Numerical Simulation for the Effect of Conductive Wall near the Exit of a 1kw Aton-type Hall Thruster Channel on Ion Focusing Acceleration

IEPC-2011-285

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

Shaowei Qing[1], Daren Yu[2] and Hui Liu[3]
Lab of Plasma Propulsion, Mail Box 458, Harbin Institute of Technology, Harbin, heilongjiang, 150001, China

Xiaogang Wang[4]
State Key Lab of Nuclear Physics & Technology, School of Physics, Peking University, Beijing 100871, China

and

Ping Duan[5]
School of Physics, Dalian Maritime University, Dalian, 116024, China

Abstract: Recent experimental studies exhibited that low emissive segmented electrodes placed near the exit of Hall Thruster channel reduce plume divergence in low gas flow rate($j_a \leq$ 2mg/s), but increase plume divergence in high gas flow rate (j_a >2mg/s). This paper demonstrated the effect of floating conductive electrodes near the exit of a 1kW Aton-type Hall thruster discharge channel on ion focusing acceleration, through simulating the two-dimensional plasma flow with a fully kinetic Particle-in-cell method for the gas flow rate range j_a =1~3mg/s. Numerical results show that low emissive electrodes trend to widen plume for all the gas flow rate range calculated, because the conductive property of segmented electrodes trend to make potential lines convex toward channel exit and even parallel to wall in near-wall region. Moreover, further investigation predicts that high emissive dielectric wall combined with segmented low emissive dielectric wall is promising to reduce plume divergence.

Nomenclature

r	=	radial coordinate
z	=	axial coordinate
j_a	=	gas flow rate
n_a	=	neutral number density
n_i	=	ion number density
V_{ir}	=	ion velocity
U_d	=	discharge voltage
I_d	=	discharge current

[1] Research Physicist, Theory Department, qshaowei@gmail.com.
[2] Research Physicist, Theory Department, yudaren@hit.edu.cn.
[3] Research Physicist, Theory Department, liuhui@hcms.hit.edu.cn.
[4] Research Physicist, Theory Department, xgwang@pking.edu.cn.
[5] Research Physicist, Theory Department, duanping591@sohu.cn.

η = thruster efficiency

$\dot{\xi}$ = erosion rate

I. Introduction

The Hall thruster so-called stationary plasma thruster is one of the most advanced space electric propulsion devices with high efficiency, high specific impulse, and large thrust density[1,2]. For a long time, people have recognized that plume divergence, namely the radial ion flow is a challenging technique problem constraining the improvement of Hall thruster performance[3,4]. On the one hand, the ion beam defocusing can reduce thrust and propellant utilization, cause wall erosion and shorten lifetime; On the other hand it can increase electron current[5] thereby decrease current utilization and thruster efficiency. Therefore, controlling ion beam focusing is a key way to improve Hall thruster performance parameters such as lifetime, thrust and efficiency. In fact, controlling ion beam focusing is to a great extent equivalent to reducing discharge current for a given operation condition of Hall thruster, because the erosion rate $\dot{\xi}$ of channel wall surface due to ion bombardment is direct proportion to discharge current I_d (namely $\dot{\xi} \propto I_d$)[6] and Hall thruster efficiency η is in inverse proportion to discharge current[7] (namely $\eta \propto 1/I_d$).

Extensive experimental and numerical studies indicated that the secondary electron emission (SEE) characteristic of channel walls present significant impact on Hall thruster performance and plasma parameters such as discharge current, electron temperature and efficiency[7-10]. The researchers generally attribute the influence of wall SEE to two ways: (1)The SEE decreases sheath potential drop and thereby increases the energy deposition of primary electron on walls[11], at the same time the emitted secondary electron with much lower energy than primary electron goes into discharge channel, resulting in a cooling of electron in discharge channel, thereby lowering the ionization rate; (2)The secondary electron flow gives rise to high cross-field electron conductivity near the walls and, consequently influences the electric potential distribution and ion acceleration process[9]. Because the SEE yield of conductive wall is generally much lower than that of a dielectric wall, especially, the SEE yield of metal wall is negligible[9,12], researchers proposed that using segmented electrodes is a promising way to control the plasma flow and, thereby enhance Hall thruster performance[13,14,15]. Many experimental investigations also demonstrated that segmented electrodes with several millimeter length placed near the exit of Hall thruster channel can remarkably increase electron temperature, reduce discharge current, change electric potential distribution and narrow plasma plume in low gas flow rate($j_a \leq$ 2mg/s) [12,16]. Although the effects of low emissive segmented electrodes wall are well documented by these studies, the cause of plume widening in high gas flow (namely j_a >2mg/s) is not fully understood.

This paper presents detailed numerical results that how the length of low emissive and non-emissive electrodes near the exit of a 1kw Aton-type Hall thruster affect the ionization position, electric potential distribution and ion acceleration process by a fully kinetic 2D PIC model for gas flow rate range j_a =1-3mg/s. The remaining part of this paper is organized as follows. In Sec. II, the numerical model is presented; In Sec. III, the results of low emissive and non-emissive electrodes are presented, and the reason for plume widening effect of segmented electrodes is analyzed. Then, a wall placement method that some high emissive dielectric walls combined with segmented low-emissive dielectric walls is proposed to reduce plume divergence in high gas flow rate; and the conclusions are given in Sec. V.

II. Numerical model

This study involves a 1kW laboratory annular Hall thruster[17,18]. The outer diameter of discharge channel is 71mm, the discharge channel width is 14mm, and the channel length is 30mm. In Fig.1, two annular segmented electrodes with length L ($0 \leq L \leq 10mm$) are placed at the channel exit, and the rest channel walls are made of boron nitride (BN) ceramic. The optimal magnetic field shown in Fig.1 was built in the Finite Elements Method Magnetics(FEMM) [19], a user-friendly magnetic field solver available on the internet. The typical magnetic field shown in Fig.1 and the discharge voltage U_d =350V were held constant, while the range of xenon mass flow rate is j_a =1~3mg/s

The model uses a cylindrical coordinate system. Two coordinates in the r (radial) and the z (axial) direction and three coordinates in velocity ($\upsilon_z, \upsilon_r, \upsilon_\theta$) are tracked in the model, where θ represents the azimuthal direction. The rectangle computational region of our PIC simulation is shown in Fig. 1. The cathode is located outside the discharge channel, so it isn't included in the model. A virtual cathode is set on the exhaust plane of the thruster. Electrons are introduced at each time step Δt from the exhaust plane. The electrons are ejected from the exhaust plane into the channel by the quasi-neutral injection method [20], and the cathode electron temperature is 5eV.

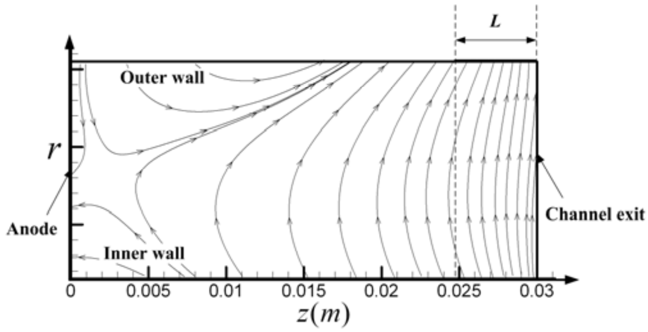

Figure 1. Computational region, segmented length *L* and magnetic field lines used in the model.

In order to accelerate the evolution of simulation, a one-dimensional fluid equation is used to get the neutral number density distribution along the channel[21]

$$v_{az} \frac{\partial n_a}{\partial z} = -v_{ionize} n_a + v_{recom} , \tag{1}$$

where the axial neutral velocity v_{az} is fixed at 105m/s, n_a is neutral number density, v_{ionize} is the ionization frequency and v_{recom} is the ion recombination frequency on the two lateral walls. Since we only care about the steady-state, the time term partial derivative can be ignored.

The leapfrog method of Boris is used to resolve Newton-Lorentzs equations[22]. Particle colliding with boundary and with each other are considered in this model[23]. The Dynamic Alternating Direction Implicit (DADI) method is used to solve Poisson equation[24]. Electric field model at the dielectric walls are in accordance with Ref. 23. The surface potential of the floating conductive wall is given by

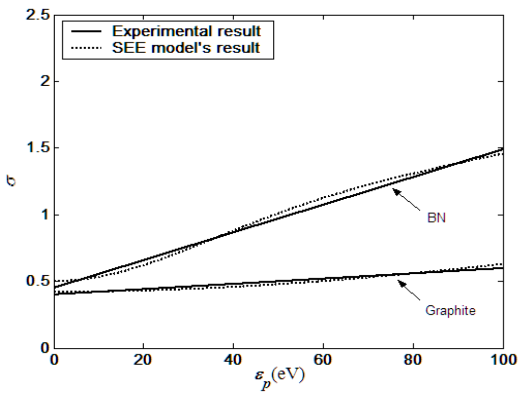

Figure 2. Comparison of SEE yield between SEE yield model and experimental data[9].

$$\Phi_s = \frac{Q_s}{C} , \tag{2}$$

where Q_s is the net charge maintained on the wall, the capacitance[20] $C = 10^{-10} F$.

SEE is considered at the dielectric (BN) surface and the emissive electrodes (graphite) surface, but is neglected at non-emissive electrodes surface. The SEE model in Ref. 25 is used to describe the SEE properties of BN and graphite. This SEE model contains the probabilities of four events that may occur when an electron with energy ε_p collides with the wall

$$\begin{aligned}
&\text{absorbed by the wall: } W_0\left(\varepsilon_p\right) = P_0 \exp\left(-\varepsilon_p^2 / \alpha_0^2\right), \\
&\text{elastically reflected: } W_r\left(\varepsilon_p\right) = P_r \exp\left(-\varepsilon_p^2 / \alpha_r^2\right), \\
&\text{one electron emitted: } W_1\left(\varepsilon_p\right) = 1 - W_0\left(\varepsilon_p\right) - W_r\left(\varepsilon_p\right) - W_2\left(\varepsilon_p\right),
\end{aligned} \tag{3}$$

two electron emitted: $W_2(\varepsilon_p) = 1 - \exp(-\varepsilon_p^2/\alpha_2^2)$,

the corresponding parameters used in our numerical computation are set as follows: $P_0 = 0.5$, $\alpha_0 = 43.5$, $P_r = 0.5$, $\alpha_r = 30$, $\alpha_2 = 127.9$ for BN wall; $P_0 = 0.58$, $\alpha_0 = 2422$, $P_r = 0.42$, $\alpha_r = 30$, $\alpha_2 = 208$ for graphite. As shown in Fig.2, the SEE model is in accordance with the experimental data of BN and graphite.

III. Results and analysis

A. Segmented electrodes

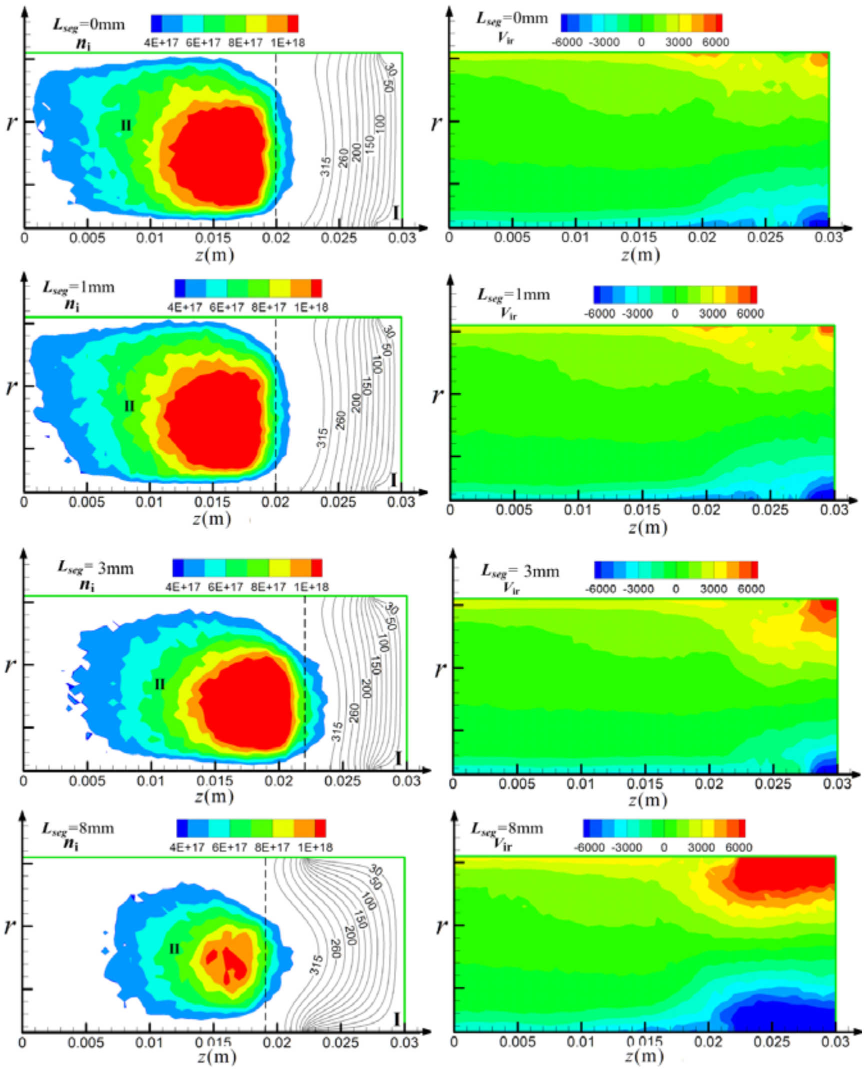

Figure 3. The distribution of plasma parameters for low emissive segmented electrodes (graphite) case, *L*=0, 1, 3 and 8mm.

In the whole gas flow rate range j_a =1~3mg/s, we didn't detect a plume reducing result for both low emissive and non-emissive electrodes. In order to reveal the reason for plume widening effect of segmented electrodes, we present results of low emissive graphite electrodes for gas flow rate j_a =3mg/s below.

The calculated steady spatial distributions of the electric potential, ion density n_i and radial ion velocity V_{ir} for the emissive electrodes (graphite) case are depicted in Fig.3. The region I is the main acceleration zone where contains ninety percent of the electric potential. Region II is the main ionization zone. The results show that, as the segmented electrodes length L increase, the ionization region moves first toward channel exit and then toward anode, accordingly the acceleration region is first shortened and then widened, the potential line is gradually bending toward channel exit which results in radial ion flow enhanced.

As we can see in Fig. 3, compared to the non-segmented wall case, the segmented electrodes make the acceleration region shortening and the electric potential line bending toward channel exit. Because the shortening of acceleration region length can enhance ion axial acceleration and reduce ion radial flux accordingly, we know that the remaining reason for ion radial flow enhancement when using segmented electrodes is the bending electric potential line that caused by the conductive characteristic of electrodes. As shown in Eq. (2) that the surface electric potential of segmented electrode is equal everywhere. Due to the continuity of plasma parameters among wall surface, near-wall sheath and channel plasma, the electric potential line in near-wall region also should be parallel to wall approximately. Obviously, this bending electric potential topography is the reason for ion beam defocusing.

B. Segmented dielectric walls

Since the above results and analysis indicate that the conductive characteristic of low-emissive segmented electrodes is responsible for plume divergence, it provides us a good inspiration to improve ion beam focusing by employing a wall placement method that the region near channel exit placed with low-emissive dielectric walls to shorten acceleration region.

In order to compare with the low-emissive segmented electrodes cases in Fig.3, we take low-emissive segmented dielectrics with the same SEE characteristic of graphite as an example. The calculated steady spatial distributions of the electric potential, ion density n_i and radial ion velocity V_{ir} for the BN channel wall combined with low-emissive dielectric wall case are depicted in Fig.4. We found that the acceleration region is significantly shorter than that of the non-segmented BN ceramic case in Fig.3. Consequently the ion beam is better focused. These results give us a belief that high emissive dielectric wall (such as BN) combined with segmented low-emissive dielectrics has the potential to reduce plume divergence in high gas flow rate.

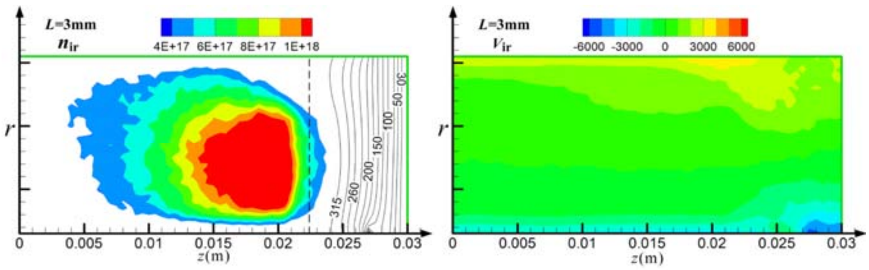

Figure 4. The distribution of plasma parameters for low emissive segmented dielectric wall case, *L*=3mm.

IV. Conclusion

The effect of segmented electrodes placed near the exit of Hall thruster on plasma plume is investigated through simulating the two-dimensional plasma flow with a fully kinetic Particle-in-cell method for the gas flow rate range j_a =1~3mg/s. For both low-emissive segmented graphite electrodes and non-emissive electrodes cases, the plasma plume is widened at any length of the segments. It suggests that the conductive property of segmented electrode seems to make potential lines convex toward channel exit and even parallel to wall in near-wall region, which is disadvantageous for plasma plume focusing. Based on these analyses, a wall placement method that dielectric wall with high emissive property combined with segmented low-emissive dielectrics is proposed, and it presents a better ion beam focusing than the non-segmented BN ceramic wall case.

Acknowledgments

Mr. Daren Yu thanks the National Science Fund for Distinguished Young Scholars (Grant No. 50925625)

References

[1]Kim, V., “Main physical features and processes determining the performance of stationary plasma thrusters”, *J. Propul. Power*. Vol. 14, pp. 736, 743, September-October 1998.

[2]Zhurin, V. V., Kaufman, H. R., and Robinson, R. S., “Physics of closed drift thrusters”, *Plasma Sources Sci. Technol*. vol. 8, R1, February 1999.

[3]Corey, R. L., Snyder, J. S., Price, X., Malone, S. P., and Randolph, T. M., “Hall Thruster Plume Model for Spacecraft Impingement Torque: Development and Validation”, *J. Spacecraft and Rockets*. Vol. 45, 2008, pp.766, 775.

[4]Boyd, I.D., Yim, J.T., “Modeling of the near field plume of a Hall thruster”, *J. Appl. Phys*. vol. 95, May 2004, pp. 4575, 4584.

[5]Ivanov, A. A., Ivanov Jr, A. A., and Bacal, M., “Effect of plasma–wall recombination on the conductivity in Hall thrusters”, *Plasma Phys. Control. Fusion*. vol. 44, August 2002, pp. 1463.

[6]Claus, C., Day, M., Kim, V., Kondakov, Y., and Randolph, T., “Preliminary Study of Possibility to Ensure Large Enough Lifetime of SPT Operating Under Increased Powers”, AIAA-97-2789, 1997.

[7]Ashkenazy, J., Raitses, Y., and Appelbaum, G., “Parametric studies of the Hall current plasma thruster”, *Phys. Plasmas*. vol. 5, May 1998, pp. 2055, 2063.

[8] Keidar, M., Boyd, I. D., Beilis, I. I., “Plasma flow and plasma–wall transition in Hall thruster channel”, *Phys. Plasmas*. vol. 8, December 2001, pp. 5315, 5322.

[9] Barral, S., Makowski, K., Peradzynski, Z., Gascon, N., Dudeck, M., “Wall material effects in stationary plasma thrusters. II. Near-wall and in-wall conductivity,” Phys. Plasmas, Vol. 10, No. 10, 2003, pp. 4137, 4152; Gascon, N., Dudeck, M., Barral, S., “Wall material effects in stationary plasma thrusters. I. Parametric studies of an SPT-100,” Phys. Plasmas, Vol. 10, No. 10, 2003, pp. 4123, 4136.

[10]Meezan, N. B., Gascon, N., and Cappelli, M. A., “Linear Geometry Hall Thruster with Boron Nitride and Diamond walls”, *in 27th International Electric Propulsion Conference* (ElectricRocket Propulsion Society, Worthington, 2001), IEPC-01-039.

[11]Hobbs, G. D., and Wesson, J. A., “Heat flow through a Langmuir sheath in the presence of electron emission,” *Plasma Phys*, Vol. 9, 1967, pp. 85, 87.

[12]Y. Raitses, L. A. Dorf, A. A. Litvak and N. J. Fisch, “Plume reduction in segmented electrode Hall thruster”, J. Appl. Phys. vol. 88,pp. 1263-1270, August 2000.

[13]Morozov, A. I., and Savel’ev, V. V., *in Reviews of Plasma Physics*, edited by B. B. Kadomtsev and V. D. Shafranov, (Consultants Bureau, New York, 2000), Vol. 21.

[14]Fisch, N. J., Raitses, Y., Dorf, L. A., and Litvak, A. A., “Design and Operation of Hall Thrusters with Segmented Electrodes”, AIAA pap. AIAA-99-2572 (1999)

[15]Fruchtman, A., Fisch, N. J., and Raitses, Y., “Control of the electric-field profile in the Hall thruster”, *Phys. Plasmas*. vol. 8, March 2001, pp. 1048, 1056.

[16]Raitses, Y., Keidar, M., Staack, D., and Fisch, N. J., “Effects of segmented electrode in Hall current plasma thrusters”, *J. Appl. Phys*. vol. 92, November 2002, pp. 4906-4911; Y., Keidar, M., Staack, D., Dunaevsky, A., and Fisch, N. J., ibid. 99, 036103 (2006); Raitses, Y., Smirnov, A., Staack, D., and Fisch, N. J., *Phys. Plasmas* 13, 014502, 2006.

[17]Yu, D. R., Li, J., Liu, H., Ning, Z. X., and Li, Y., “Study on the Relation Between Discharge Voltage and Magnetic Field Topography in a Hall Thruster Discharge Channel”, *Contrib. Plasma Phys*. vol. 49, 2009, pp. 413, 421.

[18]Yu, D. R., Li, J., Li, H., Li,Y,, and Jiang, B. H., “Experimental Study on the Effects of Magnetic Field Configuration near the Channel Exit on the Plume Divergence of Hall Thrusters”, *Plasma Sci. Technol*. Vol. 11, 2009, pp. 714, 720.

[19]FEMM, Finite Element Method Magnetics, Software Package, Ver.4.0, Foster-Miller, Inc., Boston, MA, 2004.

[20] Szabo, J. J., “Fully Kinetic Numerical Modeling of a Plasma Thruster”, Ph.D. thesis, Massachusetts Institute of Technology, 2001.

[21] Liu, H., Wu, B. Y., Yu, D. R., Cao, Y., and Duan, P., “Particle-in-cell simulation of a Hall thruster”, *J. Phys. D: Appl. Phys.* vol. 43, 165202, 2010.

[22] Birdsall, C.K., Langdon, A. B., “Plasma physics via computer simulation”, *Institute of Physics Publishing*, Bristol and Philadelphia, 1991.

[23] Liu, H., Yu, D. R., Yan, G. J., and Liu, J. Y., “Investigation of the Start Transient in a Hall Thruster”, *Contrib. Plasma Phys.* vol. 48, 2008, pp. 603, 611.

[24] Doss, S., Miller, K., “Dynamic ADI methods for elliptic equations”, *SIAM I. NUMER. ANAL*. vol. 16, 1979, pp. 837.

[25] Yu, D. R., Zhang, F. K., Liu, H., Li, H., Yan, G. J., and Liu, J. Y., “Effect of electron temperature on dynamic characteristics of two-dimensional sheath in Hall thrusters”, *Phys. Plasmas.* vol. 15, 104501, 2008.