Kinetic Analysis of Electron Transport in a Cylindrical Hall Thruster

Lubos Brieda, Shaunak Pai, and Michael Keidar

***Abstract* - Transport of electrons across magnetic field lines in a Hall thruster is driven by factors such as collisions with background heavy particles, plasma turbulence, and wall effects. In this work we analyze the influence of secondary electron emission and wall interactions on the cross-field diffusion in the Cylindrical Hall Thrusters.**

Hall Effect Thruster (HET) is a type of spacecraft propulsion device in which working gas is ionized by direct electron impact ionization. Unlike in the conventional ion thruster, which utilizes perforated electrodes to accelerate the propellant, in a Hall thruster the ionization chamber is open to the ambient environment. The thruster relies on a region of strong radial magnetic field to trap electrons in azimuthal E×B rotation. This region of increased electron density produces electrons to ionize the propellant and the potential drop to accelerate ions. Hall thrusters are capable of producing higher current densities than ion thrusters since the discharge is at all times quasi-neutral and thus not subjected to the Child-Langmuir current limit. Performance of these devices is limited by efficiency. Experimental studies of Hall thrusters indicate that current reaching the anode is greater than what can be explained by considering only the classical collision-driven diffusion across magnetic field lines, indicating inefficient confinement of electrons by the applied magnetic field.

Several mechanisms have been identified as contributing to this "anomalous" diffusion. These mechanisms, including plasma turbulence and wall interactions, are subject to active ongoing research [1]. Numerical models of Hall thruster discharges typically include some anomalous diffusion parameter used to artificially increase the cross-field transport and improve correlation with experiments. Goal of our ongoing work is to obtain better understanding of this process by directly investigating motion of electrons from first principle laws. Due to numerical constraints, it is not feasible to perform a kinetic study of an entire Hall thruster. Instead, in our work we limit the domain of interest to a single magnetic field line. Axial variation in mobility and the processes leading to the cross-field diffusion can be obtained by considering several magnetic lines in sequence.

Analysis is performed using the Princeton 2.6cm Cylindrical Hall Thruster [2]. This thruster is attractive for several reasons. First, the small physical size of the device reduces the computational overhead. Secondly, this thruster utilizes novel geometry, in which only the upstream part of the discharge channel is annular. The lack of walls in the acceleration zone reduces ion losses to the walls. In addition, strong magnetic mirror effect near the centerpole reduces electron flux and introduces interesting physics to consider.

We have developed a multi-scale model that combines hybrid and kinetic features. Our fully kinetic 1D simulation model is based on one-dimensional treatment similar to the previous work of Sydorenko [3]. However, our model has been extended to allow inclusion of radially varying magnetic field strength, as well as field curvature [4]. The simulation is initialized with inputs obtained from a hybrid (fluid electrons, kinetic ions) simulation of the thruster using the code HPHall. These results are shown in Fig. 1(a). Transversal electric field, as well as background ion and neutral densities are interpolated onto the magnetic field line, indicated in black. Electron and ion particles are generated using the prescribed distribution, and are advanced according to the Lorentz force. Electric field in the direction tangential to the field line is solved from the Poisson equation. Surface charge on the dielectric walls is computed and used to adjust the wall potential. Collisions are treated using the Monte Carlo (MCC) approach, and polarization, ionization, excitation and Coulomb interactions are considered.

Upon impacting a wall, probability of reflection or secondary emission is computed using the model described in [3]. SEE electrons are injected in direction following the cosine distribution with velocity obtained by sampling Maxwellian at the wall temperature. A representative simulation result obtained after 1.5 million time steps is shown in Fig. 1(b). It should be noted that although the code is one dimensional in the sense that field variation is limited to a single direction, all three components of particle position and velocity are retained. This allows us to account for E×B drift and rotate particles during post-processing for visualization purposes.

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The authors are with The George Washington University, Department of Mechanical and Aerospace Engineering, 801 22nd St., Washington, DC 20052 (email: lbrieda@gwu.edu)

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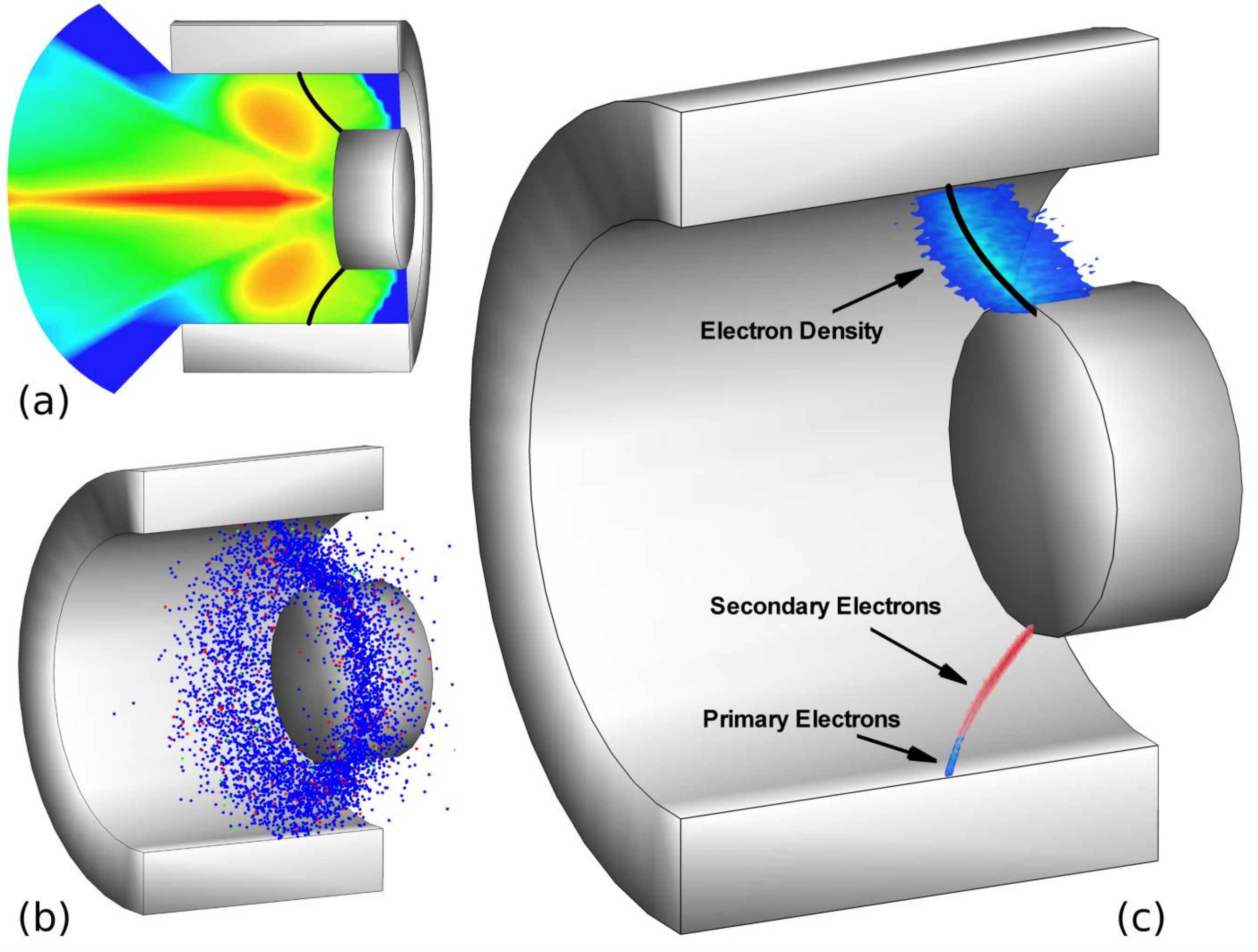

Fig. 1. (a) Geometry of the cylindrical thruster and plasma density computed by HPHall. Plume exits to the left, and anode (not shown) is located at the right end. The magnetic field line used in subsequent kinetic analysis is shown in black. (b) Electron particle distribution after 1.5 million time steps. Primary electrons shown in blue, SEE shown in green and red. (c) Axial electron density distribution for SEE and collisions (top) and SEE only (bottom).

Primary electrons born in the bulk plasma are shown in blue, while SEE originating on the inner/outer wall are shown using green/red markers, respectively. Axial transport is further visualized in Fig. 1(c). The upper half of the image shows slice through the particle data in Fig. 1(b), with particle positions interpolated to a spatial grid. The original particle distribution is also shown in black. Diffusion in the anode direction is clearly visible. The bottom half shows similar data for simulation in which only secondary electron emission was considered. Although both cases produce net anode transport (computed by considering mean axial velocity term), the actual distributions of particles are much different. In the absence of collisions, diffusion is limited to SEE electrons which are found several Larmor radii from the field line. This effect is most pronounced in the vicinity of the inner wall, where the primary population is depleted due to the magnetic pressure effect, and electron population is dominated by secondary electrons born at the outer wall.

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