

Particle Simulation of High Specific Impulse Operation of Low-Erosion Magnetic Layer Type Hall thrusters

*Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015*

Shinatora Cho¹, Hiroki Watanabe², Kenichi Kubota³,
Shigeyasu Iihara⁴, Kenji Fuchigami⁵, Kazuo Uematsu⁶
and Ikkoh Funaki⁷

^{1, 3, 7}Japan Aerospace Exploration Agency, Japan

²Tokyo Metropolitan University, Japan

⁴IHI Aerospace Co., Ltd., Japan

^{5, 6}IHI Corporation, Japan

Abstract: High discharge voltage operation of a conceptual low-erosion magnetic layer type Hall thruster was designed and modeled by an axial-radial two dimensional fully kinetic particle simulation code. No anomalous diffusion model was used to self-consistently capture the physics of electron cross-field transport and wall erosion of the thruster. For the verification of the size of the computational domain, simulation was conducted on two computational domains with different radial size. It was shown that the size of the computational domain had significant impact (>30%) on wall erosion prediction, though its influence on thrust performance was minor (<3%). The performance of the designed conceptual thruster was predicted to be >50% in anode efficiency and <0.3 mm/kh wall erosion rate inside the discharge channel, though >1.5 mm/kh erosion rate was observed for the front wall. The cause of the relatively high front wall erosion was shown to be the bulk plasma potential structure leading to the ion acceleration toward the wall, which might be able to explain the pole-piece erosion experimentally observed for “magnetic shielding” Hall thrusters presented in previous studies.

Nomenclature

Roman:

g	= Gravitational acceleration, m/s
I_d	= Discharge current, A
I_{sp}	= Anode specific impulse, s
$\dot{m}$	= Xenon mass flow rate
T	= Thrust, N
V_d	= Discharge voltage, V

Greek:

η_a	= Anode efficiency
----------	--------------------

¹ Researcher, Institute of Aeronautical Technology, 7-44-1 Jindaiji, Higashi-machi, Chofu-shi, Tokyo, Japan

² Assistant Professor, Department of Aerospace Engineering, 1-1 Minami-Osawa, Hachioji-shi, Tokyo, Japan 192-0397

³ Researcher, Institute of Aeronautical Technology, 7-44-1 Jindaiji, Higashi-machi, Chofu-shi, Tokyo, Japan

⁴ Chief Engineer, 900, Fujiki, Tomioka-shi, Gunma-ken 370-2398 Japan

⁵ Senior Researcher, 1, Shin-nakahara-cho, Isogo-ku, Yokohama 235-8501 Japan

⁶ Senior Technical Advisor, 1, Shin-nakahara-cho, Isogo-ku, Yokohama 235-8501 Japan

⁷ Associate Professor, Department of Space Flight System, 3-1-1 Yoshinodai, Chuo-ku, Sagami-hara, Kanagawa 252-5210 Japan

I. Introduction

High specific impulse (I_{sp}) Hall thruster propulsion system not only enables a wide range of scientific exploration missions, but also is considered to be cost competitive or beneficial compared to chemical propulsion or gridded ion propulsion systems¹. However, high I_{sp} Hall thruster faces severer lifetime issues² due to the channel wall erosion compared to conventional operation discharge voltage around 300 V, mainly because of the increased electron temperature. Naturally, low-erosion or even erosion-less design is of great interest of high I_{sp} Hall thruster development.

Recently, the emerging “Magnetic Shielding” technique³ is suggested to be able to reduce the wall erosion of Hall thrusters to negligibly low level and effectively eliminates the wall erosion as the primary lifetime limiting factor of Hall thrusters. Promising begin-of-life test result was also shown for the magnetic shielded (MS) high I_{sp} Hall thrusters.⁴ Still, however, there are various concerns and uncovered physics about MS Hall thrusters. First of all, the MS Hall thruster is reported⁵ to suffer thrust performance penalty in terms of reduced thrust and conversely increased fractions of multiply charged ions, beam divergence, and magnet power, which consequently resulted in the reduced total efficiency. Moreover, recent experimental study⁶ suggests that the pole-piece of MS Hall thrusters will wear instead of channel wall, which can be the next likely lifetime limiting factor. Unfortunately, however, these mechanisms are yet to be fully understood. Therefore, it is critically important to uncover the physics of MS or MS-like low erosion Hall thrusters to achieve both high efficiency and long system lifetime for the future application of high I_{sp} Hall thrusters to scientific exploration missions.

The final goal of this study is to investigate the physics of low-erosion Hall thrusters, especially the process of pole-piece or front wall erosion. As the first step, we numerically modelled a conceptual design of low-erosion Hall thrusters, which has a magnetic file topology close to the MS-like type but not the classic plasma-lens type⁷. Although intensive investigation about MS Hall thrusters can be found in previous studies³⁻⁵, these discussions are mainly based on the simulation results of fluid modelling. Assumptions used in these models omit the effects of non-Maxwellian velocity distribution function and electron inertia, though they can be important for the plasma-wall interaction of low or zero-erosion design Hall thrusters due to their small characteristic length of magnetic field topology. Therefore, our approach is kinetic simulation⁸ utilizing the fully kinetic particle-in-cell code developed in JAXA and The University of Tokyo⁹. It has been also shown that this approach can reasonably model high I_{sp} Hall thrusters without assuming any anomalous diffusion models¹⁰, which greatly enhance the self-consistency of the simulation result compared to fluid-based approaches which must incorporate measured electron transport profile.

A serious concern about the modelling of the front wall erosion is the size of the computational domain, because fully kinetic simulation tend to use narrow computational domain limited to the discharge channel and its vicinity. This is a reasonable compromise between the accuracy and the computational cost if the target of interest is the physics inside the discharge channel. However, the pole-piece erosion observed in the MS Hall thruster was widely spreaded throughout almost the entire front surface of the inner pole, which poses question to use narrow computational domain. Therefore, the simulation was conducted on two computational domains with different radial size to verify the uncertainty, and to capture the physics of front wall erosion. The introduction of the numerical methods are made in section II, and the section III presents the simulation result of overall thrust performance, wall erosion inside the discharge channel, and the wall erosion on the front wall surface. The influence of the size of the computational domain and the possible cause of the predicted front wall erosion, which was not fully captured in previous study¹¹, is discussed.

II. Numerical Methods

A. Overview

A conceptual magnetic layer type Hall thruster was simulated by an axial-radial two-dimensional fully-kinetic particle-in-cell (full-PIC) code. The magnetic field topology of the thruster was designed for low-erosion high-specific-impulse operation. The magnetic field calculated by the free software Finite Element Method Magnetics (FEMM) was used for the simulation, and the plasma induced magnetic field was assumed to be negligibly small and was omitted. The movement of electrons, ions, and neutrals were traced directly by computing the equation of motion, whereas the electric field was calculated by solving the Poisson equation. Uniform rectangular mesh was used and the particles were linearly assigned to the cell according to the cloud-in-cell (CIC) method. The charge density and potential were calculated on the cell center whereas the electric field was computed on the grid points. The technique of artificial electron mass was used to speed up the computation, though artificial permittivity or other unphysical manipulation was not introduced. The inter-particle collisions were treated by Monte Carlo Collision (MCC) method. No anomalous collision models were used in the simulation. This was because our previous study has shown it was not necessary to implement artificial collisions for the full-PIC

simulation of high I_{sp} Hall thrusters¹⁰, which greatly enhance the self-consistency of the simulation. Further detailed description of the model has been presented elsewhere^{9,10}.

The simulation was performed on the KDK computer system at the Research Institute for Sustainable Humansphere, Kyoto University. The convergence of the computation was confirmed by the invariant or periodic time-history of the simulation particles. Usually, this was achieved after simulation over approximately 1 millisecond starting from the spatially-uniform plasma distribution. The simulation results presented in this study were time-averaged over 0.1 millisecond after the confirmation of convergence. **Table 1** summarizes the simulation conditions.

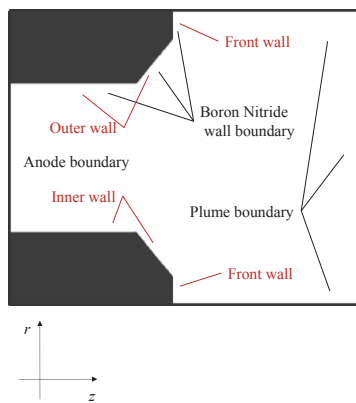
B. Computational Domain and Boundary Conditions

Simulation was conducted in two different computational domains in order to (1) capture the physics of front wall erosion; and (2) quantify the simulation uncertainty due to the size of the computational domain. **Figure 1** illustrates the used computational domains in cylindrical coordinates. Both domains consists of the discharge channel sandwiched by the Boron Nitride (BN) inner and outer rings, and the near-field outside the channel. The notation of the walls are also shown here that the “inner wall” and “outer wall” means the inner and outer wall surface inside the discharge channel, respectively, and the “front wall” means the wall surface outside the discharge channel covering the magnetic pole-piece. The small computational domain (SD) is annular shape, which is the one conventionally used for full-PIC simulation of Hall thrusters. In contrast, the large computational domain (LD) contains the axis of symmetry, which can capture the erosion of the entire inner front wall. The axial length was the same for both large and small computational domains. Note that the cathode was assumed to be located at the outside of the computational domain and was not directly simulated.

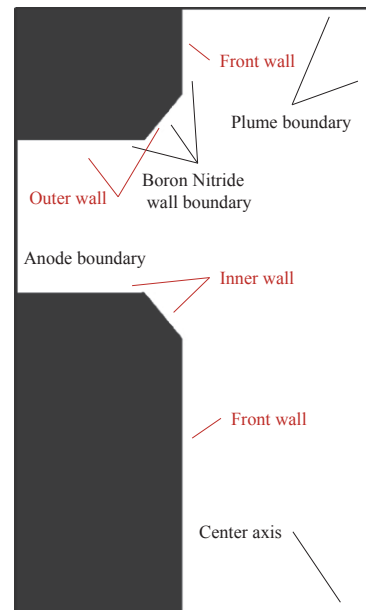
On the BN wall boundaries, ions are neutralized whereas electrons are lost and the electron-induced secondary electron emission (SEE) was processed. The SEE coefficient of BN wall was assumed to be $(T_e/35)^{0.5}$ according to the incident electron energy T_e ¹². The charge was deposited on the wall surface, which was included in the field computation. Furthermore, ions and neutrals were randomly scattered according to the assumed thermal accommodation coefficient of 0.9. This means after the wall collision, 90% of the incident particle was

Table 1. Simulation condition

Item	Value
Timestep	1.0×10^{-11} s
Grid spacing	2.0×10^{-4} m
Artificial mass ratio	Electron mass multiplied by $f^2 = 2500$
Macro particle size	Magnetic field correction $f_B = f^{2/3} = 13.6$
Particle species	2.0×10^7 e^- , X_e^+ , X_e^{2+} , X_e^{3+} $e^- - X_e$ elastic scattering $e^- - X_e$ excitation $e^- - X_e$ ionization $e^- - X_e^+$ ionization $e^- - X_e^{2+}$ ionization Collision $X_e - X_e^+$ CEX $X_e - X_e^{2+}$ CEX $X_e - X_e^{3+}$ CEX Coulomb collisions



a) Small domain



b) Large domain

Figure 1. Cylindrical computational domain of the simulated conceptual Hall thruster. Only the large domain contains the axis of symmetry. The axial length is the same for both small and large computational area.

thermalized by the wall temperature and the rest of the 10% remains its energy unchanged. On the anode boundary, electrons are lost and ions are neutralized. The heavy particles are scattered the same way as on the BN wall. All of the particles are lost on the plume boundary. The anode and wall temperature were assumed to be 500 K and 700 K, respectively. Wall erosion rate was calculated when ions collide with the BN wall boundaries. The sputtering yield was computed according to the ion energy (threshold energy 35 electron volts) and incident angle dependency of the sputtering model. The detail of the used sputtering model was presented in Ref. 9.

Neutrals were injected from the slit located at the center of anode boundary with assumed Mach number 1. The xenon mass flow rate $\dot{m}$ of 4 mg/s condition was simulated in this study. The initial energy distribution of the injected propellant was set to be the Maxwellian distribution with temperature equals to the anode temperature. No neutral inflow from the plume boundaries (i.e. cathode neutral flow and back streaming neutrals due to facility pressure) was assumed. Electrons are injected from the plume boundaries. The amount of electron injection was decided to keep the local quasi-neutrality, so the total injection current was not fixed. The initial energy distribution of the injected electrons was assumed to be the Maxwellian distribution with temperature of 4 electron volts¹³.

Acceleration voltage of 700 V was imposed on the anode boundary. Note the cathode coupling potential drop¹³ occurring outside of the computational domain was assumed to be 50 V, so that discharge voltage V_d of 750 V in total was used for the calculation of anode efficiency. Dirichlet condition of 0 V was imposed on the plume boundaries and Neumann condition was used for the other boundaries.

Finally, the simulation results of the discharge current I_d was derived by the inflow of electron particles on the anode boundary, whereas the thrust T was computed by the mean axial velocity of the heavy particles on the plume boundaries. Note that the thrust can also be derived by the integration of $\mathbf{E} \times \mathbf{B}$ current over the computational domain, which was confirm to be coincide with the thrust calculated from the heavy particles. The anode efficiency η_a and specific impulse I_{sp} can be derived as follows against given discharge voltage V_d and mass flow rate $\dot{m}$ conditions:

$$\eta_a = \frac{T^2}{2\dot{m}I_dV_d} \quad (1)$$

$$I_{sp} = \frac{T}{\dot{m}g} \quad (2)$$

III. Results and Discussion

A. Simulation Results

Thrust performance simulation result is tabulated in **table 2**. The simulation predicted >50% anode efficiency and >2,400s anode I_{sp} performance of the conceptual Hall thruster. The SD and LD results did not show noticeable difference, though the thrust and discharge power was higher for the SD case by approximately 2%. This result indicates that the impact of radial size of the computational domain on the overall thrust performance was insignificant.

Figure 2 presents the erosion rate of the inner and outer BN wall computed according to the wall incident ion energy and flux. The horizontal axis is the axial position normalized by the channel length. Note that the discharge channel has tapered shape as shown by **figure 1** and the shown erosion rate at this tapered area is the wall recession rate in radial direction. The predicted maximum erosion rate was less than 0.3 mm/kh, which was lower than that of the conventional magnetic layer type Hall thrusters by approximately one order of magnitude. The maximum erosion rate was observed at the starting point of the tapered area ($z/L_c = 0.0775$) of the outer wall. In contrast, the erosion rate of the straight upstream channel was negligibly low. In comparison of the two simulation conditions, the discrepancies of the SD and LD results were limited. However, there were two notable differences found. First, the erosion rate at the channel exit of inner wall was higher for the LD case than the SD case. Second, the maximum erosion rate located at the outer wall taper edge was higher for the SD case than the LD case by approximately 30%. Especially, the latter one can change the bottleneck of the thruster lifetime so it is indicated that the radial size of the computational domain have substantial impact on the channel wall erosion rate. There were considerable total wall incident ion current, 0.32 A and 0.26 A for SD case and LD case, respectively, suggesting the mean energy of wall incident ions were low compared with the BN erosion threshold energy (35 eV), which means the low-erosion

Table 2. Thrust performance simulation result

Item	Small Domain	Large Domain
Discharge voltage, V (given)	750	750
Xenon mass flow rate, mg/s (given)	4	4
Discharge current, A	2.8	2.8
Discharge power, W	2097	2060
Thrust, mN	98	96
Anode efficiency, %	57	56
Anode specific impulse, s	2497	2445

design of the thruster successfully suppressed the erosion driven by wall-sheath. The reason of the low energy of wall incident ions are considered to be the high potential and low electron temperature at the vicinity of the channel wall according to the noble concept presented by Mikellides et al.³, which will be shown by the electron temperature simulation result later in this paper.

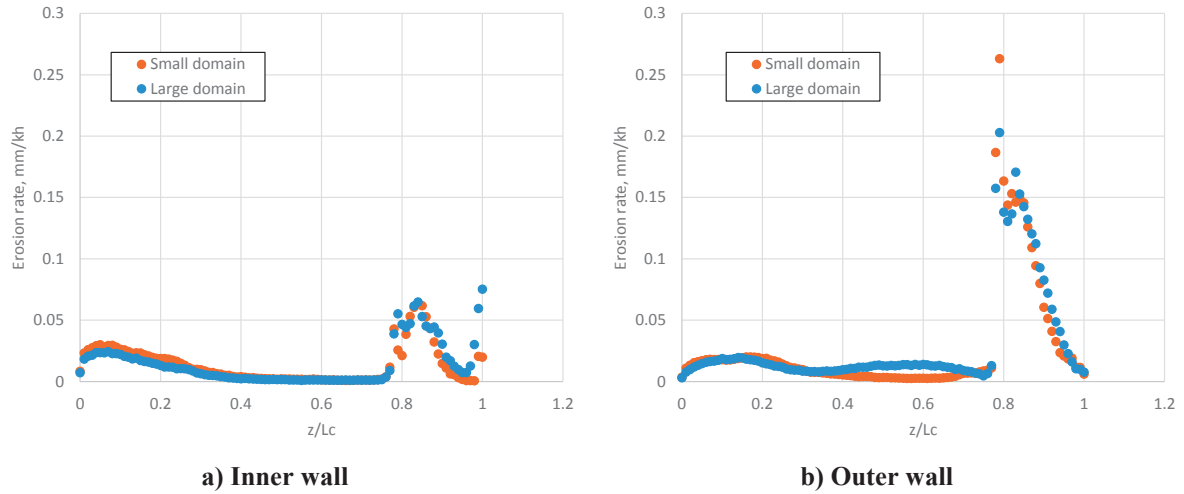


Figure 2. Channel wall erosion rate (wall recession rate in radial direction). The horizontal axis denotes the axial position relative to the channel exit.

Figure 3 presents the simulation result of erosion rate of the thruster front wall (i.e. wall recession rate in axial direction). Unfortunately, relatively high erosion rate was observed compared with the inner and outer wall. The predicted maximum erosion rate was 1.8 mm/kh, which was nearly one orders of magnitude higher than that of the wall inside the discharge channel. The predicted erosion profile was interesting. There were no erosion observed at the vicinity of the channel exit for both inner and outer front wall, however, the erosion rate drastically increased to its maximum value on the inner front wall. Although this trend itself was observed for both SD and LD cases, the difference of the maximum value was significant, indicating it is necessary to use wide enough computational domain to capture the front wall erosion. It is notable that the predicted front wall erosion is the phenomenon observed by the noble magnetic shielding thruster^{6,11}. The total front-wall incident current of ions was 0.0016 A and 0.028 A for SD and LD case, respectively, which is one order of magnitude lower than that of the inner and outer wall. The low wall incident current and the high erosion rate indicate that the ions causing the erosion has much higher energy than the threshold energy of BN sputtering.

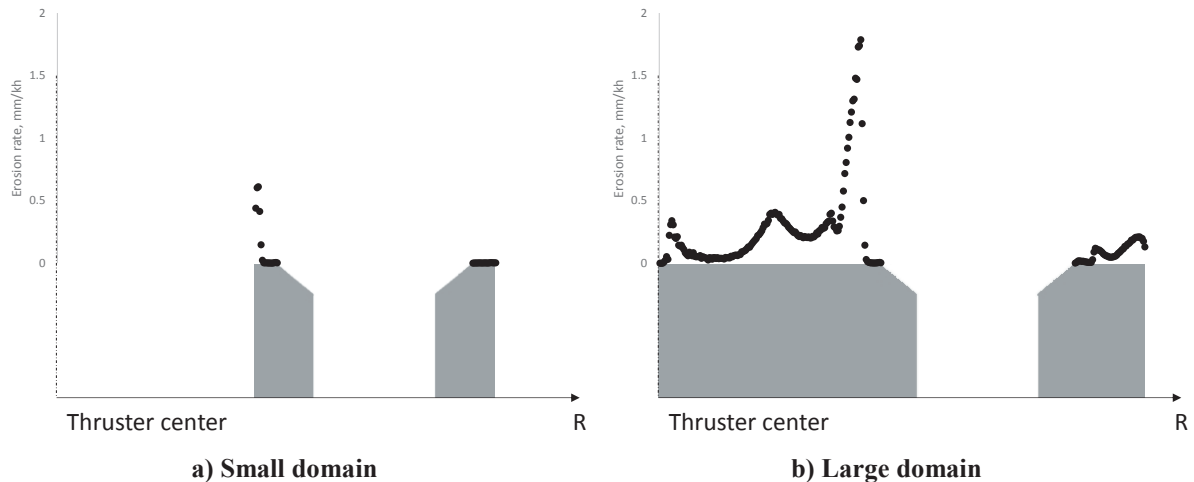


Figure 3. Erosion rate of front wall (wall recession rate in axial direction). The horizontal axis denotes the radial position and the colored area is the thruster channel wall.

Figure 4-6 illustrates the simulation result of the potential distribution, electron temperature, and electron number density overlaid with the applied magnetic field lines. There were clear discrepancies found between the SD and LD simulation conditions. In the LD case, the equipotential lines tended to follow the magnetic field lines. The near-wall region was covered with high-potential and low-electron temperature region, which is ideal

condition to suppress the sheath-driven wall erosion. In contrast, the equipotential lines does not follow the magnetic field lines especially near the outer wall, and high electron temperature (30-40 eV) region “touches” the outer wall in SD case. This was considered to be the direct reason of the discrepancy of outer wall erosion rate result shown by **figure 2(b)**. The distorted potential and electron temperature distribution of the SD case is apparently caused by the imposed fixed potential boundary condition on the plume boundaries, which is crossing over with the magnetic field lines. Thus, it is suggested that the computational domain should be taken not to cross over with the magnetic field lines accompanied with potential drop, though it is non-trivial to find where the potential drop ends.

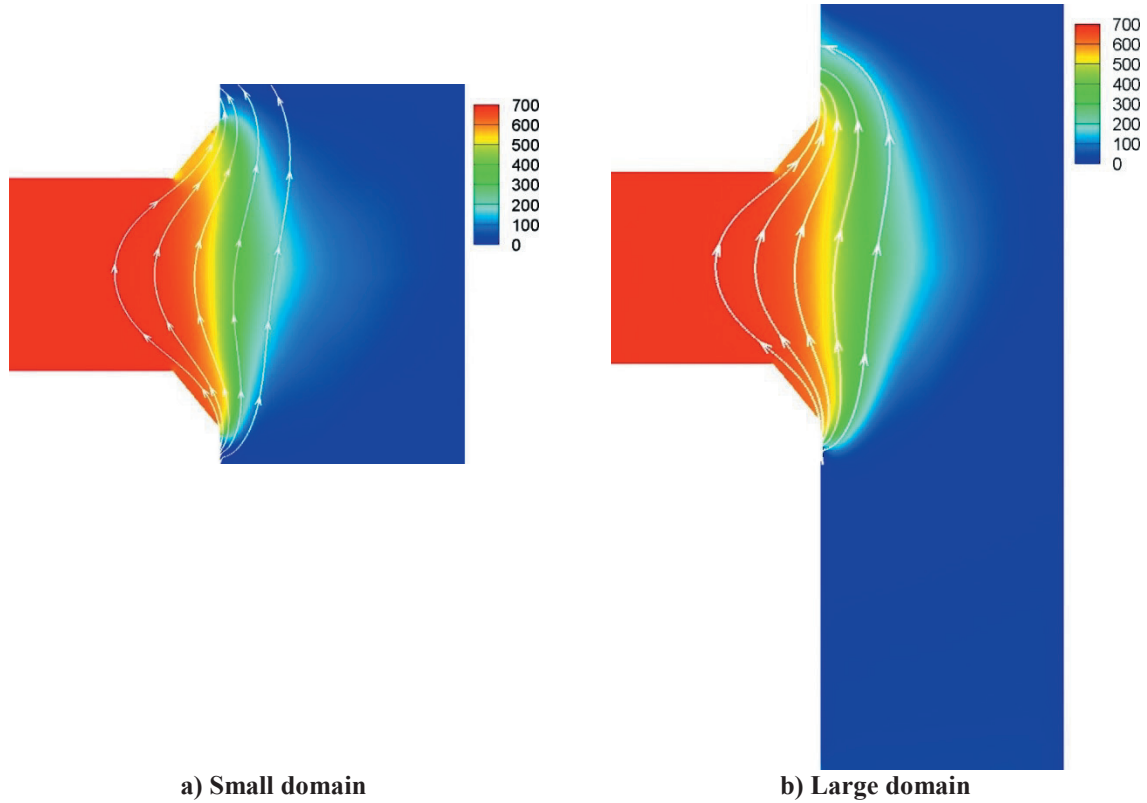


Figure 4. Potential distribution simulation result (V). *The white stream traces on the figure denotes the magnetic field lines.*

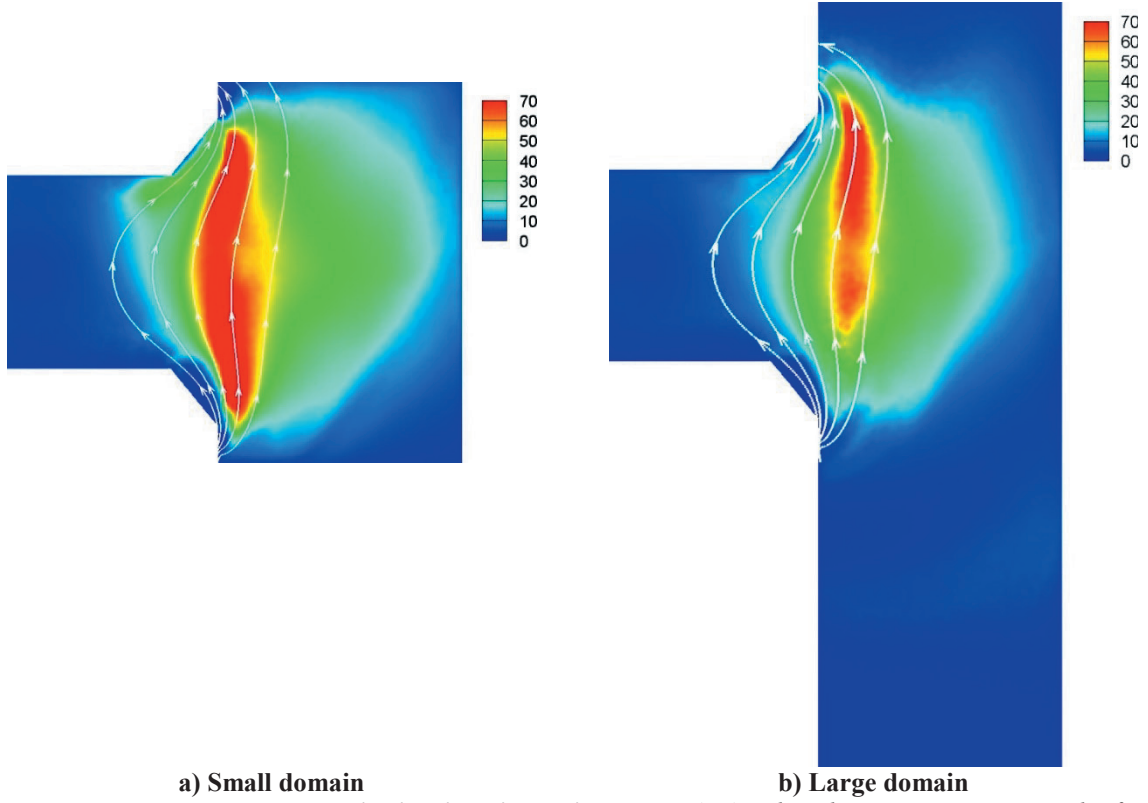


Figure 5. Electron temperature distribution simulation result (eV). *The white stream traces on the figure denotes the magnetic field lines.*

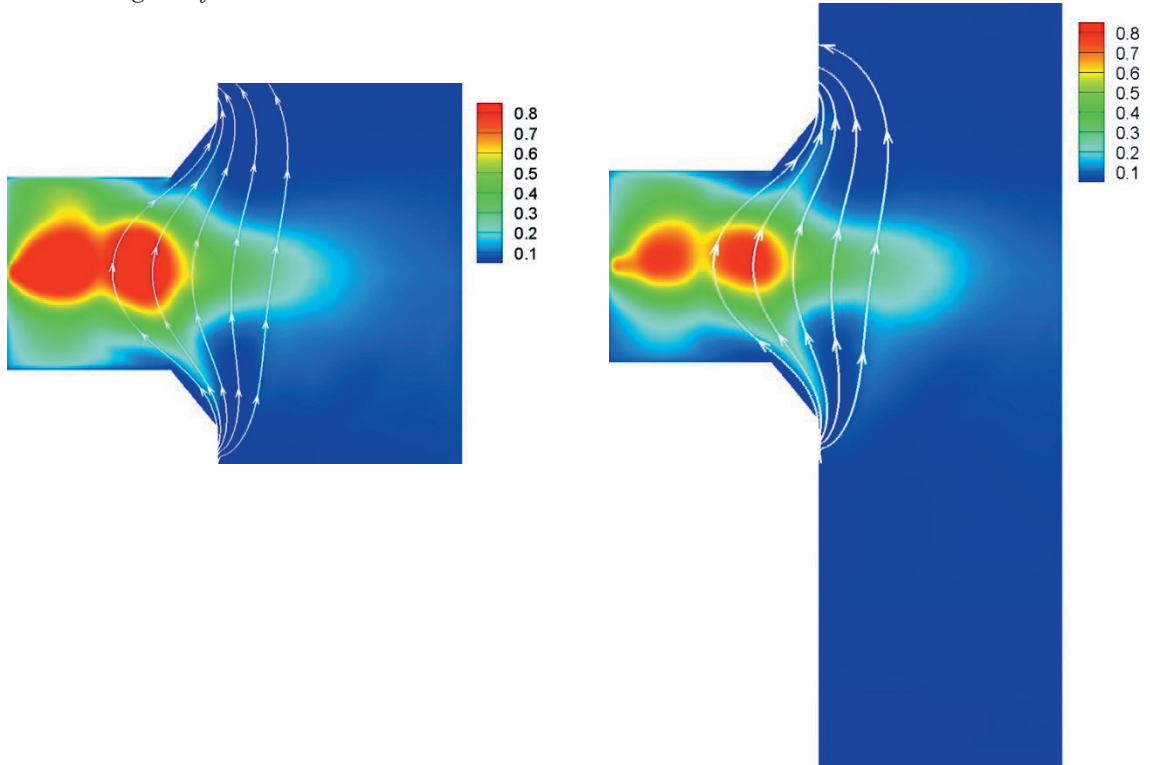


Figure 6. Simulation result of electron number density distribution ($10^{18}/\text{m}^3$). *White lines represents the applied magnetic field.*

B. Discussions

The electron temperature distribution presented by **figure 5(b)** did not show the existence of high electron temperature region at the vicinity of the front wall, which suggests the mechanism of observed front wall erosion

is not driven by wall sheath, i.e. the large sheath potential drop originates to the high electron temperature accelerates the local low-energy ions to gain energy higher than the erosion threshold. Instead, the structure of ion acceleration toward the wall outside the wall sheath is expected to explain the observed erosion. **Figure 7** illustrates the plasma properties at the vicinity of inner wall observed in the LD simulation case. It was shown that the near-wall electron temperature never exceeds 10 eV, which is confirmed to be unable to cause high wall erosion itself. However, the potential distribution suggested the existence of potential structure leading to the ion acceleration toward the wall. The equipotential lines shaped convex toward the front wall apparently forms electric field and ion flux heading toward the entire inner front wall as shown by figure 7(c), which reasonably explains the predicted wide-spreaded front wall erosion. The place of the concentration of the equipotential lines, or the strongest electric field on the surface of the front wall coincide with the place of maximum erosion rate, which is considered to be the direct cause of the high energy ions impact at this point. Therefore, it was suggested that the observed front wall erosion was caused by the high energy ions accelerated toward the front wall according to the bulk potential structure.

It is notable that this near-front-wall potential structure is not following the magnetic field lines, because otherwise the ions will be repelled from the front wall as shown in previous study¹¹. The qualitative reason of this deviation is clear as pointed out by Morozov⁷ that when magnetic field lines cross over with wall, the presence of ion-attracting pre-sheath, which is necessary for the maintenance of wall sheath, let the equipotential lines deviate from the magnetic field lines. Thus, it was implied that capturing the pre-sheath structure along the magnetic field lines is essential for the prediction of front wall erosion of “magnetic shielding” like low-erosion Hall thrusters. Further quantitative investigation of the possible influential factors of the pre-sheath formation, the ion and electron velocity distribution, finite Larmor radius effect, and perturbation of electric field well be interesting as the future work of this study.

Finally, it is to be noted that although the front wall erosion numerically predicted in this study is similar to the pole-piece erosion experimentally observed by the JPL’s “magnetic shielding” Hall thruster⁶, the situation is not exactly the same because the JPL thruster has magnetic pole-piece directly exposed to the plasma whereas we assumed BN layer coverage of the front side of our conceptual thruster. Furthermore, the detailed thruster and magnetic field design is apparently not the same. Therefore, the simulation results of this study is limited to be numerical findings and the experimental validation is reserved for future works.

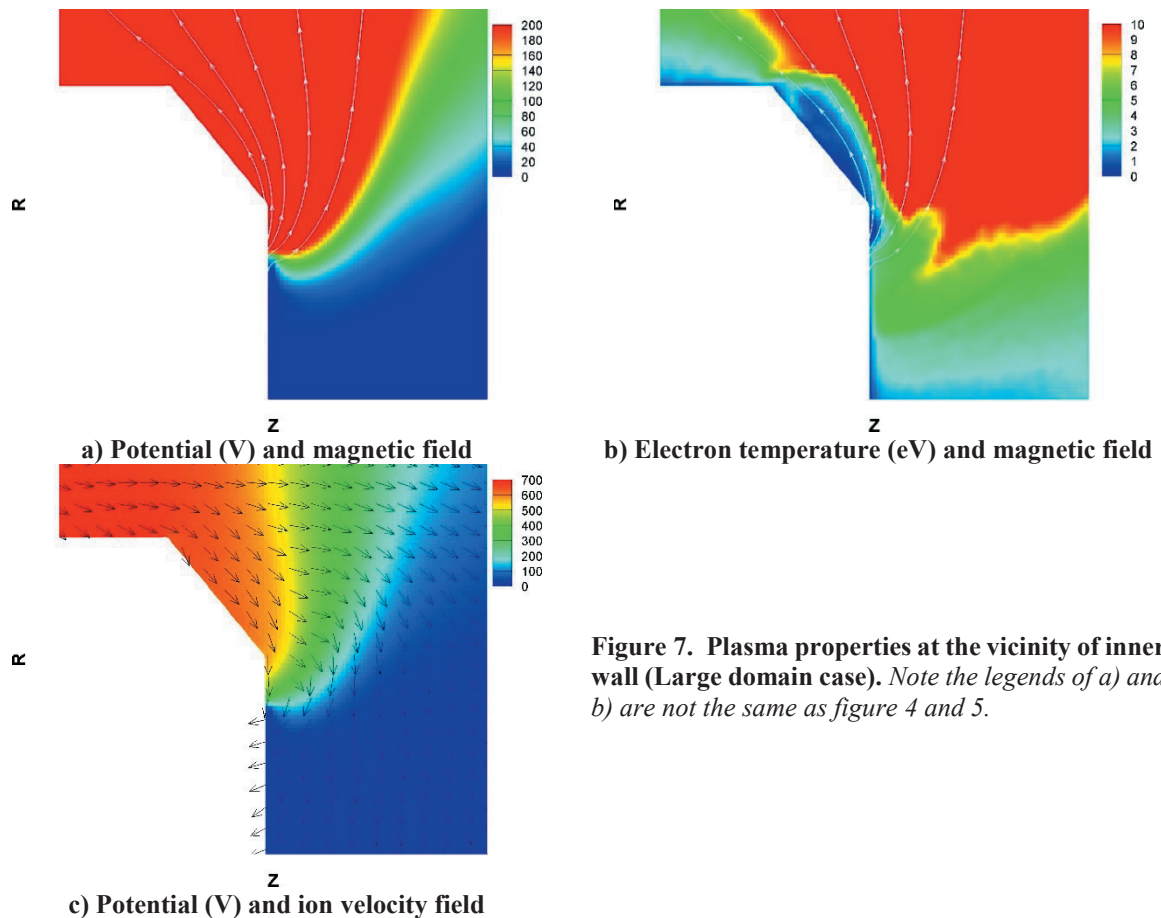


Figure 7. Plasma properties at the vicinity of inner wall (Large domain case). Note the legends of a) and b) are not the same as figure 4 and 5.

IV. Conclusion

A conceptual Hall thruster designed for low-erosion high-specific impulse operation was modeled by an axial-radial fully kinetic particle code. No artificial permittivity or additional anomalous diffusion models were used to enhance the self-consistency of the computation. Two different computational domain, small one and large one, were tested to quantify the numerical uncertainty due to the radial size of the computational domain. The comparison of the two simulation cases suggested the radial size of the computational domain has limited influence on the predicted thruster performance, though have non-trivial impact on the erosion prediction of inside channel wall, and is critically important for the erosion prediction of thruster front wall. It is suggested having computational domain boundaries intersect with magnetic field lines accompanied with potential drop will distort the potential distribution and cause significant change of the simulated wall erosion.

Over 50% anode efficiency and <0.3 mm/kh wall erosion rate inside the discharge channel was predicted by the simulation, though relatively high front wall erosion > 1.5 mm/kh was observed. The profile of the predicted front wall erosion is similar to the pole-piece erosion experimentally observed by magnetic shielding Hall thrusters. The simulated plasma properties distribution suggested the front wall erosion was caused by the high energy ions accelerated toward the wall by bulk potential structure, but not the potential drop inside the wall sheath. The fundamental cause of the formation of the wall heading bulk potential structure, which has equipotential lines deviate from the magnetic field lines, was considered to be caused by the formation of ion-attracting pre-sheath.

Acknowledgement

The authors acknowledge that the presented computer simulation was performed on the KDK computer system at Research Institute for Sustainable Humanosphere, Kyoto University.

References

- ¹ Kamhawi, H. et al., Overview of the Development of a Low Cost High Voltage Hall Accelerator Propulsion System for NASA Science Missions, AIAA 2011-5520 (2005).
- ² Kamhawi, H. et al., In-Space Propulsion High Voltage Hall Accelerator Development Project Overview, AIAA 2009-5282 (2009).
- ³ Mikellides, I. G. et al., Magnetic shielding of walls from the unmagnetized ion beam in a Hall thruster, Appl. Phys. Lett. 102, 023509 (2013).
- ⁴ Mikellides, I. G. et al., The Effectiveness of Magnetic Shielding in High-Isp Hall Thrusters, AIAA 2013-3885 (2013).
- ⁵ Hofer, R. R., et al., Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase II: Experiments, AIAA 2012-3788 (2012).
- ⁶ Goebel, D. M., et al., Pole-piece Interactions with the Plasma in a Magnetically Shielded Hall Thruster, AIAA 2014-3899 (2014).
- ⁷ Morozov, A. I., et al., Fundamentals of Stationary Plasma Thruster Theory, Reviews of Plasma Physics Volume 21 (2000), pp 203-391.
- ⁸ J. C. Adam, A. Heron and G. Laval, Phys. Plasmas, 11, 295 (2004). doi:10.1063/1.163290
- ⁹ Cho, S., et al., Kinetic Particle Simulation of Discharge and Wall Erosion of a Hall Thruster, Physics of Plasmas, 20, 063501 (2013).
- ¹⁰ Cho, S., et al., Parametric Kinetic Simulation of an IHI High Specific Impulse SPT-Type Hall Thruster, AIAA 2014-3426 (2014).
- ¹¹ Mikellides, I. G. et al., Assessment of Pole Erosion in a Magnetically Shielded Hall Thruster, AIAA 2014-3897 (2014).
- ¹² V. Viel-Inguibert, in Proceedings of the 28th IEPC, Toulouse, IEPC-2003-258, 2003.
- ¹³ D. M. Goebel, K. K. Jameson and R. R. Hofer, J. Propul. Power, 28, 355 (2012). doi:10.2514/1.B34275