Hall Thruster Electron Mobility Investigation using Full 3D Monte Carlo Trajectory Simulations

IEPC-2007-291

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Darren A. Alman,* Joshua L. Rovey,† Robert A. Stubbers,‡ and Brian E. Jurczyk§
Starfire Industries LLC, Champaign, IL. 61820

Abstract: Axial electron transport represents a loss in efficiency for crossed field devices, such as Hall-effect thrusters (HETs). Previous experimental and computational investigations have revealed an anomalous axial mobility that cannot be explained with classical theory. This work describes the development of a computational model that calculates electron mobility in HETs using known electric and magnetic fields. Specifically, a full 3D Monte Carlo trajectory simulation code is developed to simulate HET internal electron dynamics. Simulations were completed using the AFRL/University of Michigan P5 HET. The magnetic field for this thruster is known from magnetostatic simulations and the electric field present during thruster operation has been experimentally measured by Haas. Comparison of the axial mobility from our code and the mobility calculated by Koo for the P5 shows agreement.

Nomenclature

B	=	magnetic field vector
E	=	electric field vector
r	=	radial coordinate, with zero being the thruster centerline
v	=	electron velocity vector
z	=	axial coordinate, with zero being the anode location
μ	=	electron mobility

I. Introduction

HALL-EFFECT thrusters (HETs) are a type of space propulsion device that use electric fields to accelerate and expel ionized propellant to generate thrust. A schematic of an HET is shown in Figure 1. A HET is a coaxial device that utilizes a radial magnetic field crossed with an axial electric field. Electrons emitted by the cathode drift in the $\vec{E} \times \vec{B}$ direction, forming an azimuthal Hall current. Neutral xenon atoms injected through the anode collide with these electrons producing xenon ions that are subsequently accelerated by the electric field to produce thrust. The magnitude of the magnetic field is designed such that only the electrons are magnetized. A mixture of electrons and ions in the acceleration zone creates a quasi-neutral plasma and thus the operation of the HET is not space-charge limited in ion current density as is the case with gridded ion thrusters.

* Research Engineer, 60 Hazelwood Drive, Suite 143/203A, AIAA Member.
† Propulsion Research Engineer, 60 Hazelwood Drive, Suite 143/203A, AIAA Member.
‡ Vice President, 60 Hazelwood Drive, Suite 143/203A, AIAA Member.
§ President, 60 Hazelwood Drive, Suite 143/203A, AIAA Member.

Transverse electron mobility represents a loss in efficiency of the device, so ideally electrons would be confined to drift in the Hall current indefinitely. Unfortunately this is not realizable in practice and electrons do migrate to the anode. Furthermore, axial mobility can not be characterized by a purely classical collisional diffusion model. In fact, experimental measurements in the SPT-100 have shown that the electron collision frequency is on the order of 10^7-10^8 Hz.[3] Calculations from both internal and global measurements have shown that the collision frequency based off classical theory is 1,000 times lower.[4] Because of this discrepancy, the term "anomalous" mobility has been used to describe the increased axial mobility present in cross-field devices such as HETs.[5] Explanations of the "anomalous" mobility have been suggested and two main candidates are plasma turbulence[4,6] and wall-effects.[7-9] More efficient HETs that better confine Hall current electrons may be possible if a clearer understanding of the mobility in these devices is developed. With this in mind, Starfire Industries LLC is using both numerical modeling and experiment to investigate and study mobility in HETs.

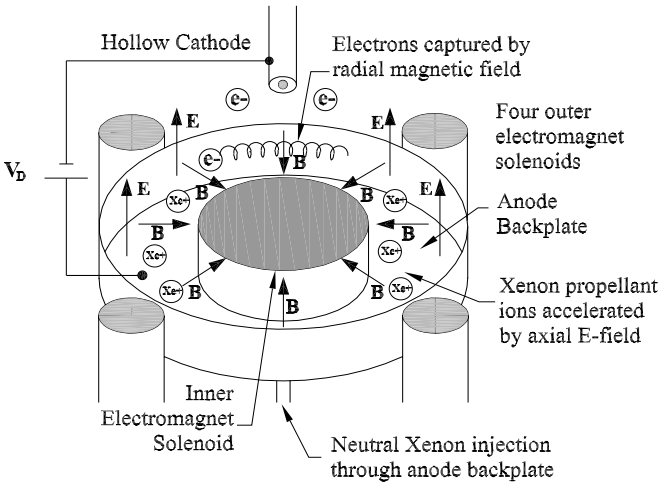


Figure 1: Schematic of a Hall-effect thruster (HET).

II. Full 3D Monte Carlo Trajectory Simulations

Starfire Industries has developed a 3D Monte Carlo trajectory simulation code to investigate electron transport in HETs. The simulations are carried out by rigorously simulating the electron trajectory over a series of very small timesteps, ~10^{-13} seconds. The forces on the electron due to magnetic and electric fields are calculated at each timestep and the particle is moved and its velocity is adjusted. The possibility of a collision occurring is checked at a somewhat larger interval (because the probability over one Δt is extremely low), and if necessary the electron's velocity (energy and direction) is modified according to the tabulated collision data. If the electron leaves the simulation volume it either collides with a wall, and is handled appropriately, or escapes and finishes its flight depending on the properties of the wall object that it strikes. Tallies of desired properties are output to data files both periodically throughout the run and at the completion of all electron flights. Data for each individual electron history (coordinates, velocities, local properties, forces, collision probabilities, etc.) can be saved after each flight. Due to the abundance of data collected, much can be learned from the simulations and most of the interesting properties or occurrences can be studied in detail after the simulations are completed.

Three electron-neutral collisions with xenon are sampled - elastic scattering, excitation, and ionization. Data on electron collision cross sections were taken from the literature[10] and the Evaluated Electron Data Library[11] from Lawrence Livermore National Laboratory. The values used by the code for elastic scattering over one example electron flight are shown in Figure 2. Again, elastic collisions play a dominant role in the electron transport process since the scattering of the Hall drifting electrons results in a change in electron direction and subsequent orbit-center motion along the z-axis. Wall collisions are treated with a varying level of detail, with initial simulations simply returning the incident electron back into the thruster channel with a cosine angular distribution and a Maxwellian energy distribution sampled from the wall temperature. This simplified wall treatment can be expanded to account for improved energy of incidence, angle of incidence, and surface roughness effects to potentially improve code accuracy.

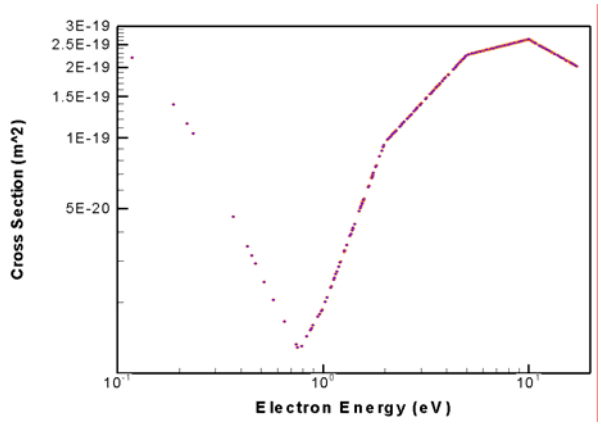
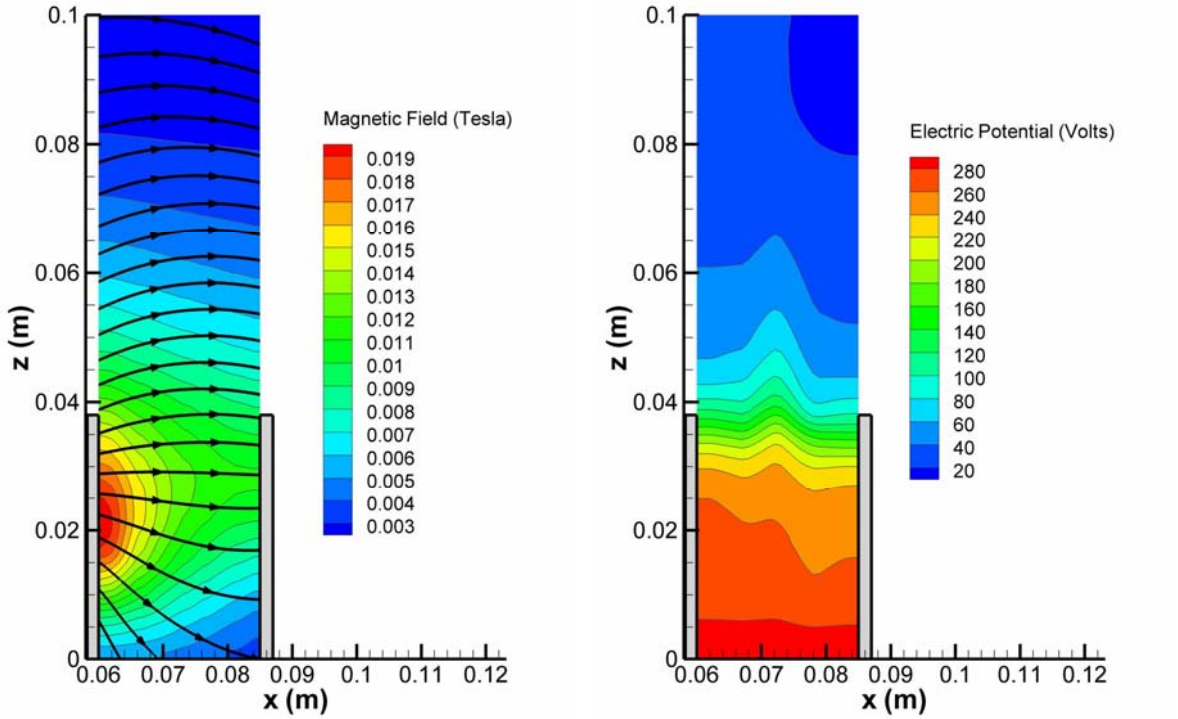
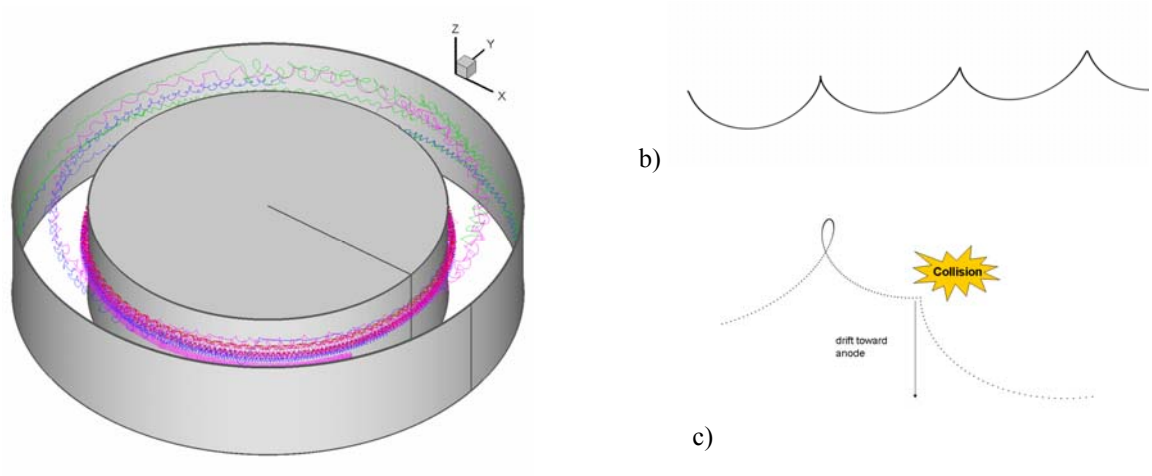


Figure 2. Electron elastic scattering cross section values used in the Monte Carlo code during one electron flight



a) b)

Figure 3. Contour plots of a) magnetic field and b) electric potential used as input to the electron trajectory code, from experimental measurements by Haas.[1,2]



a) b) c)

Figure 4. Plots of an electron trajectory from the Monte Carlo code showing a) an overview of the simulation volume, b) an electron exhibiting the classical hall drift, and c) an elastic collision causing electron transport toward the anode.

To get good statistics, typically tens or hundreds of thousands of electron flights are run for a given set of conditions. Electrons start with a Maxwellian energy distribution with a low initial temperature and a random direction in three dimensions. Electrons were simulated for up to one to ten microseconds (user definable) or until they reach the anode, whichever comes first. A time limit must exist, because some electrons were found to be very well trapped, and these flights would otherwise never come to a conclusion. The trade-off is between increased accuracy and simulation time requirements.

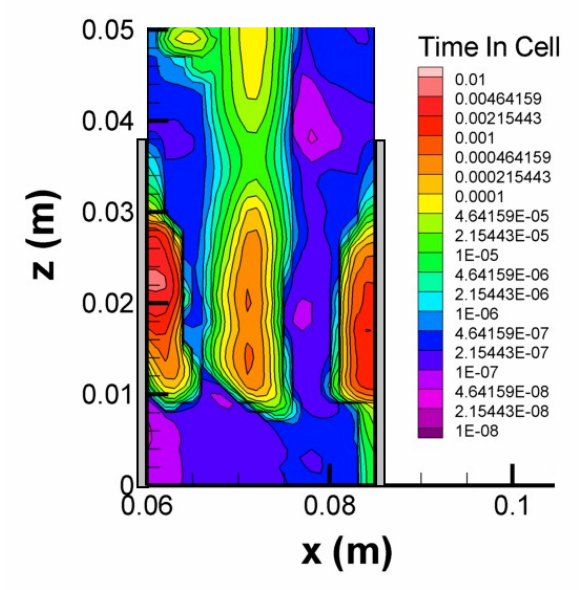


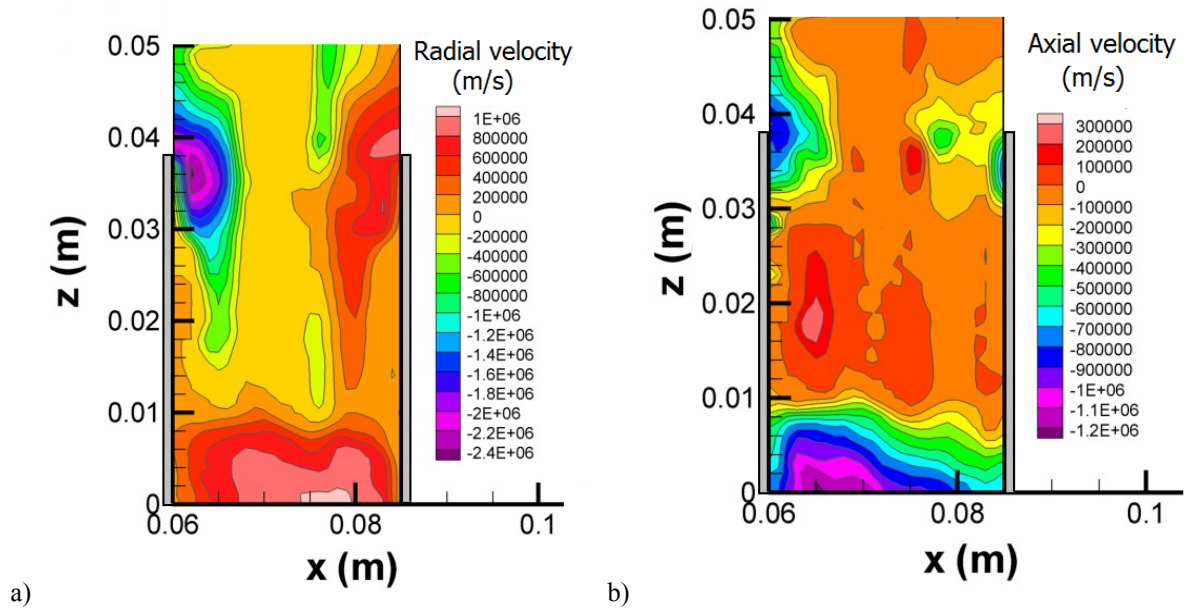
Figure 5. Total time that electrons spent at each (r,z) location, totaled over 10,000 flights.

III. Simulation Results for the P5 Hall thruster

Simulations using the code described above were performed on the AFRL/University Michigan P5 HET. A calculated magnetic field and experimental measurements of the electric potential[1,2] were used as input to the code. The geometry of the simulation and a contour plot of the electric potential and magnetic field are shown in Figure 3. In this and subsequent plots, the x-axis and z-axis are the thruster radial and axial dimensions, respectively.

Figure 4a shows the overall simulation volume, and examples of some electrons traveling within the thruster channel. A small, greatly magnified portion of a single electron trajectory, output from the Monte Carlo code, is shown in Figure 4b. The electron displays the traditional orbit in crossed electric and magnetic fields. Of course, the electrons do not always perfectly follow such an archetypical Hall orbit. There are many forces that tend to complicate the electron path, including slight variations in electric and magnetic field directions, varying strengths of these fields, and collisions with the background gas. An example of the latter is given in Figure 4c, where the electron has a collision, changes direction, and is forced by the fields to resume the Hall drift. Any additional velocity that the electron keeps beyond what the Hall drift requires results in extra features in the trajectory, for example, an extra loop at the top of the orbit like that shown in Figure 4c.

Simulations of tens of thousands of individual electron trajectories were used to calculate the desired outputs, such as spatial and velocity history throughout the thruster computational domain. Figure 5 shows the total amount of time spent by electrons as a function of location in the thruster. This figure shows that electrons spend a lot of time in the center of the channel, which results in higher efficiency since the electrons are not reaching the anode. To some extent, they are trapped there and prevented from drifting toward the anode due to the strong magnetic field. However, these results also show there is a significant amount of electron transport to both the inner and outer walls of the channel, where electrons also spend a good deal of time.



a) b)

Figure 6. Average velocity of all electrons vs. location in the thruster a) in the radial direction and b) in the axial direction.

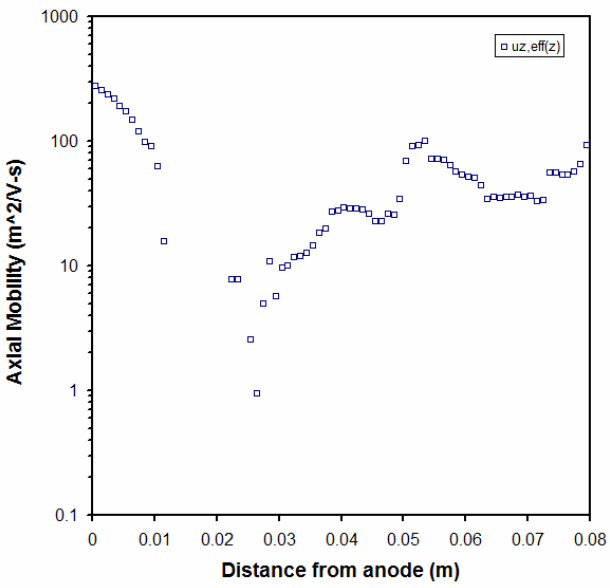


Figure 7. Electron trajectory simulation results for the axial electron mobility averaged radially across the thruster versus distance from the anode.

The most important output for investigating the electron mobility is the average velocity that electrons have at each (r, z) location because velocity is directly related to electron mobility. Figure 6a shows the average radial velocity over all electrons as a function of location in the thruster. This plot backs up the conclusions of Figure 5, namely that the electrons have little radial velocity at the center of the thruster channel, but do pick up speed toward the walls as they move away from the center. The average velocity towards the inner wall increases as an electron moves toward the inner wall from the center of the channel, and the velocity increases toward the outer wall as an electron moves toward the outer wall from the center. Therefore the electron trapping that does occur near the channel center is an unstable equilibrium.

Figure 6b shows the average axial velocity for all electrons. Overall, the average velocities are directed toward the anode, as would be expected. However, there are small pockets of axial velocity directed downstream away from the anode, due to variations in the magnetic field direction ,etc. The average velocities toward the anode are largest in the low-magnetic field region near the anode, and to a lesser extent downstream of the thruster exit plane. Average axial velocities are low in the high-field acceleration region of the thruster.

From these calculated velocities and the electric field in each cell, the electron mobility can be calculated in each cell. The mobility and velocity are related through $\mathbf{v} = \mu \mathbf{E}$, where $\mathbf{v}$ is the velocity vector, μ is the electron mobility, and $\mathbf{E}$ is the electric field vector. This relationship becomes somewhat more complicated in the case of crossed electric and magnetic fields, where an electric field in one direction can lead to a velocity in a perpendicular direction (e.g.; an axial electric field giving rise to an azimuthal electron velocity and Hall current). In this case the mobility is a tensor. The Monte Carlo electron transport code calculates the full 3D electron mobility tensors for a given thruster and set of initial conditions. For comparison purposes however, these detailed tensor mobilities were collapsed into an effective 1D axial mobility, as shown in Figure 7. These results can be compared to the best fit mobility to experimental data that was previously plotted by Koo,[12-14]. There is agreement between the shape of the code output and the previous fit to experiment, indicating that the major relevant physics are indeed included in the simulations. In both cases, the axial mobility is highest near the anode, drops to a minimum further downstream toward the high-magnetic field region of the thruster, and then rises again as you move beyond the exit plane - but not to the near-anode levels.

IV. Conclusions

A full 3D Monte Carlo trajectory simulation code has been developed to simulate HET internal electron dynamics. Electron transport is important to thruster performance, because electron current reaching the anode represents a loss in efficiency. Previous experimental and computational investigations have revealed an anomalous axial mobility that cannot be explained with classical theory. This makes predictive modeling of HETs difficult because the electron mobility values are not known without performing measurements on existing hardware. The goal of the transport code is to enable calculation of the mobility directly from the knowledge of electric and magnetic fields.

Simulations were completed using data from the AFRL/University of Michigan P5 HET. The magnetic field for this thruster is known from magnetostatic simulations and the electric field present during thruster operation has been experimentally measured by Haas. Key outputs from the Monte Carlo code include information on where electrons spend their time, and how they move throughout the thruster. The latter output, the average velocity of electrons versus position in the thruster, allows calculation of the full 3D electron mobility tensor. An effective 1D

mobility can be defined that takes the mobility tensor and expresses it in terms of axial velocity and axial electric field. Comparison of the 1D axial mobility from our code and the mobility calculated by Koo for the P5 shows agreement, indicating that the transport code is correctly simulating the major relevant physics. Improvements to the model can be made, e.g. in the level of detail for wall interactions. The code can be used to calculate electron mobilities for known fields, without the need for experimental measurements of mobility from each thruster and set of conditions. This represents a major improvement to Hall thruster modeling, allowing predictive modeling to be performed.

Acknowledgements

The authors would like to thank Dr. James Haas and Dr. Justin Koo at AFRL for valuable discussions. This work was supported by SBIR Phase II contract number FA9300-05-C-0017.

References

[1]Haas, J. M., "Low-Perturbation Interrogation of the Internal and Near-field Plasma Structure of a Hall thruster using a High-Speed Probe Positioning System," Doctoral Thesis, Dept. of Aerospace Engineering, University of Michigan, Ann Arbor, MI, 2001.

[2]Haas, J. M., Gallimore, A. D., "Internal Plasma Potential profiles in a Laboratory-model Hall thruster," *Physics of Plasmas*, Vol. 8, No. 2, pp. 652-660, February 2001.

[3]Ahedo, E., Gallardo, J. M., Martinez-Sanchez, M., "Effects of the radial plasma-wall interaction on the Hall thruster discharge," *Physics of Plasmas*, Vol. 10, No. 8, pp. 3397-3409, 2003.

[4]Meezan, N. B., Hargus, W. A., Cappelli, M. A., "Anomalous electron mobility in a coaxial Hall discharge plasma," *Physical Review E*, Vol. 63, No. 2, Feb. 2001.

[5]Janes, G. S., Lowder, R. S., "Anomalous Electron Diffusion and Ion Acceleration in a Low-Density Plasma," *Physics of Fluids*, Vol. 9, No. 6, pp. 1115-1123, June 1966.

[6]Knoll, A., Thomas, C., Gascon, N., Cappelli, M., "Experimental Investigation of High-Frequency Oscillations within Hall Thrusters," AIAA-2006-5171, *42nd Joint Propulsion Conference*, Sacramento, CA, July 9-12, 2006.

[7]Keidar, M., Beilis, I. I., "Electron Transport Phenomena in Plasma Devices with ExB Drift," *IEEE Transactions on Plasma Science*, Vol. 34, No. 3, pp. 804-814, June 2006.

[8]Raitses, Y., Staack, D., Keidar, M., Fisch, N. J., "Electron-wall interaction in Hall thrusters," *Physics of Plasmas*, Vol. 12, No. 5, May 2005.

[9]Raitses, Y., Smirnov, A., Staack, D., Fisch, N. J., "Measurements of secondary electron emission effects in the Hall thruster discharge," *Physics of Plasmas*, Vol. 13, No. 1, Jan. 2006.

[10]Date, H., Ishimaru, Y., Shimozuma, M., "Electron collision processes in gaseous xenon," *Nucl. Instr. and Meth. in Phys. Res. B*, Vol. 207, No. 4, pp. 373-380, August 2003.

[11]Perkins, S. T., Cullen, D. E., Seltzer, S. M., "Tables and Graphs of Electron-Interaction Cross Sections from 10 eV to 100 GeV Derived from the LLNL Evaluated Electron Data Library (EEDL)," UCRL-50400, LLNL, Livermore, CA, November 1991.

[12]Koo, J. W., "Hybrid PIC-MCC Computational Modeling of Hall Thrusters," Doctoral Thesis, Dept. of Aerospace Engineering, University of Michigan, Ann Arbor, 2005.

[13]Boyd, I. D., "Modeling a Hall Thruster from Anode to Plume Far Field," *Air Force Office of Scientific Research: Space Propulsion and Power Contractors Meeting*, Annapolis, MD., Sept. 25-29, 2006.

[14]Koo, J. W., Boyd, I. D., "Modeling of anomalous electron mobility in Hall thrusters," *Physics of Plasmas*, Vol. 13, No. 3, March 2006.