Numerical Simulation for Magnetic Mirror Effect on Electron Movement in a Hall Thruster

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Abstract: The effect of magnetic mirror on near wall conductivity (NWC) is studied in the channel of a Hall thruster. Electron dynamics process in the plasma is described by test particle method that electrons are randomly emitted towards the inner wall from the centerline of the channel. Monte Carlo method is applied to solve the model. The numerical results show that more than half of the electrons are reflected back to central region by radial magnetic field force, which are unlikely to collide with the wall. The current density peak due to NWC increases linearly with the increase of magnetic mirror ratio. Especially when considering the anisotropy of electron velocity distribution in hall thrusters, the magnetic mirror effect would be more obvious. We also obtain the two dimensional distribution of electron current due to NWC. Finally, we deduce the analytical results of magnetic mirror effect which accords with the simulation results.

Nomenclature

$T_{e\perp}$	=	Electron temperature in the direction perpendicular to magnetic lines
$T_{e\parallel}$	=	Electron temperature in the direction parallel to magnetic lines
$v_{\perp}$	=	Electron velocity in the direction perpendicular to magnetic lines
$v_{\parallel}$	=	Electron velocity in the direction parallel to magnetic lines
T_{ew}	=	Wall temperature
ϕ	=	Electric potential
Ψ	=	Magnetic flux
E	=	Electric field
B	=	Magnetic field
N_0	=	Number of emitted electrons
n_e	=	Electron number density
j_e	=	Electron current density
μ_e	=	Electron mobility
α_{ECC}	=	Effective collision coefficient

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ν_{ew}	=	Frequency of electron-wall collisions
β	=	Magnetic mirror ratio
e	=	Magnetic mirror ratio
k	=	Boltzmann constant
m_e	=	Electron mass
c	=	Anisotropy coefficient
Γ_{ew}	=	Electron flux to the wall

I. Introduction

In hall thrusters, collisions between electrons and neutral atoms are not sufficient to explain electron transport across the magnetic field lines inside the channel, especially in the exhaust region where the magnetic field is maximal and the atom density is rather small due to intense ionization. Various theories have been proposed to explain this anomalous electron transport. A. I. Morozov speculated near wall conductivity (NWC) theory that when an electron collides with the wall, and thus the steady hall drift of the electron would be destroyed, the electron would obtain energy from electric field and transport across the *B* field lines[1]. The NWC theory successfully explains the anomalous electron transport. Experimental results also show that NWC plays a significant role in hall thrusters[2,3], especially in exhaust region. The previous studies show that NWC is influenced by many factors, such as erosion surface, magnetic field gradient in radial direction, plasma wall recombination, oscillating sheath etc[4-9].

Previous studies of NWC only considered the radial component of the magnetic field. However, magnetic field in hall thrusters has a concave shape specially designed to focus ion. This magnetic topology leads to an additional effect of increased magnetic field magnitude near the channel walls in comparison with the channel centerline, the so-called magnetic mirror effect[10]. Magnetic mirror effect forms a net force to prevent certain groups of electrons to reach the channel walls, and therefore deminishs electron flux to the channel walls. NWC current decreases accordingly with the reduction of electron flux to the channel walls. The magnetic field intensity near the channel wall is generally two times stronger than that near the centerline of the channel in exhaust region[11], which leads obvious magnetic mirror effect. In Ref.12, Sullivan used kinetic (PIC) simulations, and found that when there exists magnetic mirror effect, the electron flux to the walls is less than expected, and the sheaths are weaker than expected as well. Furthermore, he derived conditions for an electron outside the sheath to reach the walls. Keidar used 1D and 2D fluid model to simulate potential distribution in a Hall thruster, taking into account the magnetic mirror effect on the electron dynamics. The results show that magnetic field gradients in radial directions affect the presheath structure and potential distribution. The length of the radial presheath region decreases in the presence of a magnetic field gradient. The two-dimensional potential shape is affected by magnetic mirror ratio[13].

In this paper, we calculate the current density due to NWC in curved magnetic field. Since it is difficult to use the analytic method in Ref.1 due to the field nonuniformity, the electron dynamics process in the plasma is described in the test particle method in current theories that electrons are randomly emitted towards the inner wall from the centerline in the channel. Monte Carlo method is employed to numerically calculate the movement of electrons, thermally "emitted" from the channel wall. Then the electron mobility due to NWC can be calculated by statistically averaging the axial electron velocity. The numerical results show that magnetic mirror effect influences electron mobility greatly, which reduces with the increase of magnetic mirror ratio. Especially when considering the anisotropy of electron velocity distribution function (EVDF) in hall thrusters, i.e. the temperature of electrons perpendicularly to the magnetic field is greater than that of electrons parallel to the magnetic field, electron mobility due to NWC decreases further. Thus we conclude that the anisotropy can magnify magnetic mirror effect. Besides, we simulated the r-z distribution of electron mobility and electron density. Finally, we deduced the analytical results of magnetic mirror effect on NWC which accords with the simulated results.

The organization of the paper is as follows. In Sec. II, we briefly describe the model and basic equations used to calculate the current density and electron mobility due to NWC considering the magnetic mirror effect. In Sec. III, we numerically solve the model equations in different cases, and analyze the physical mechanism. The paper is then summarized in Sec. IV with conclusions.

II. THE MODEL

In hall thrusters, the magnitude of magnetic field increases from the anode to the exit plane, and the maximal value locates in exhaust region. Consider that the electron mean free path for all types of collisions ($\lambda \approx 100cm$) is much greater than the channel length (L=2–5 cm) in exhaust region where collisions between electrons and heavy particles can be neglected, collisions between electrons and wall would play a more important role in this region[14]. For these reasons, the model includes the only exhaust region. Experimental results in Ref. 15 showed that the length of exhaust region is about 10mm.

In our work, imposing that electrons are emitted from channel centerline to the inner wall, we adopt the leapfrog method of Boris[16] for discretizing the equations of motion. We define $T_{e\perp}$ and $T_{e\parallel}$ electron temperature in the direction perpendicular and parallel to the magnetic filed lines respectively, and assume the initial EVDF is Maxwellian and anisotropic. The EVDF in these two directions can be written as:

$$f(v_{\perp 0}) = n_e \frac{m_e}{2\pi k T_{e\perp 0}} \exp\left(-\frac{m_e v_{\perp 0}^2}{2kT_{e\perp 0}}\right) \tag{1}$$

$$f(v_{\parallel 0}) = n_e \frac{m_e}{2\pi k T_{e\parallel 0}} \exp\left(-\frac{m_e v_{\parallel 0}^2}{2kT_{e\parallel 0}}\right), \quad v_{\parallel 0} < 0 \tag{2}$$

In above equations, 0 denotes initial state. Electrons colliding with the inner wall are definitely accommodated and reemitted according to a half Maxwellian distribution of wall temperature T_{ew}. We use the polar form of the Box–Muller transformation to sample velocity.

The magnetic field is generated by a magnetic model using the Finite Element Method Magnetics (FEMM) software package[17]. Supposing the magnetic field is axisymmetric, we only consider the axial and radial components of magnetic field. Under the cold plasma assumption, equipotential contours tend to line up with the magnetic field lines. This is the case in conventional Hall thruster channels. The relation between the electric potential and the magnetic flux can take a form of $\phi = \alpha\Psi$ [18], where, ϕ and Ψ are electric potential and magnetic flux in the channel, respectively, and α is a constant.

Finally, the electron current density and mobility due to the NWC effect are calculated as follows:

$$j_e(r) = \frac{e n_e \sum_{i=1}^{N(r)} v_z(r)}{N_0} \tag{3}$$

$$\mu_e(r) = \frac{j_r}{n_e \cdot E_z(r)} = \frac{e \sum_{i=1}^{N(r)} v_z(r)}{N_0 \cdot E_z(r)} \tag{4}$$

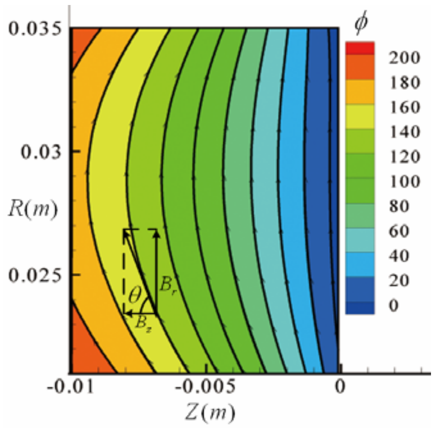


Figure 1. The simulated region, magnetic field topology and electric potential distribution in simulation

Where n_e is the electron density, N_0 is the amounts of emitted electrons, $N(r)$, $v_z(r)$, $E_z(r)$ are the amount, velocities and local electric intensity of electrons in different radial position. Parameters of simulations correspond to the experimental results of the Hall thruster operating at 5.4A, 300V in Ref.15. $n_e = 3.5\times10^{17}/m^3$.

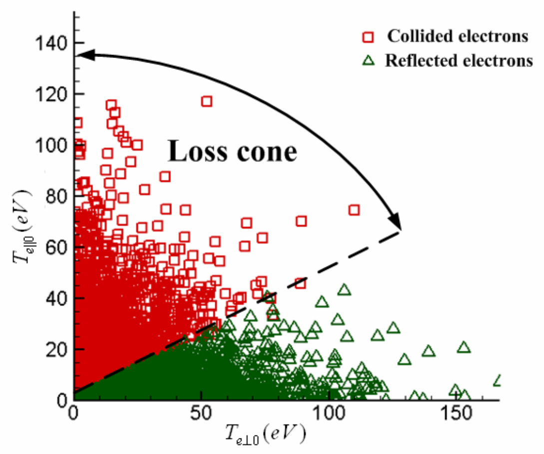
III. CALCULATION RESULT AND ANALYSIS

A. Influence of magnetic mirror ratio on NWC

The simulated region, magnetic field topology and electric potential distribution are shown in Fig. 1. The inner and outer radii, are $r1$=21mm and $r2$=35mm, respectively. The axial domain is 10mm long inside the thruster from exhaust plane. Potential drop in entire region is 200V.

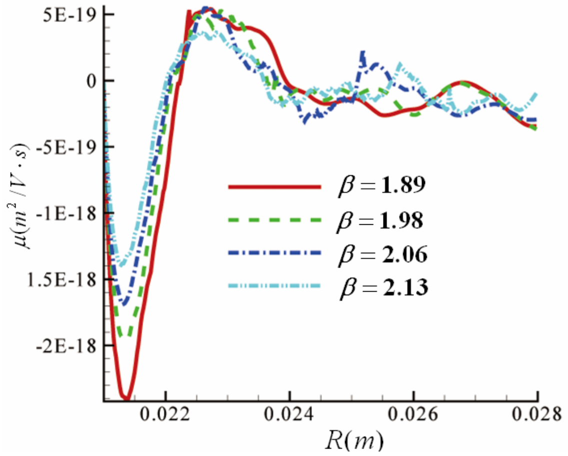
Each electron is emitted in the centerline of exhaust plane, and the emitted number is $N_0 = 1\times 10^5$.

In hall thrusters, the EVDF is anisotropic (Ref. 19,20,21). It can be explained that electrons in hall thrusters are heated in the direction perpendicular to magnetic lines and scatter due to elastic collisions in the direction parallel to magnetic lines, but the energy relaxation time for electrons are longer than the scattering time due to collisions. The ratio of the electron temperatures $T_{e\perp}/T_{e\|}$ is typically two. In our model, we use the simulated results in Ref. 20, $T_{e\|0} = 10eV$, $T_{e\perp 0} = 20eV$ respectively, and neglect the sheath as in Ref. 9. The electrons are reflected isotropic after colliding with the wall, with temperature T_{ew}=1eV.



(a)

Figure 2. The initial distributions of electrons collide with the wall and reflected by magnetic mirror



(b)

Figure 3. The electron mobility variations calculated with different magnetic mirror ratios

The simulation results reveal that the emitted electrons can be divided into two parts apparently due to magnetic mirror effect, (see Fig. 2). Most of the electrons are reflected by magnetic mirror. The condition of electrons colliding with the wall can be described by loss cone. Only those electrons in loss cone can escape from magnetic mirror and collide with the inner wall.

In a Hall thruster, the electron current density caused by the electron-wall collisions can be expressed as:

$$j_{e,\,NWC} \approx \frac{\nu_{ew}}{\omega_{ce}^2}\frac{n_e e^2}{m_e}E_z = \nu_{ew} m_e n_e \frac{E_z}{B^2} \tag{5}$$

Where, ν_{ew} is the frequency of electron-wall collisions. It is known that the $E\times B$ configuration in hall thrusters results in only an azimuthal drift of the electrons without movements in the axial direction unless other disturbances perturb the steady Hall drift. In our model, only if an electron collides with the inner wall, the hall drift is destroyed; the electron acquires energy from electric field and traverse magnetic lines towards anode. However, the electrons reflected by the magnetic mirror can not produce NWC. Denoting as ν_{ref} the electron-wall collision frequency in the absence of a magnetic mirror, and α_{ECC} the effective collision coefficient representing the ratio of the flux density of wall-colliding electrons to that of incident electrons, $\nu_{ew} = \alpha_{ECC}\cdot\nu_{ref}$. Therefore, NWC is proportional to α_{ECC}.

We define $\beta = \frac{B_w}{B_c}$ as magnetic mirror ratio. B_w and B_c are the magnetic field intensity of the inner wall and the center of exhaust plane respectively. The magnetic mirror ratio was changed by adjusting coil current while keeping the magnetic field intensity constant in the center of exhaust plane. The electron mobility due to NWC calculated with different β are shown in Fig. 3. We can find from the results that when increasing magnetic mirror ratio, the ratio of reflected electrons increases, the value of α_{ECC} and the electron mobility peaks decrease accordingly.

B. Influence of anisotropic EVDF on NWC

The quantity $\frac{mv_\perp^2}{B}$ is known as an adiabatic invariant. In the absence of electric field, electrons colliding with the wall must satisfy:

$$\frac{v_{\perp 0}^2}{v_{\perp 0}^2 + v_{\parallel 0}^2} < \frac{1}{\beta} \qquad (6)$$

Eq.（6）can be written as:

$$\frac{v_{\parallel 0}}{v_{\perp 0}} > \sqrt{\beta - 1} \qquad (7)$$

We can see from Eq.（7）and Fig. 2, only if the ratio $\frac{v_{\parallel 0}}{v_{\perp 0}}$ of an electron is greater than $\sqrt{\beta - 1}$, the electron in loss cone can collide with the wall. When we change the ratio of initial velocities of electrons, the ratio of electrons colliding with the wall would alter. We define a parameter $c = \frac{T_{e\perp 0}}{T_{e\parallel 0}}$ to denote the anisotropy of EVDF. Then $T_{e\perp 0}$ is varied, keeping $T_{e\parallel 0}$ constant to change parameter *c*. The electron currents with different *c* are shown in Fig. 5. With the decreasing of *c*, i.e. increase anisotropy of EVDF, the ratio of electrons colliding with the wall and the NWC current decreases nearly linearly.

When the discharge voltage increases in hall thruster, as the results shown in Ref. 19, anisotropy of EVDF increases furthermore. So we can deduce that magnetic mirror effect would become more significant, and NWC current will be even smaller in case of high discharge voltage.

On the other hand, when electrons move towards the wall, energy in the direction parallel to magnetic field will be partially converted to the direction perpendicular to magnetic field, so magnetic mirror effect can aggravate anisotropy of EVDF.

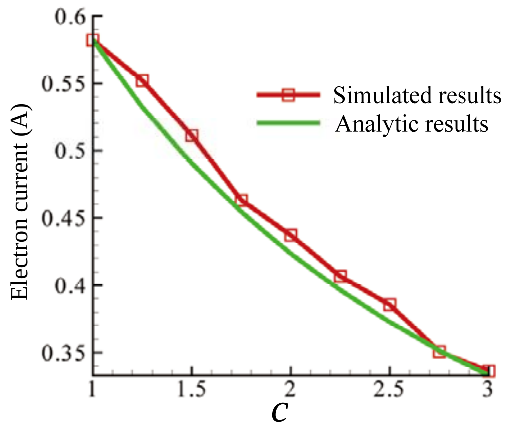


Figure 4. The electron currents calculated with different

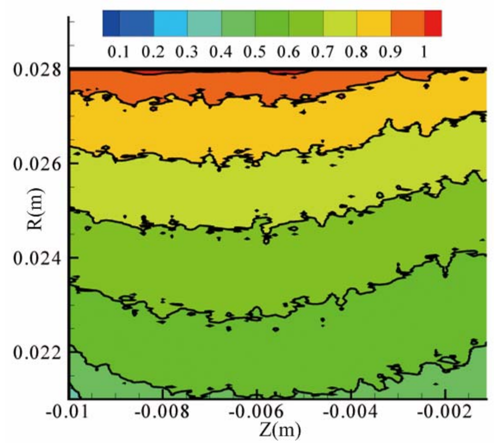
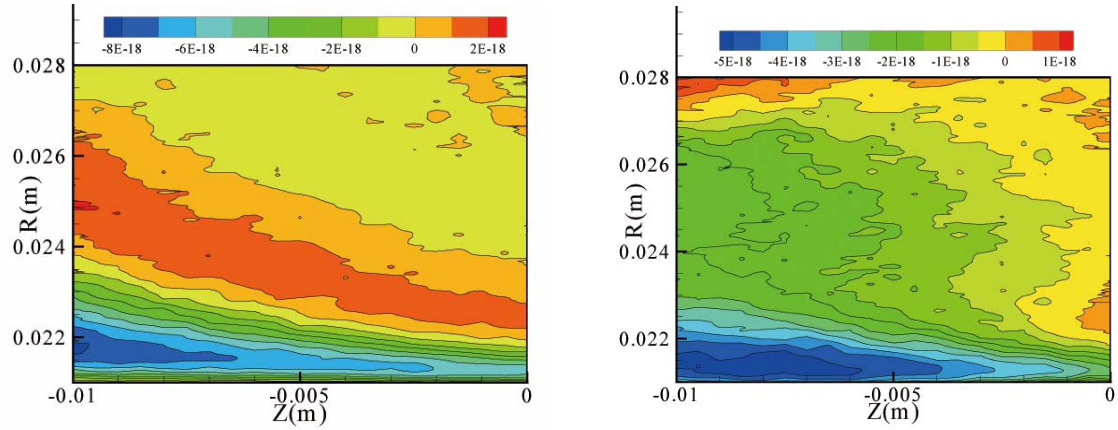


Figure 5. Electron density distribution when magnetic lines are curved (normalized with electron density on the centerline)

C. 2D distribution of NWC current

Previous studies of NWC in Ref. 4-9 only consider 1D NWC current distribution along radial direction. However, NWC current changes along axis accordingly, as the magnetic mirror ratio and magnetic field intensity are varied along axial direction. We analyze the space profile of electron number density and electron mobility due to NWC, both in axial and radial directions. In our 2D model, we initialize a uniform distribution of electrons along channel centerline. Every electron moves towards the inner wall as we did in the 1d simulation of NWC above, and we also assume the initial EVDF is Maxwellian, $T_{e\perp 0} = 20eV$, $T_{e\|0} = 10eV$; and calculate electron mobility using Eq.（4）. Electron densities on the centerline equal to: $n_e = 3.5\times10^{17}/m^3$. Electrons are reflected isotropic after colliding with the wall, with temperature T_{ew}=1eV. The total amount of simulated electrons is 1×10^6.



(a) **(b)**

Figure 6. Profiles of electron mobility (a) with only radial component of magnetic field and (b) magnetic lines is curved

Fig. 5 shows the 2D electron density distribution in case of curved magnetic lines. We can find that when electrons move from the channel centerline to inner wall, parts of electrons are reflected by magnetic mirror forces, and electron density decreases gradually from the channel centerline to inner wall. When there exists only radial component of magnetic field, magnetic mirror effect vanishes, and electron number density equal everywhere in the channel.

The electron mobility distribution due to NWC in the channel is shown in Fig. 6. We can observe that the peak and width of electron mobility increase from thruster exhaust plane towards anode direction, no matter whether the magnetic lines are curved or not. The reason is that either the peak or the width of electron mobility due to NWC is proportional to the inverse of magnetic field intensity. While magnetic field intensity decreases from exhaust plane to anode direction, the peak and width of electron mobility increases accordingly. But from Fig. 6 (b) we can find that if there is magnetic mirror effect caused by curved magnetic lines, the peak of electron mobility is smaller in every axial position compared with the result of only radial component of magnetic field. We conclude that, when considering the magnetic mirror effect, NWC is less important than estimation before. The reduction of mobility in exhaust region due to the magnetic mirror effect indicates the increasing of potential drop in this region, which is profitable for accelerating ion.

D. Analysis of physical mechanism

Now let us discuss the physical mechanism of the influence of magnetic mirror effect and anisotropy of EVDF on NWC. If an electron is reflected by magnetic mirror, the steady hall drift is not destroyed. The reflected electron can not produce NWC current and therefore NWC current is proportional to electron flux to the wall. First, it is necessary to analyze magnetic mirror effect and anisotropy of EVDF on electron flux to the walls. In Ref. 12, Sullivan deduced the relation of magnetic mirror ratio and electron flux, but he did not consider anisotropy of EVDF in his model. We discuss the physical mechanism based on the model of Sullivan, considering anisotropic EVDF in hall thrusters furthermore.

For conservation of magnetic moment, the total energy can be integrated in the form:

$$\frac{1}{2}m_e v_{\|}^2 + \frac{1}{2}m_e v_{\perp 0}^2 \frac{B_w}{B_c} - e\phi = \frac{1}{2}m_e v_{\|0}^2 + \frac{1}{2}m_e v_{\perp 0}^2 - e\phi_0 \quad (8)$$

Since the axial component of magnetic field is small in exhaust region, we can assume that the magnetic lines are perpendicular to the walls approximately. ϕ is the electric potential, B is magnetic field intensity. 0 represents an initial point. Only the electrons in loss cone can collide with the wall due to the magnetic mirror effect, and those initial velocities of electrons colliding with the walls must satisfy:

$$v_{r0}^2 > \left(\frac{B_w}{B_c}-1\right)v_{\perp 0}^2 + \frac{2e\Delta\phi}{m_e} \quad (9)$$

$\Delta\phi = \phi_0 - \phi_w$, denotes the potential drop between emitted point and the walls. The flux of electrons arriving the wall is:

$$\Gamma_e = n_e\left(\frac{m_e}{2\pi k}\right)^{\frac{3}{2}} \frac{1}{T_{e\perp 0}(T_{er0})^{\frac{1}{2}}} \int_{v_r=\sqrt{\frac{2e\Delta\phi}{m_e}}}^{\infty} \exp^{-\frac{m_e v_r^2}{2kT_{er0}}} v_r dv_r \int_{v_{\perp 0}=0}^{v_{\perp 0}=\sqrt{(v_r^2-\frac{2e\Delta\phi}{m_e})/(\frac{B_w}{B_c}-1)}} \exp^{-\frac{m_e v_\perp^2}{2kT_{e\perp 0}}} 2\pi v_\perp dv_\perp \quad (10)$$

The inner integral yields: $\frac{2\pi kT_{e\perp 0}}{m_e}\left(1-e^{-(\frac{m_e v_r^2}{2kT_{e\perp 0}}-\frac{e\Delta\phi}{kT_{e\perp 0}})/(\frac{B_w}{B_c}-1)}\right)$.

So that with the substitution $x = \frac{m_e v_r^2}{2kT_{e\perp 0}}$, Eq.（10） reduces to

$$\Gamma_e = n_e c\sqrt{\frac{kT_{er0}}{2\pi m_e}} \int_{\frac{e\Delta\phi}{kT_{e\perp 0}}}^{\infty} \left[1-e^{-(x-\frac{e\Delta\phi}{kT_{e\perp 0}})/(\frac{B_w}{B_0}-1)}\right] e^{-xc} dx \quad (11)$$

Let $a = \frac{e\Delta\phi}{kT_{e\perp}}, \bar{c}_e = \sqrt{\frac{8}{\pi}\frac{kT_{er0}}{m_e}}$, we can get:

$$\begin{aligned}\Gamma_e &= \frac{n_e\bar{c}_e c}{4}\int_a^{\infty}(e^{-cx} - e^{\frac{a}{\beta-1}} e^{-\frac{1+c\beta-c}{\beta-1}x})dx \\ &= \frac{n_e\bar{c}_e}{4}(e^{-ac} - \frac{c(\beta-1)}{1+c(\beta-1)}e^{-ac}) \\ &= \frac{n_e\bar{c}_e}{4}\frac{1}{1+c(\beta-1)}e^{-ac}\end{aligned} \quad (12)$$

When there is no sheath, electron flux to the wall is

$$\Gamma_e = \frac{n_e\bar{c}_e}{4}\frac{1}{1+c(\beta-1)} \quad (13)$$

According to Eq. （13） we can find both magnetic mirror effect and anisotropic EVDF influence electron flux to the wall. Regardless of EVDF and magnetic mirror effect, electron flux is $\Gamma_e = \frac{n_e\bar{c}_e}{4}$. While after considering these two effects, the effective collision coefficient α_{ECC} reduces by the factor of order $\frac{1}{1+c(\beta-1)}$. According to Eq.（5）, the electron current due to NWC is proportional to α_{ECC}. NWC current will also reduce $\frac{1}{1+c(\beta-1)}$ times. So the value of NWC current can be significantly influenced by magnetic mirror effect. The NWC current calculated using these formulas agree well with the values obtained in test particle simulations (Fig. 4).

IV. CONCLUTION

The effect of the magnetic mirror is described in this paper. Numerical results show that the electron mobility due to NWC decreases greatly due to magnetic mirror effect; the greater the magnetic mirror ratio, the smaller the NWC current. The basic physical mechanism of magnetic mirror effect on NWC is that when electrons move toward the walls, partial of electrons are reflected by magnetic mirror forces, diminishing the electron flux to the wall as well as NWC current consequently. Taking into account that anisotropy of EVDF increases with the increment of discharge potential in a hall thruster, electron mobility due to NWC reduces; the magnetic mirror effect would be more evident. Besides, we show the two dimensional distribution of NWC current and electron density. Since the magnetic field intensity and magnetic mirror ratio decreases from exhaust region to anode direction, the peak and the width of electron mobility increase towards anode.

Nevertheless, the effect of the sheath on NWC has been neglected in our model. It should be noted that the existences of the sheath will deminish electron flux to the walls further. The model used in this paper and previous work is equivalent to a single test particle calculation. The Monte Carlo method is actually an ensemble average of a randomly emitted electron motion in fixed external electric and magnetic fields. However, such electron motions might at least perturb the electric field distribution. A self-consistent field treatment should be applied taking into account the interaction between plasma and the field. We will consider these effects in future work. However, we have to point out that the magnetic mirror effect discussed in this paper has already contributed to the designs of Hall thrusters.

At last, we derived simplified analytical formulas between magnetic mirror effect and electron flux to the wall and NWC, $\Gamma_e = \frac{n_e \bar{c}_e}{4} \frac{1}{1+c(\beta-1)}$. Since the magnetic mirror effect diminishs the electron flux to the wall, NWC current will be $\frac{1}{1+c(\beta-1)}$ times smaller considering the magnetic mirror effect.

To summarize: In order to improve performance and raise the hall thruster discharge potential, it deserves further attention to study how magnetic mirror ratio would affect the performance of Hall thrusters.

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