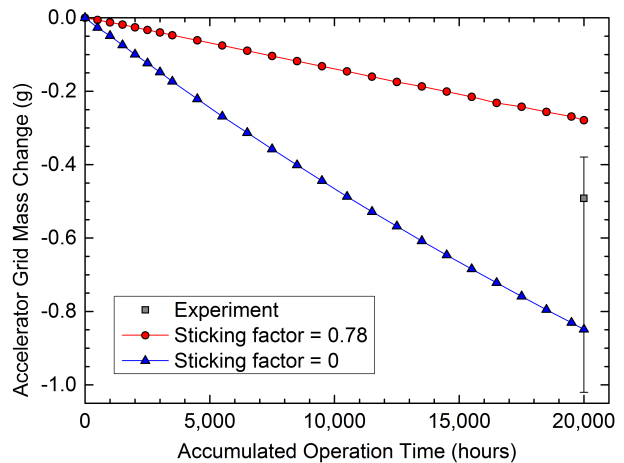


Figure 6. History of the accelerator grid mass change for different sticking factors at baseline configuration (line “2” of Table 1).

with re-deposition behaves the same as the original grid surface, the case without re-deposition has to be assessed as the worst case scenario in order to qualify the evaluation of an ion thruster's lifetime by the JIEDI tool.

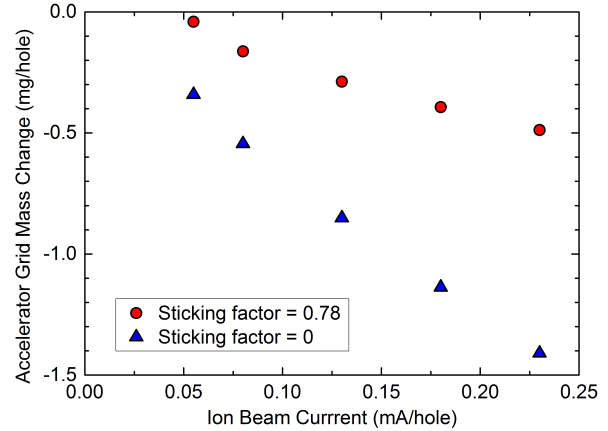
B. Sensitivity of the sticking factor to lifetime

Figure 7 shows the sensitivity analysis of the effect of the sticking factor on the lifetime of ion acceleration grids. Figure 7(a) shows the accelerator grid mass change after 20,000 h of operation as a function of ion beam current per grid hole for different sticking factors. The accelerator grid mass change in the very-high-current region was the largest regardless of the choice of sticking factor, as shown in Fig. 7(a). In the very-high-current region, the accelerator grid mass loss at 20,000 h was 190% larger for a sticking factor of 0 compared to that determined for a sticking factor of 0.78.

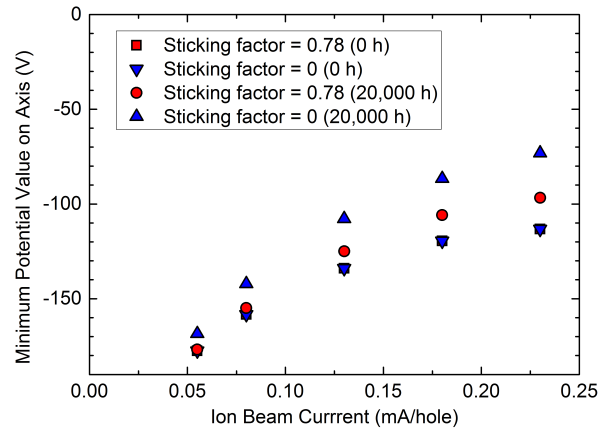
The onset of electron backstreaming can be determined by monitoring the minimum potential value on the axis of the ion optics. Figure 7(b) shows the minimum potential value on the axis as a function of the ion beam current per grid hole for different sticking factors. The minimum potential at 0 h for a sticking factor of 0.78 was equal to that obtained for a sticking factor of 0, regardless of the ion beam current. The minimum potential in the very-high-current region was the highest of all current regions as shown in Fig. 7(b). In the very-high-current region the potential value at 0 h was around -115 V. At 20,000 h, this value had dropped -95 V (considering re-deposition) or -75 V (without re-deposition). If the required lifetime of $\mu 10\text{PM}$ is 20,000 h, then electron backstreaming will not occur because the barrier created by the negative potential will still be sustained. The rate of increase of the minimum potential value from 0 h to 20,000 h is also the highest in the very-high-current region: it increases by 140% for a sticking factor of 0 compared to that obtained for a sticking factor of 0.78. As a result, it is considered that the electron backstreaming occurs 140% faster for a sticking factor of 0 (compared to 0.78).

With regards to the grid structural failure, severe erosion of the decelerator grid has been reported to appear in the lower current region³²; this decelerator grid erosion is one of the life-limiting factors. Figure 7(c) shows the decelerator grid mass change after 20,000 h of operation, as a function of ion beam current per grid hole for different sticking factors. The decelerator grid mass change in the very-low-current region was the largest regardless of the choice of sticking factor. The decelerator grid mass at 20,000 h was 16% lower for a sticking factor of 0 compared to that for a sticking factor of 0.78, as shown in Fig. 7(c). Compared to the sensitivity of the accelerator grid mass change to the sticking factor, the sensitivity of decelerator grid mass change is low.

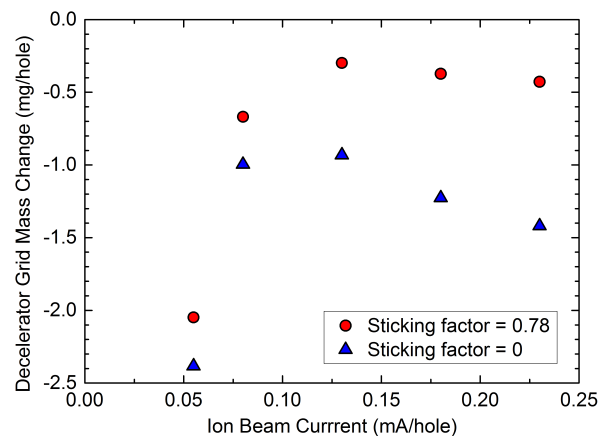
The grid mass change depends on the erosion rate and re-deposition rate. Without re-deposition (sticking factor = 0), the grid mass change (Fig. 7(a) and 7(c)) shows the



(a) Accelerator grid mass change after 20,000 h of operation as a function of ion beam current.



(b) Minimum potential value on axis at 0 h and 20,000 h as a function of ion beam current.



(c) Decelerator grid mass change after 20,000 h of operation as a function of ion beam current.

Figure 7. Sensitivity analysis of the effect of the sticking factor on the lifetime of ion acceleration grids at the baseline configuration (line "2" of Table 1).

grid mass change by erosion only. When accelerated primary ions are not directly impinging on the grid surface, the erosion rate depends on the amount of ion/neutral impingement produced by charge exchange collisions or elastic collisions. The reaction rate of these collisions is a function of the ion beam current and neutral density, as described in Eqs. (8) and (9). Therefore, the accelerator grid mass loss after 20,000 h increases as the ion beam current per grid hole is increased, as shown in Fig. 7(a). The decelerator grid mass loss also increased as the ion beam current per grid hole increased with the exception of the loss in the lower current region shown in Fig. 7(c). Figure 8 shows the ion beam trajectory at the BOL as a function of the ion beam current per grid hole. As the ion beam current decreases ions are generally accelerated with highly diverted angles, as shown in Fig. 8. Thus, the mainstream ions directly impinge onto the decelerator grid surface in lower current region and as a result the decelerator grid mass loss sharply increases as the ion beam current per grid hole is decreased. In the very-low-current region, the accelerator grid mass loss is small whereas the decelerator grid mass loss is large. Therefore, the re-deposition rate of sputtered accelerator grid material onto the decelerator grid is much lower than the erosion rate of the decelerator grid. The low sensitivity of the sticking factor to the decelerator grid mass change can be explained by the low re-deposition rate of sputtered accelerator grid material onto the decelerator grid.

C. Sensitivity of other input parameters on the lifetime

As with the sensitivity analysis of the sticking factor (shown in Fig. 7), the sensitivities of other input parameters to the lifetime of ion acceleration grids were evaluated. Figure 9 shows the sensitivity of the effect of the operation conditions and grid geometry to the life-limiting factors. The horizontal axis in Fig. 9 shows the change in rate of minimum/maximum value of the input parameter with respect to the middle value of the input parameter. The vertical axis in Fig. 9 shows the change in rate of the result of the minimum/maximum value with respect to the result from the baseline configuration (middle value). The sensitivity corresponds to this rate and the result for the baseline value for each parameter is therefore the same (0%), as shown in Fig. 9. In Fig. 9, the steepness of slope (of the line plots) indicates the level of sensitivity.

Figure 9(a) shows the sensitivity with respect to the accelerator grid mass loss after 20,000 h in the very-high-current region, which was particularly sensitive to the propellant utilization efficiency and the sticking factor. Figure 9(b) shows the increasing rate of minimum potential from 0 h to 20,000 h in the very-high-current region where the propellant utilization efficiency and the sticking factor still have a high sensitivity. A 6% change in the propellant utilization efficiency corresponds to about a 20% change in both the accelerator grid mass loss and the increasing rate of minimum potential. The data presented in Fig. 9(a) and 9(b) show that the accelerator grid erosion influences the electron backstreaming time, which depends on the increasing rate of minimum potential.

When the propellant utilization efficiency was varied, the neutral mass flow rate through the grid holes was varied, as shown in Eq. (1). The neutral density in grid holes which affects the reaction rate of charge exchange collisions and elastic collisions strongly depends on the neutral mass flow rate. The change in neutral density thus causes the high sensitivity of the propellant utilization efficiency. A 6% change in the propellant utilization efficiency, which results in a 20% change in the accelerator grid mass loss, corresponds to about a 30% change in the neutral mass flow rate. When doubly charged ion fraction is varied, the neutral mass flow rate is also varied. A 65% change in the doubly charged ion fraction corresponds to about a 10% change in the neutral mass flow rate. This variation of the neutral mass flow results in the 10% change in the accelerator grid mass loss, as shown in Fig. 9(a). Accordingly, the neutral mass flow rate is an important factor when estimating the accelerator grid erosion, and the response of the neutral mass flow rate is approximately equal to the response of the accelerator grid erosion.

Compared with the sensitivity of the sticking factor that was discussed in the previous section, the sensitivity of neutral mass flow rate is lower, as shown in Fig. 9(a). As such, it is reasonable to say that the uncertainty in the sticking factor is the most sensitive parameter when estimating the accelerator grid erosion and electron backstreaming time. In the worst case scenario of grid erosion (without re-deposition), the neutral mass flow rate is

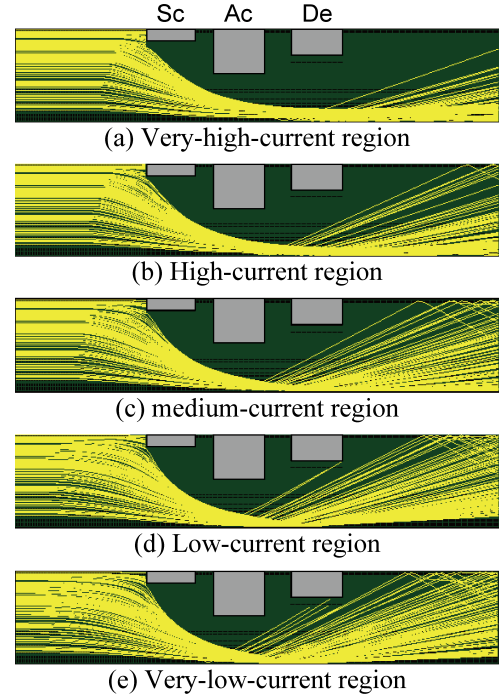


Figure 8. Ion beam trajectory at beginning-of-life for different ion beam currents at the baseline configuration (line “2” of Table 1).

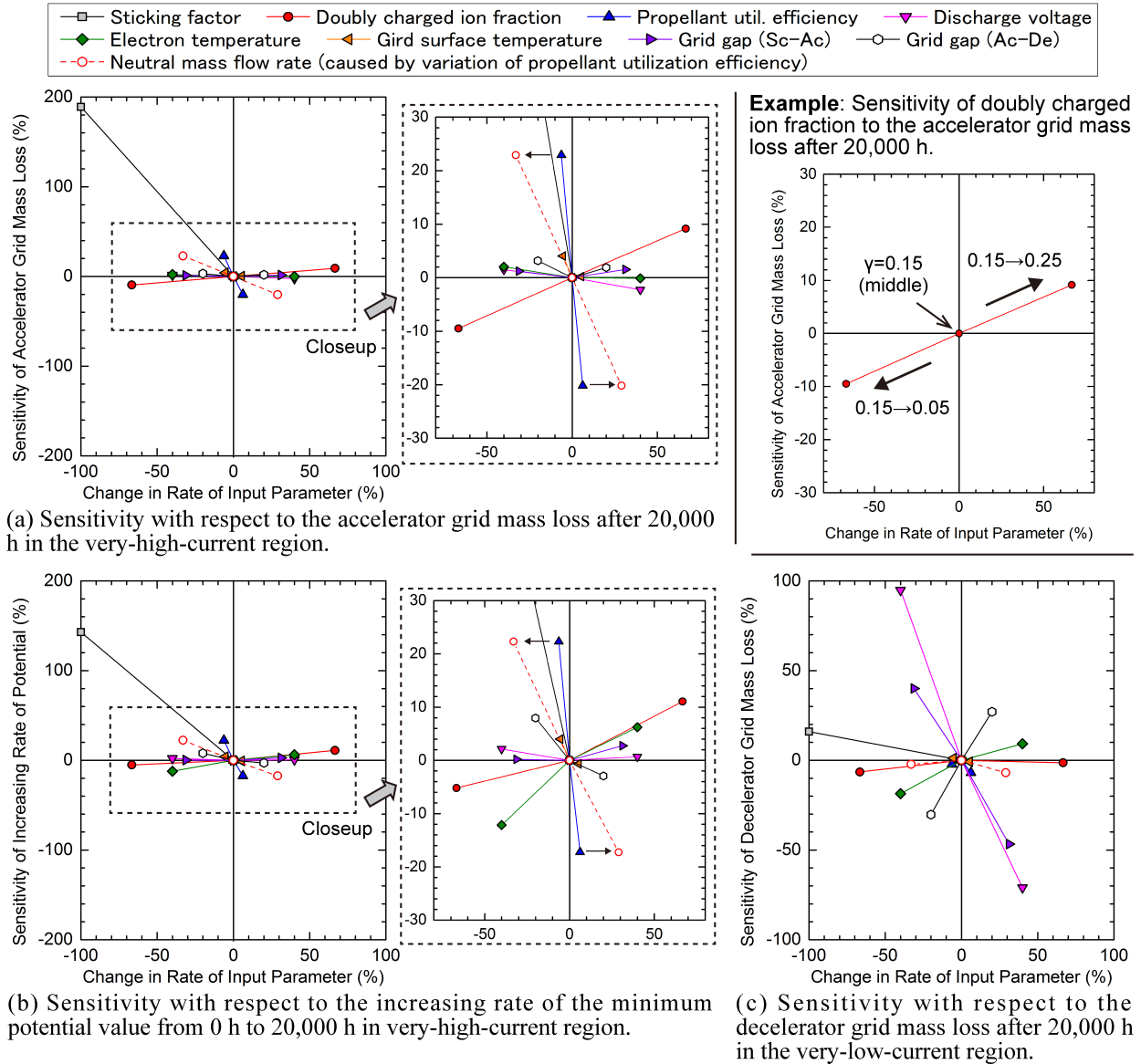


Figure 9. Sensitivity of operation conditions and grid geometry to (a) the accelerator grid mass loss in the very-high-current region, (b) the increasing rate of the minimum potential value in the very-high-current region, and (c) the decelerator grid mass loss in the very-low-current region. The horizontal axis in each figure shows the change in rate of minimum/maximum value of the input parameter with respect to the middle value of the input parameter. The vertical axis in each figure shows the change in rate of the result of the minimum/maximum value with respect to the result from the baseline configuration (middle value). The sensitivity corresponds to this rate and the result for the baseline value for each parameter is therefore the same (0%). The steepness of slope (of the line plots) indicates the level of sensitivity.

also important when estimating the lifetime of ion acceleration grids.

Figure 9(c) shows the sensitivity with respect to the decelerator grid mass loss after 20,000 h in the very-low-current region. The decelerator grid was the most eroded in the hole of the lowest ion beam current as shown in Fig. 7(c). This erosion is mainly caused by direct impingement of mainstream ions that are insensitive to the neutral number density. The data presented in Fig. 9(c) shows that the discharge voltage and grid gap, both of which affect the ion beam trajectory, are highly sensitive with respect to the decelerator grid mass loss. A 40% change in the discharge voltage corresponds to about a 90% change in the decelerator grid mass loss. A 30% change in the grid gap between the screen grid and the accelerator grid corresponds to about a 40% change in the decelerator grid mass loss. The sensitivity of the discharge voltage and the grid gap to the decelerator grid mass loss is higher than that of

the sticking factor. Therefore, the uncertainties in the discharge voltage and grid gap are important when estimating decelerator grid erosion.

V. Conclusion

The sensitivity analysis of input parameters of this JIEDI tool were conducted. Comparison of the simulation results of the JIEDI tool with experiment showed that the full lifetime test of $\mu 10\text{PM}$ could be successfully reproduced by the JIEDI tool. Sensitivity analysis showed that the sticking factor is the most sensitive to estimating the accelerator grid erosion and electron backstreaming time. The accelerator grid mass loss was 190% larger for a sticking factor of 0 (without re-deposition) compared to that determined for a sticking factor of 0.78 (considering re-deposition). In the worst case scenario of grid erosion (without re-deposition), the uncertainty in the neutral mass flow rate through grid holes is important when estimating the accelerator grid erosion. A 30% change in the neutral mass flow rate, which was caused by a 6% change in the propellant utilization efficiency, corresponded to about a 20% change in the accelerator grid mass loss as well as the increasing rate of minimum potential on the axis. In contrast to the accelerator grid erosion, the decelerator grid erosion was mainly caused by direct impingement of mainstream ions that are insensitive to the neutral number density. Therefore, the uncertainties in the discharge voltage and the grid gap, both of which affect the main ion beam trajectory, are important when estimating the decelerator grid erosion. A 40% change in the discharge voltage corresponded to about a 90% change in the decelerator grid mass loss. In addition, a 30% change in the grid gap between the screen grid and the accelerator grid corresponded to about a 40% change in the decelerator grid mass loss.

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