

Ion Current in Hall Thrusters

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In order to match observed thrust and discharge current in Hall thrusters, computer simulations have typically assumed anomalous electron transport mechanisms, such as Bohm diffusion, to enhance electron mobility across magnetic field lines. Without enhanced electron transport, the simulations predict much lower discharge current than observed, and too much of the potential drop is downstream of the channel exit. Rather than search for mechanisms to increase the electron scattering frequency, we seek to identify mechanisms that would increase the fraction of the current carried by ions, thus reducing the required electron current. We describe two mechanisms that enhance the current carried by ions. The first increases the ion current carried in the channel by simply including the effects of doubly-charged ions on the plasma response. The importance of using accurate ionization cross sections and the need to include doubly-charged ions even for 300 V discharge voltages is discussed. The second is a process we term “ion reflux.” In this process, current is carried by ions generated downstream of the channel exit. A portion of these ions impact the center insulator and are neutralized by cathode electrons. A large fraction of the resultant neutral atoms are re-ionized as they pass through the main exhaust beam and these newly born ions then carry additional current through the plume. Both of these mechanisms tend to reduce the need to invoke anomalous electron transport mechanisms. These are just two specific mechanisms that enable ions to carry more of the cross-field current. There may be more mechanisms revealed as this general concept is further pursued.

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I. Introduction

HALL thrusters are rapidly becoming the most widely accepted form of electric propulsion on communications satellites. Since the 1970s, more than 50 satellites with over 200 Hall thrusters have been flown [1]. However, there are still questions about the basic physical mechanisms that determine the electrical characteristics and performance of these thrusters. Computer simulations, such as HPHall-2 [2-4], have been developed that model Hall thruster plasma and erosion processes. These codes assume that inside the channel about three quarters of the current is carried by beam ions and about one quarter is counter streaming electrons from the hollow cathode (Figure 1). If the simulations use only classical electron scattering mechanisms, they predict much lower circuit currents and performance than measured. Simulations can be made to agree more closely with experimental data by invoking anomalous transport mechanisms, such as “Bohm diffusion” [5], to enhance electron transport across magnetic field lines.

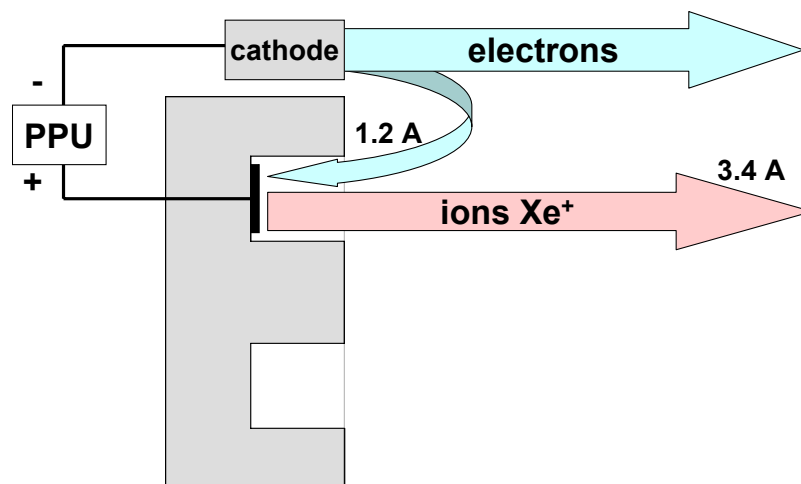


Figure 1. Current flow in a typical Hall thruster simulation. About a quarter of the current in the channel is by electrons that originated in the hollow cathode.

In the past few years, research on the electron transport mechanisms in the channel has focused on the interactions between the plasma and the channel walls [6]. Several advances have been made, in particular the plasma has been forced to satisfy the Bohm sheath condition [7], and accurate formulations have been developed to model the transport due to secondary electron emission at the channel wall [8]. Other researchers have shown that the channel width is too short to develop high amplitude scattering due to changes in the energy distribution caused by secondary electrons accelerated by the wall plasma sheath [9]. Another group has shown that the magnitude of the “anomalous” scattering required in the channel is much less than that required downstream of the exit plane to transport electrons from the hollow cathode into the channel. Recent results [10] have shown that inside the channel, only a small fraction of “Bohm diffusion” is required. However, outside the channel enhanced electron transport of the magnitude of Bohm diffusion is needed to obtain plasma potentials and densities that resemble the experimental measurements.

The low electron mobility calculated in Hall thrusters by the codes is not unexpected. The magnetic fields in Hall thrusters are designed to reduce electron mobility so much that electrons move up the channel slower than the ions that are accelerated down the channel. As discussed above, most of the current in the channel is carried by the ions. The ions are massive enough that their trajectories are not modified significantly by the magnetic field, but the electrons are trapped on field lines until undergoing a scattering event. Rather than search for mechanisms to increase the electron scattering frequency, the objective of this paper is to identify mechanisms that would increase the fraction of the current carried by ions in the simulations, and thus reduce the required electron current. Increasing the ion current has great leverage, since, even in the present simulations, ions carry three times the channel current of electrons. A one percent increase in ion current would reduce the electron current by 3 percent.

Two mechanisms have been identified that increase the calculated ion current. The first increases the ion current carried in the channel by simply including the effects of doubly-charged ions. The second is a process we term “ion reflux”. In this process, current is carried by ions generated downstream of the channel exit. A portion of these ions impact the center insulator and are neutralized by cathode electrons. A large fraction of the resultant neutral atoms are re-ionized as they pass through the main exhaust beam and these newly born ions then carry additional current through the plume. This new concept of current flow in Hall thrusters is shown in Figure 2.

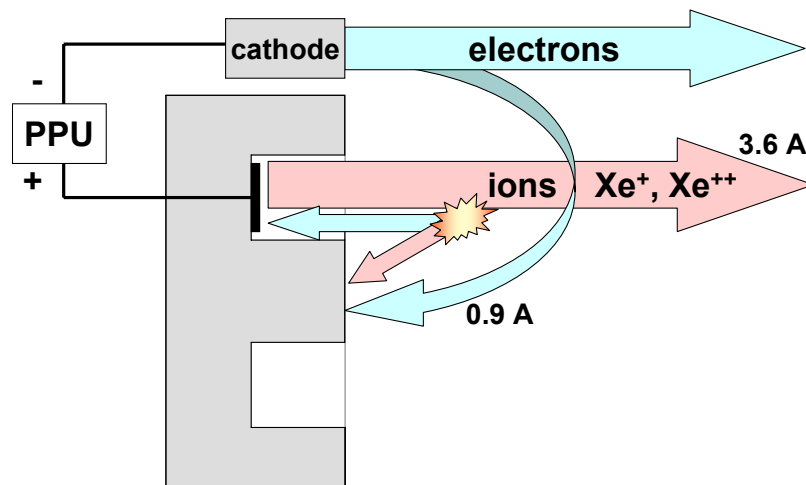


Figure 2. New concept of current flow in Hall thrusters with a greater fraction of the cross field current carried by ions, including “ion reflux” near the thruster center line.

The first mechanism has a simple basis. HPHall uses an ad-hoc electron impact cross section for ionization from Xe^+ to Xe^{++} that is much smaller than published cross-sections from experiments. Calculations for the SPT-100 thruster are presented below that use the published cross-sections. These calculations show that, even with the decrease of the effective Bohm coefficient to 0.028 in the channel region, the code shows an increase in the ion current by 8% and a reduction in the channel electron current by 25% for the same fixed total current condition. Including triply-charged xenon would further reduce the channel electron current and the need for enhanced electron scattering.

The second mechanism is more difficult to implement in present simulations. Presented below are “back of the envelope”, non-self consistent calculations that demonstrate the viability of the “ion reflux” mechanism in carrying current across thruster magnetic field lines. These are just two specific mechanisms that enable ions to carry more of the cross-field current. There may be more mechanisms revealed as this general concept is further pursued.

II. Doubly-Charged Ions

For discharge voltages of 300 V or less, it is common practice in the literature to neglect the effects of multiply-charged ion species on the plasma response. This approximation is usually justified based on experimental data showing that the species density fraction of doubly-charged ions is about 6-11% at this voltage. However, it has been observed that the fraction of multiply-charged ion species increases with discharge voltage [11].

Previous work at JPL using HPHall-2 ran the simulation with singly-charged ions for SPT-100 geometries [10,12,13]. We have now activated the doubly-charged ion species option in HPHall-2 since our plasma and erosion modeling of the BPT-4000 requires discharge voltages up to 400 V, and there is a need to model other high voltage Hall thrusters.

However, when first activating the doubly-charged ion model it was noticed that the ionization rates predicted by the code was very low. It turns out that, in the absence of finding experimental data in the literature, Fife [2] made an “educated guess” in the original version of HPHall for the ionization cross-section of singly- to doubly-charged xenon ($\text{Xe}^+ \rightarrow \text{Xe}^{2+}$) that underestimated the ionization rate compared with the experimental data of Bell, et al [14]. Figure 3 compares the ionization rate parameter from Fife with that of Bell, et al. For electron temperatures of 10-30 eV, Fife underestimates the ionization rate parameter by a factor of three to five. This change significantly alters the predicted ion current in the channel. By implementing the published double ionization rates, the calculated SPT-100 ion current inside the channel increases by approximately 8% (with respect to a model considering singly-charged ions only), decreasing the channel electron current needed to match the experimental discharge current by 25% (Figure 4). It seems then that neglecting doubly-charged ions, even for discharge voltages of only 300 V, can lead to non-negligible errors in the calculated ion and electron currents.

The calculated double ion number fraction of 7% is consistent with other experimental measurements and reproduces the observations that the double ion plume is more divergent than the single ion plume (Figure 5) [11,15-18]. The net effect of implementing accurate higher ionization rates ($\text{Xe}^+ \rightarrow \text{Xe}^{2+}$, and in the future, $\text{Xe}^{2+} \rightarrow \text{Xe}^{3+}$), is to reduce or eliminate the need for anomalous electron transport within the channel.

The electron scattering frequencies in the channel are shown in Figure 6. Ref. [4] describes the details of the electron scattering frequency model. Note that everywhere the total classical scattering frequency, which is the sum of the electron-neutral, electron-ion, and electron-wall frequencies, exceeds the 2.8% of Bohm diffusion that the simulation required to match the total circuit current.

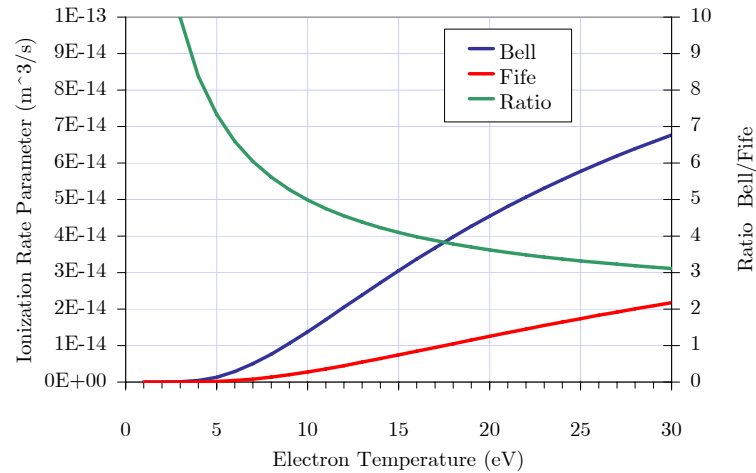


Figure 3. Xe^+ ionization rate parameter based on measured cross-sections from Bell, et al [14] compared with the estimates made by Fife in the original version of HPHall [2].

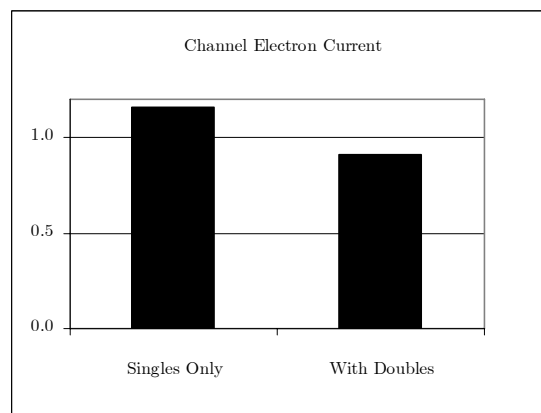


Figure 4. Electron current in the channel is reduced by 25% by using published ionization cross sections [14].

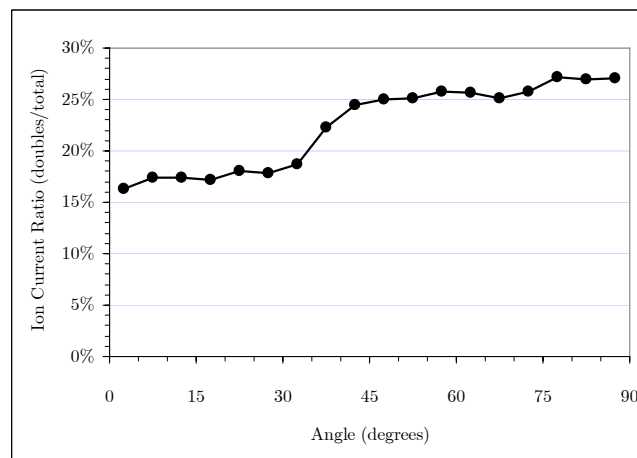


Figure 5. Calculated ratio of double ion current to total ion current increases away from the centerline. The plume averaged double ion number fraction is 7%.

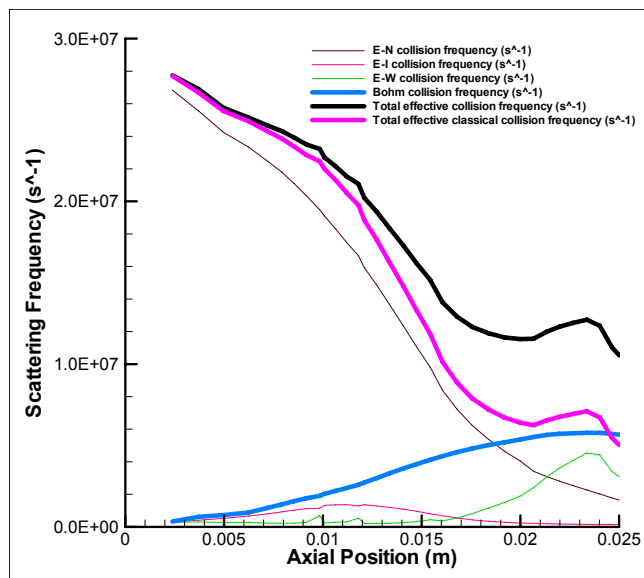


Figure 6. Electron scattering frequency in the channel. The “Bohm” frequency is only 2.8% of standard Bohm diffusion.

III. Ion Reflux

Downstream of the thruster exit plane, we propose that ions play a major role in the current transport between the hollow cathode and the channel. About half the low energy ions generated downstream of the exit plane drift toward the thruster centerline. These ions eventually impact the front of the thruster and are neutralized. Calculations presented below show that the resultant neutral has a high probability of being ionized before passing through the main beam, and will once again drift toward the centerline to be neutralized on the front of the thruster. This process, which we have termed “ion reflux,” results in electrons born in the beam by ionization, and the ions carrying the current across field lines and out of the beam. The hollow cathode provides electrons to maintain charge balance on the thruster surface, as well as the electrons to current neutralize the ion beam. The ion transport is similar to the cathode plasmas in low pressure gas discharges [19].

To provide a quantitative estimate of the ion reflux current, calculations were performed on the probability that a neutral xenon atom would be ionized after leaving the insulator surface at the center of the thruster. Also calculated was the probability that the gas atom would be ionized before reaching the ion beam density peak encountered radially in the plume from the axis. The assumption is that since the potentials along the magnetic field lines follow the density, ions generated at radii smaller than the peak density would be accelerated back into the center by the potential gradient. These particles would eventually hit the insulator surface and recombine. Each ionization event inside the beam then generates an electron that contributes to the channel electron current.

Assume that half of the neutral gas escaping the channel has an inward radial velocity component, and half is directed outward. If the channel ionization fraction is η , the ion current generated in the first transit equals the neutral gas flux times the ionization probability. Ions generated inside the radius of the

density peak will eventually impact the center insulator. The resultant neutral gas is assumed to leave the surface with an isotropic cosine distribution. Those atoms that were ionized in the first pass of neutrals from the center region then make up the second transit current. The fraction of these atoms ionized inside the density peak, that, after being neutralized, impact the center insulator and are ionized on their way out, make up the third transit current. The resultant series can be summed to give the total “ion reflux” current.

To calculate the probability of a neutral being ionized, the beam plasma density was obtained from an EPIC (Electric Propulsion Interactions Code) [20] calculation of the SPT-100 (Figure 7). For simplicity, it was assumed that the electron temperature in the plasma was uniform, and that all neutral xenon particles were emitted from the centerline of the downstream surface of the thruster.

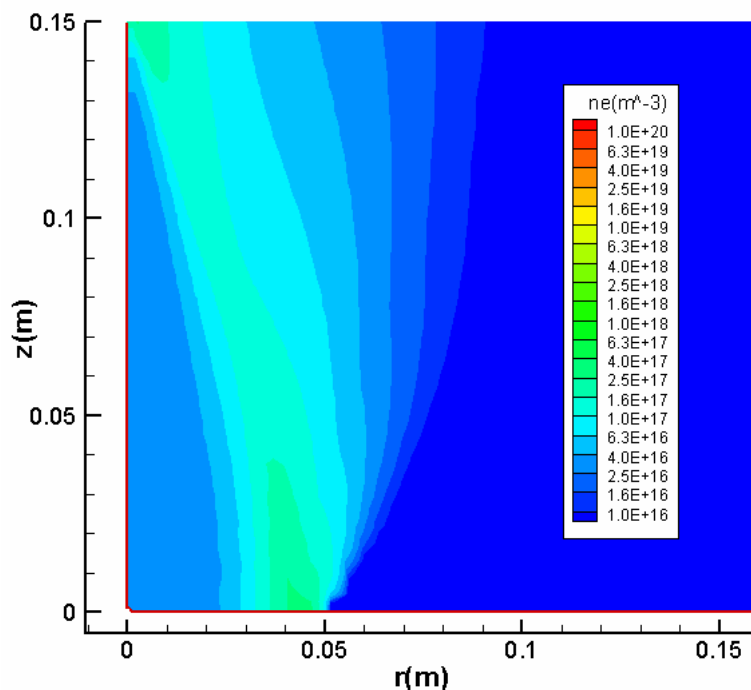


Figure 7. SPT-100 plume density as calculated by the EPIC code used to estimate current due to ion reflux [20].

For each emission angle, both the total plasma column density, N^∞ , and the column density to the plasma peak, N^p , are calculated from

$$\begin{aligned} N^\infty &\equiv \int_0^\infty n_e(x) dx \\ N^p &\equiv \int_0^{peak} n_e(x) dx \end{aligned} \quad (1)$$

The velocity of the neutral atom is assumed to be the thermal velocity associated with a surface temperature of 300° C given by

$$v = \sqrt{\frac{8 k T_e}{\pi m_e}} = 300 \text{ m/s} . \quad (2)$$

The probability of a neutral being ionized is expressed in terms of the plasma column density along its path, and is given by

$$\begin{aligned}
\frac{dn}{dt} &= -\dot{n} = -n n_e(x) \alpha(T_e) \\
\frac{dn}{dt} &= \frac{dn}{dx} \frac{dx}{dt} = v \frac{dn}{dx} \\
\frac{1}{n} \frac{dn}{dx} &= - \frac{n_e(x) \alpha(T_e)}{v} \\
\ln\left(\frac{n}{n_0}\right) &= - \frac{\alpha(T_e)}{v} \int_0^\infty n_e(x) dx. \\
N &\equiv \int_0^\infty n_e(x) dx \\
P_{ion} &\equiv 1 - \frac{n}{n_0} \\
P_{ion} &= 1 - \exp\left(-\frac{N \alpha(T_e)}{v}\right)
\end{aligned} \tag{3}$$

The ionization probabilities are averaged over the cosine of the angle with respect to the normal given by

$$\begin{aligned}
P_{ion}^\infty &= \left\langle 1 - \exp\left(-\frac{N^\infty \alpha(T_e)}{v}\right) \right\rangle_{\cos\theta} \\
P_{ion}^{peak} &= \left\langle 1 - \exp\left(-\frac{N^{peak} \alpha(T_e)}{v}\right) \right\rangle_{\cos\theta}
\end{aligned} \tag{4}$$

The loss rate of neutrals is proportional to the electron density times the temperature dependent ionization rate coefficient, α , divided by the neutral atom velocity. The ion current is estimated by assuming all the neutrals leave the channel at the peak in the plasma density. Half leave the channel with positive radial velocities. The probability that these neutrals are ionized is approximately P_{ion}^{peak} . The probability that the other half of the neutrals with negative radial velocities will be ionized before they reach the next density peak is approximately P_{ion}^∞ . These ions are transported to the center insulator by the local fields, where they recombine. The resultant neutrals have a probability of P_{ion}^{peak} of being ionized again before reaching the ion beam density peak. Those that are ionized before the peak are again transported back to the center insulator, where they are again re-emitted as a neutral. When the neutral makes it past the beam density peak, it still has a finite probability, $P_{ion}^\infty - P_{ion}^{peak}$, of being ionized, but will no longer be focused back to the center insulator. The total ion current generated by the neutral gas coming from the thruster is then given by

$$\begin{aligned}
I_i &= e\dot{n}_i \\
&= (1-\eta) \frac{e\dot{m}}{m_{Xe}} \left(\frac{1}{2} P_{ion}^{peak} + \frac{1}{2} P_{ion}^{\infty} (1 + P_{ion}^{peak} (1 + P_{ion}^{peak} (1 + \dots))) + \frac{1}{2} (P_{ion}^{\infty} - P_{ion}^{peak}) \right) \\
&= (1-\eta) \frac{e\dot{m}}{m_{Xe}} \left(\frac{1}{2} P_{ion}^{peak} + \frac{1}{2} P_{ion}^{\infty} \frac{1}{1 - P_{ion}^{peak}} + \frac{1}{2} (P_{ion}^{\infty} - P_{ion}^{peak}) \right) \\
I_i &= (1-\eta) \frac{e\dot{m}}{m_{Xe}} \frac{1}{2} P_{ion}^{\infty} \left(1 + \frac{1}{1 - P_{ion}^{peak}} \right)
\end{aligned} \tag{5}$$

Values from the SPT-100 calculation presented in the previous section were used to estimate the electron current generated in the channel by ion reflux. The results of these calculations were

$$\begin{aligned}
\eta &= 0.9 \\
\frac{e\dot{m}}{m_{Xe}} &= 3.65 \text{ A} \\
P_{ion}^{\infty} &= .97 \\
P_{ion}^{peak} &= 0.81 \\
I_i &= (1-\eta) \frac{e\dot{m}}{m_{Xe}} \frac{1}{2} P_{ion}^{\infty} \left(1 + \frac{1}{1 - P_{ion}^{peak}} \right) \\
I_i &= 1.14 \text{ A}
\end{aligned} \tag{6}$$

This estimate suggests that the ion reflux mechanism could supply 1.14 A of electrons into the beam, a current that exceeds the 0.9 A of electrons in the HPHall-2 calculation. While this is just an estimate, and there are certainly some electrons that go directly from the hollow cathode into the channel, this simple calculation shows that ion transport downstream of the channel exit may play an important role in transporting electrons across field lines and completing the circuit.

Conclusion

Two mechanisms, ion current from multiply-charged ions in the thruster channel and “ion reflux” downstream in the near-field plume, have been presented that increase the fraction of current carried across field lines by ions and reduce the need to invoke anomalous electron transport in Hall thruster simulations. Since the electron current in the channel is less than a third of the ion current, small percentage increases in the current carried by ions leads to large fractional decreases in the electron current. With respect to multiply-charged ions, the major contribution in this paper is to point out the importance of using accurate ionization cross sections and the need to include multiply-charged ions even for 300 V discharge voltages.

The importance of the second mechanism, “ion reflux”, is supported by numerical estimates, and remains to be validated with 2-D, self-consistent calculations and laboratory measurements. The estimates presented, however, show that ions play a significant role in closing the circuit between the hollow cathode and the thruster channel. Ions play a similar role near the cathode plasma in low pressure gas discharges, so the presence of this mechanism in Hall thrusters should not be considered unreasonable.

Since the ions are not magnetized, unlike the electrons, they move easily between the channel and the center insulating surface providing current transport that reduces the need for anomalous electron transport mechanisms to be invoked.

The calculations presented show the importance of using accurate models of the classical processes in Hall thruster simulations. The need for accurate classical models extends well beyond ionization cross-sections, and also includes, for example, wall sheath interactions and neutral atom transport. It is anticipated that improved models will eventually enable Hall thruster simulations that are truly predictive, and that fully describe the thruster physics.

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