Multiscale Modeling of Hall Thrusters

Lubos Brieda, Shaunak Pai, and Michael Keidar
Department of Mechanical and Aerospace Engineering, The George Washington University

Understanding Hall Thrusters

Hall thruster is one of the most fuel-efficient devices for keeping satellites in orbit. Instead of burning propellant to produce force, these devices generates thrust by accelerating ionized gas (plasma) using **electromagnetic fields**.

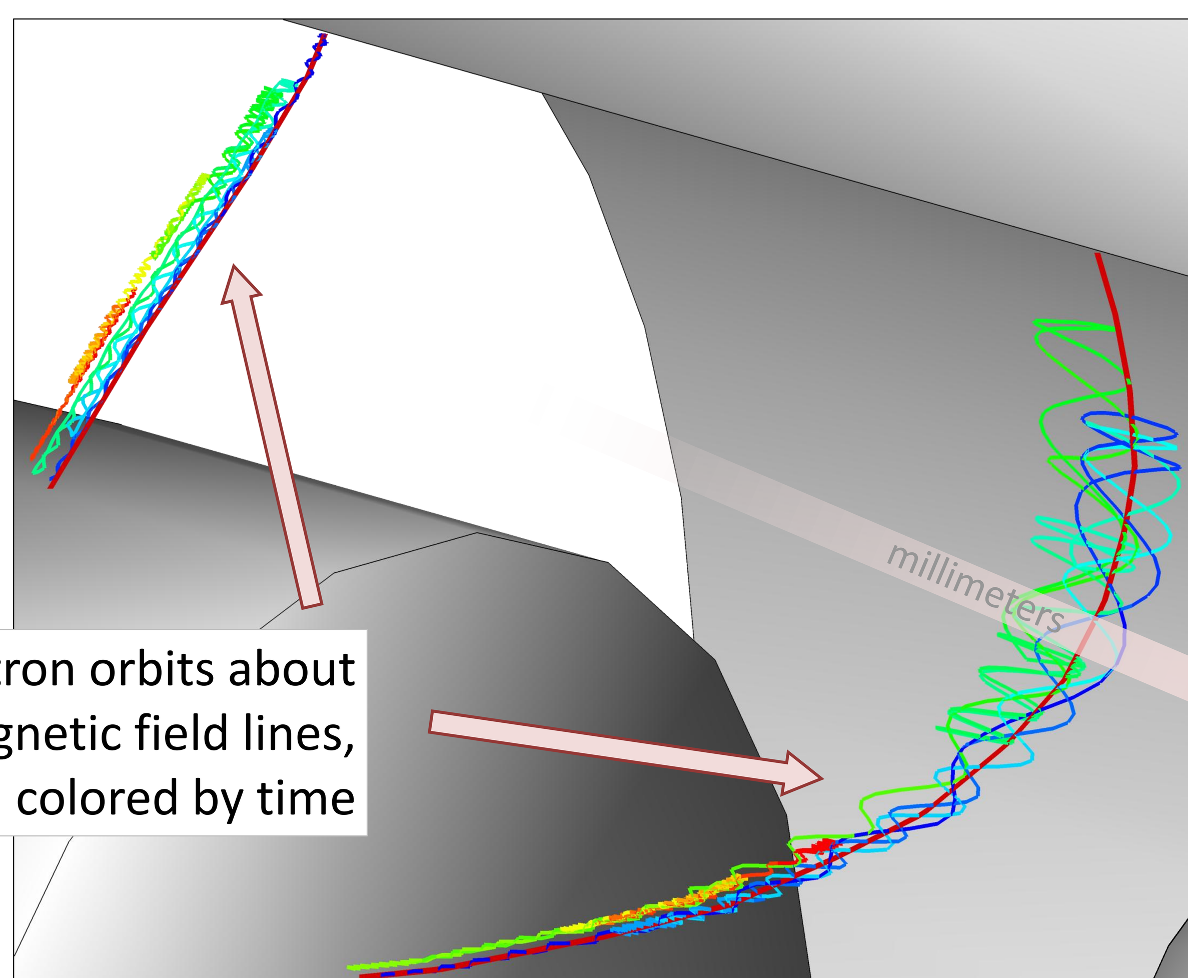
Hall thrusters have been flown since early 70s. Yet despite this flight heritage, we still lack complete understanding of their operation. Primary unresolved issue is **anomalous diffusion** of electrons across magnetic field lines. Hall thrusters work by trapping electrons in spiral orbits around magnetic field lines. Classical theory tells us that electrons move across field lines only if they undergo **collisions**. However, from experiments we see that transport is in reality much greater than predicted by theory. This unexplained mobility results in lower-than-predicted efficiency as well as difficulties in numerically modeling the discharge inside these devices.

Multiscale Modeling

Accurate model of the thruster discharge is needed to perform **plume modeling** to determine if the thruster poses risk to spacecraft instruments. The problem with current Hall thruster codes is that they do not resolve electron diffusion self-consistently. Several processes, such as turbulence and wall emission, have been identified as possibly contributing to transport. These occur on length scales too small to resolve computationally on domains size of spacecraft or even the thruster. Hence, at MpNL we are investigating Hall thrusters via multiscale modeling. Plasma dynamics is resolved separately at **electron**, **thruster**, and **spacecraft** spatial scales, and the three solutions are iteratively coupled through shared parameters.

Beyond Basic Physics

Anomalous diffusion is not limited to Hall thrusters. This process is observed across a wide range of **disciplines** in all devices utilizing magnetic confinement (such as fusion reactors). By simulating diffusion at the atomic scale, we hope to shed new light onto this elementary physical process. In addition, our research is expected to produce a fully predictive tool for the spacecraft community, which will provide mission and thruster designers with the ability to study effect of varying design parameters without requiring expensive laboratory testing or fabrication of multiple lab models.



Electron orbits about magnetic field lines, colored by time

1. At the **electron scale**, we resolve motion of electrons around magnetic field line by directly simulating electrons as particles. Particle position is advanced by integrating velocity (1). Collisions and emissions of secondary electrons from channel walls are also taken into account. Mobility (2) is computed from the average normal component of velocity. By simulating series of magnetic field lines, we obtain axial variation in mobility.

$$m\frac{d\vec{v}_e}{dt} = -e\left(\vec{E}+\vec{v}_e\times\vec{B}\right) \quad (1) \qquad \mu_e = \bar{u}/E_{\hat{n}} \quad (2)$$

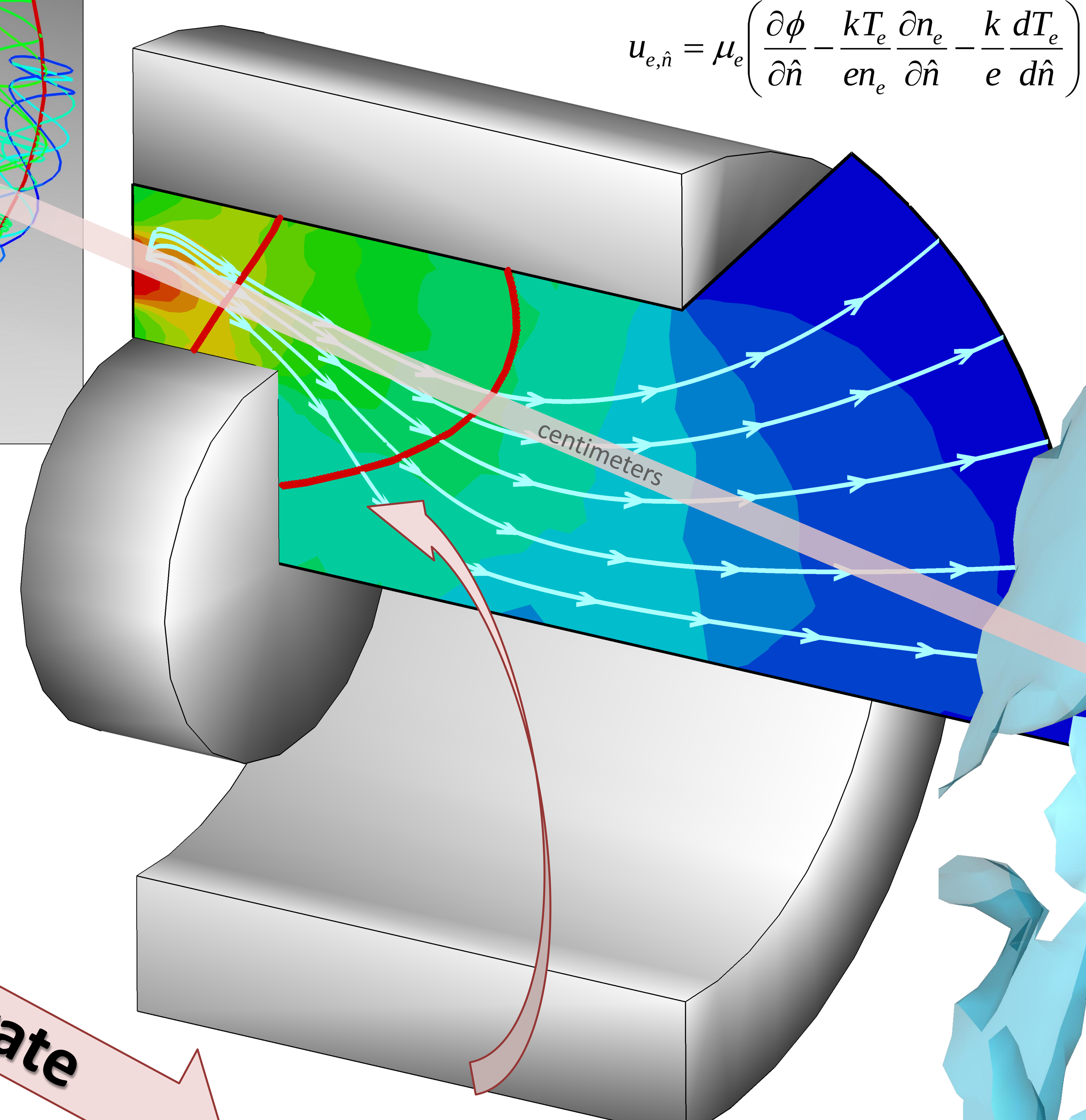
2. Plasma discharge at the **thruster scale** is modeled using radial code developed previously at MIT by Fife. This code directly simulates ions and neutrals, but electron density is obtained from the momentum equation (3) with axial electron velocity computed by Ohm's Law (4). We have modified the code to support axial variation in mobility computed in **Step 1**. Steps 1 and 2 are coupled, since transport depends on neutral densities as well as potential gradient, both of which are computed at the thruster scale based on solution from Step 1. These steps iterate until convergence is achieved.

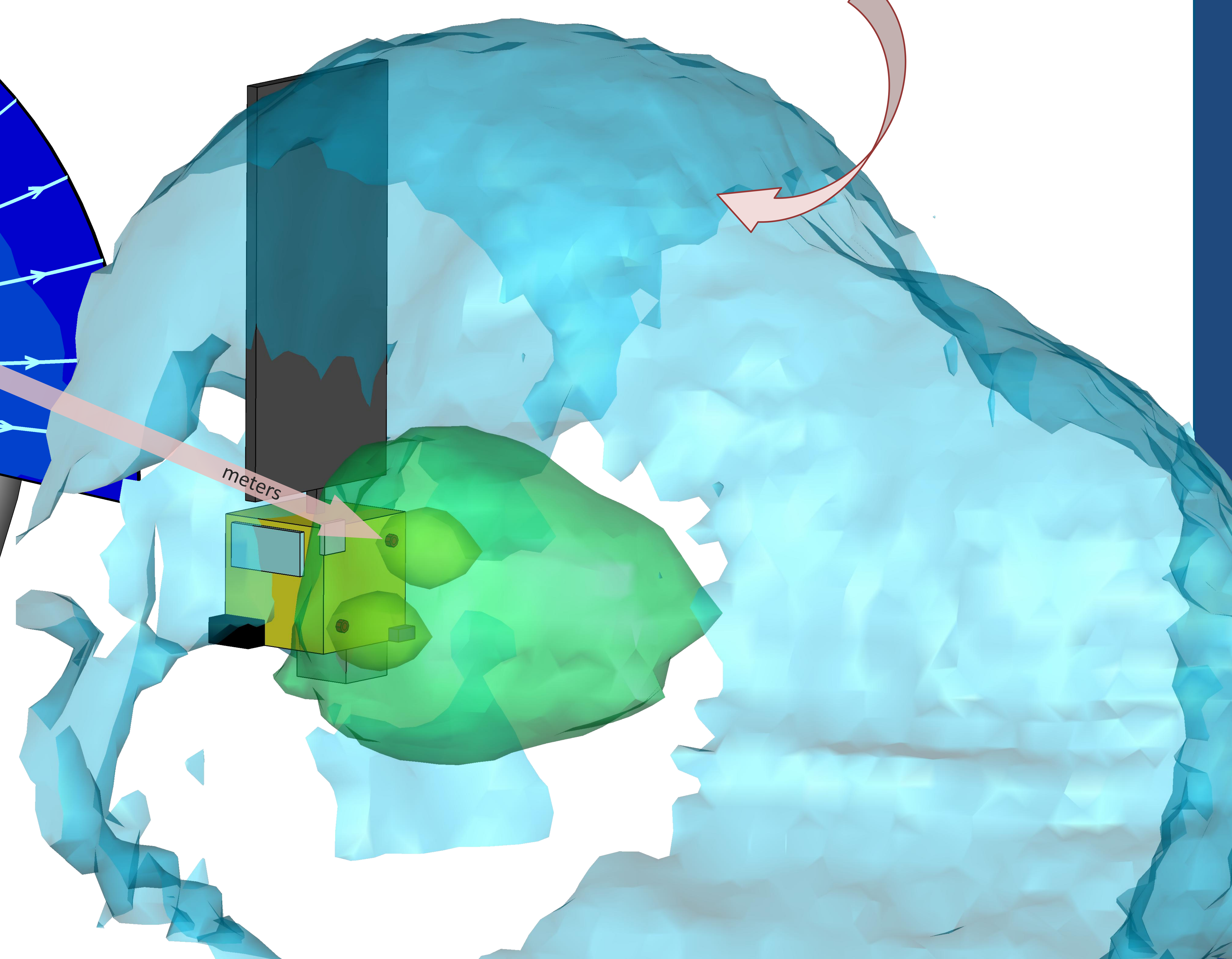
$$en_e\vec{E} = -\nabla p_e + m_e n_e \nu_{ei}\left(\vec{u}_i - \vec{u}_e\right) \quad (3)$$

$$u_{e,\hat{n}} = \mu_e\left(\frac{\partial\phi}{\partial\hat{n}} - \frac{kT_e}{en_e}\frac{\partial n_e}{\partial\hat{n}} - \frac{k}{e}\frac{dT_e}{d\hat{n}}\right) + u_{i,\hat{n}} \quad (4)$$

3. At the **spacecraft scale**, we are interested in determining impact of the thruster plume on spacecraft instruments. Some plume ions undergo a charge-exchange collision and backflow to regions with no direct line of sight of the thruster. To model this contamination, we inject ions at the location of the thruster(s) using data sampled in **Step 2**. Reduced force equation is used to update ion positions (5) and simplified relationship for electron density is used to compute the electric potential (6).

$$m\frac{d\vec{v}_i}{dt} = Z_i e\vec{E} \quad (5) \qquad \nabla^2\phi = -\frac{e}{\varepsilon_0}\left[n_i - n_0\exp\left(\frac{\phi-\phi_0}{kT_e}\right)\right] \quad (6)$$





Charge Exchange Ions

Iterate

Magnetic field lines studied in Step 1 are shown in red.

Princeton Cylindrical HT

Our work is based on the Princeton 2.6 cm Cylindrical Hall Thruster. This thruster offers a novel configuration in which only the upstream section of the thruster uses the conventional annular geometry. The lack of inner wall in the downstream section reduces ion losses.