Simulating a 5 kW Class Hall Thruster

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Introduction

- A 5 kW class Hall effect thruster has undergone extensive ground testing, but there are currently no corresponding thruster simulations available in the literature.
- Extrapolating upon available limited thruster geometric properties and magnetic field profiles, a preliminary thruster model is created using HPHall.
- HPHall is a hybrid-PIC code that models highly mobile electrons as a quasi-1D fluid and heavier species using a particle-in-cell (PIC) method. [2]

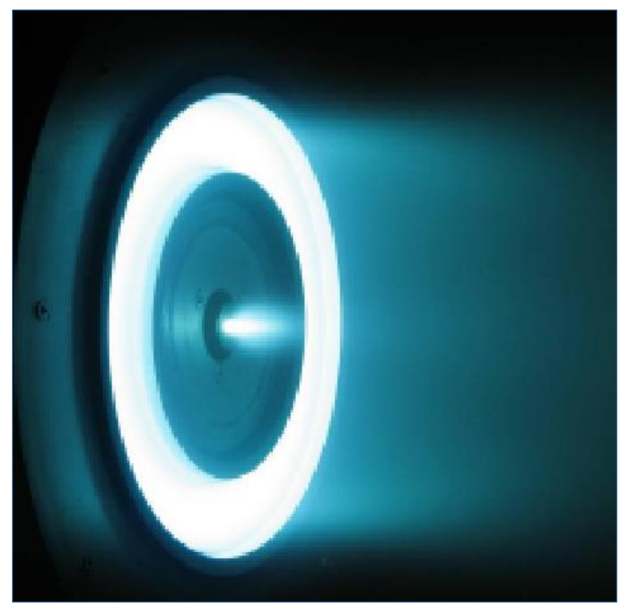

Fig. 1: Xenon Hall Thruster [1]

Simulation Preprocessing: Magnetic Field

- Using radial magnetic field data taken at the thruster discharge channel centerline, inner diameter, and outer diameter, a magnetic field configuration complying to the following assumptions is generated:
  - Magnetic field variations due to plasma currents and changing electric fields are small compared to the field produced by the electromagnet. [2]

    $$\nabla \times \vec{B} = 0$$

  - The magnetic field is purely solenoidal ($\nabla \cdot \vec{B} = 0$) . Therefore, a magnetic potential function, σ, exists, and Laplace's equation must be satisfied in the plasma region.

    $$\vec{B} = \nabla\sigma \quad \text{and} \quad \frac{\partial^2\sigma}{\partial z^2} + \frac{\partial^2\sigma}{\partial r^2} + \frac{1}{r}\frac{\partial\sigma}{\partial r} = 0$$

  - A magnetic stream function, λ, whose gradient is everywhere orthogonal to **B**, can be defined.

    $$\frac{\partial\lambda}{\partial z} = r\frac{\partial\sigma}{\partial r} = rB_r \quad \text{and} \quad \frac{\partial\lambda}{\partial r} = -r\frac{\partial\sigma}{\partial z} = -rB_z$$

- Once σ is known, the magnetic field can be calculated. In this case, a field is created to satisfy available experimental data. However, because the exact magnet locations are not known, the simulated magnetic field topology will differ somewhat from the experimental field.

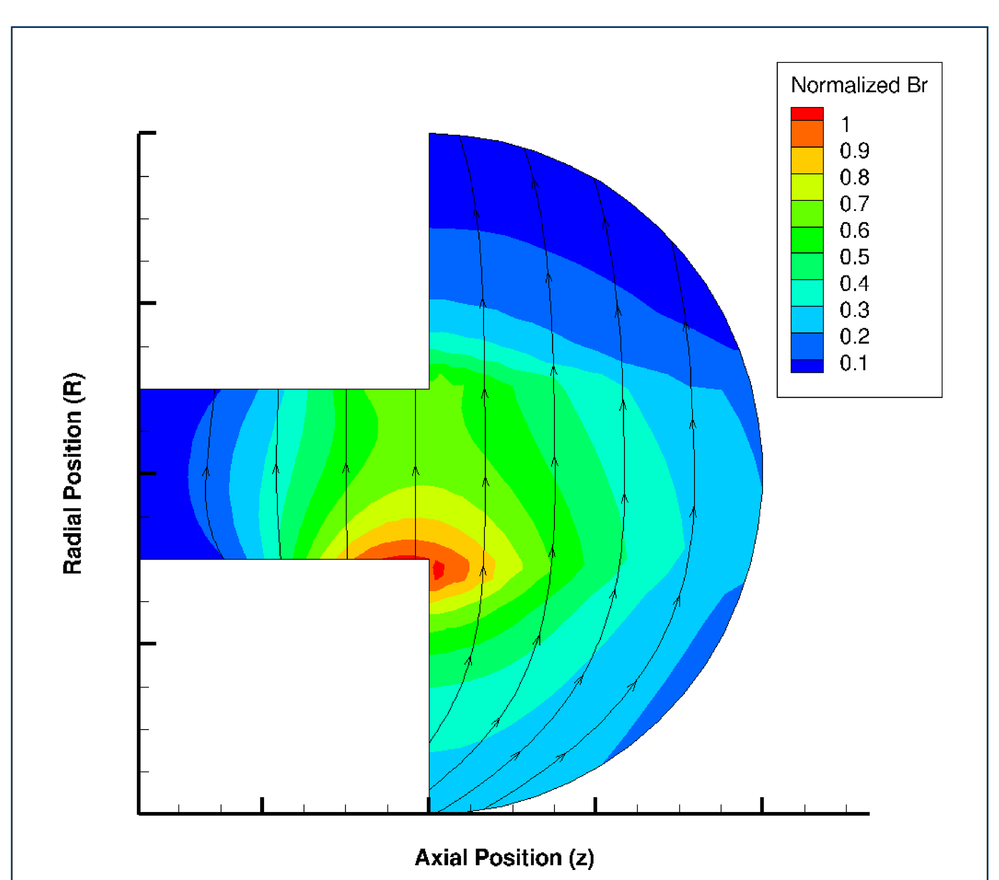

Fig. 2: Normalized Radial Magnetic Field

Simulation Setup

Parameters:

- Thruster run-time: 1ms start up, 4ms on with plasma physics
- Ion & neutral particle step size: 5 x 10^{-8} s
- Electron step size: 1 x 10^{-11} s
- Background pressure and discharge voltage: experimental inputs

Results

- 20+ cases were simulated, mainly altering the electron mobility coefficients from one case to the next. The results shown here are those for which the highest average thrust was achieved.
- Avg Thrust: 75.61%; Avg Discharge Current: 92.7% achieved; Avg Ion Current: 110.0% achieved

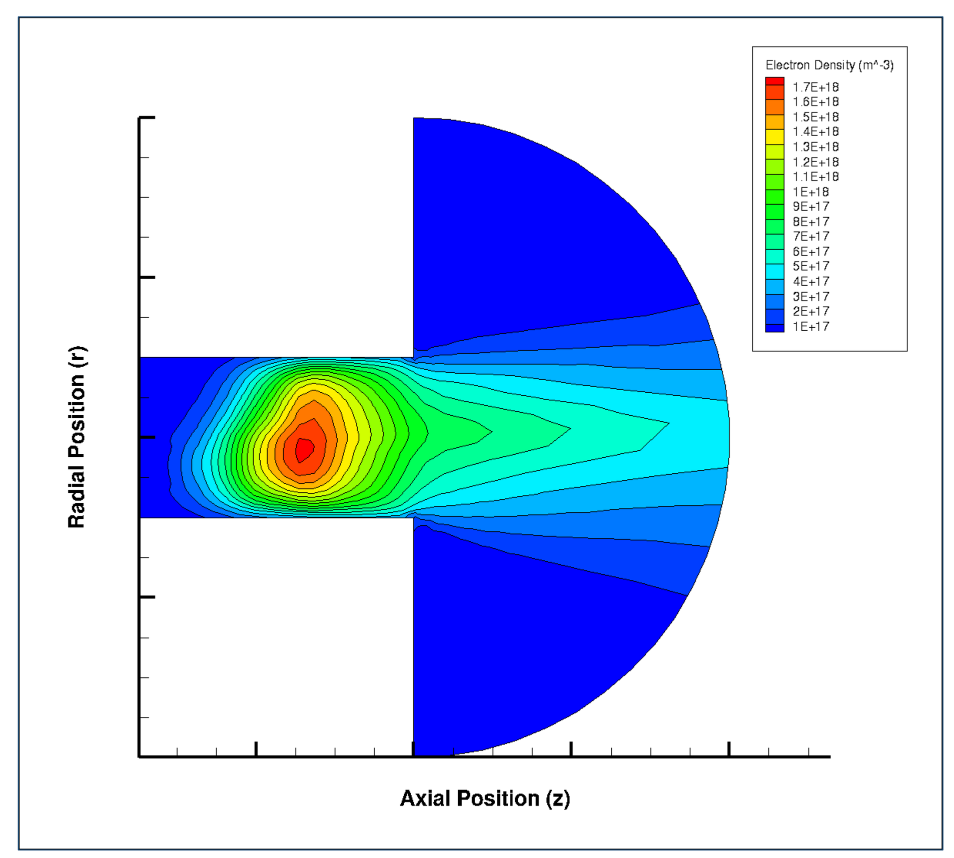

Fig. 3: Electron Number Density (m^{-3})

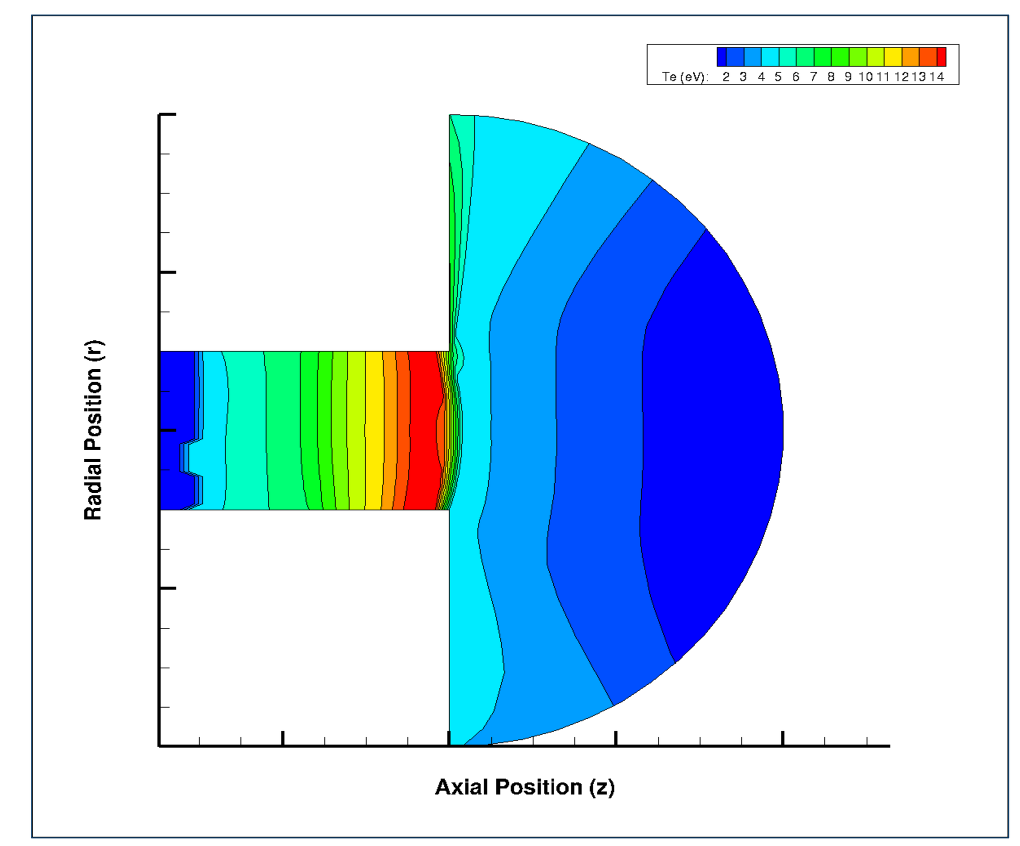

Fig. 4:Electron Temperature (eV)

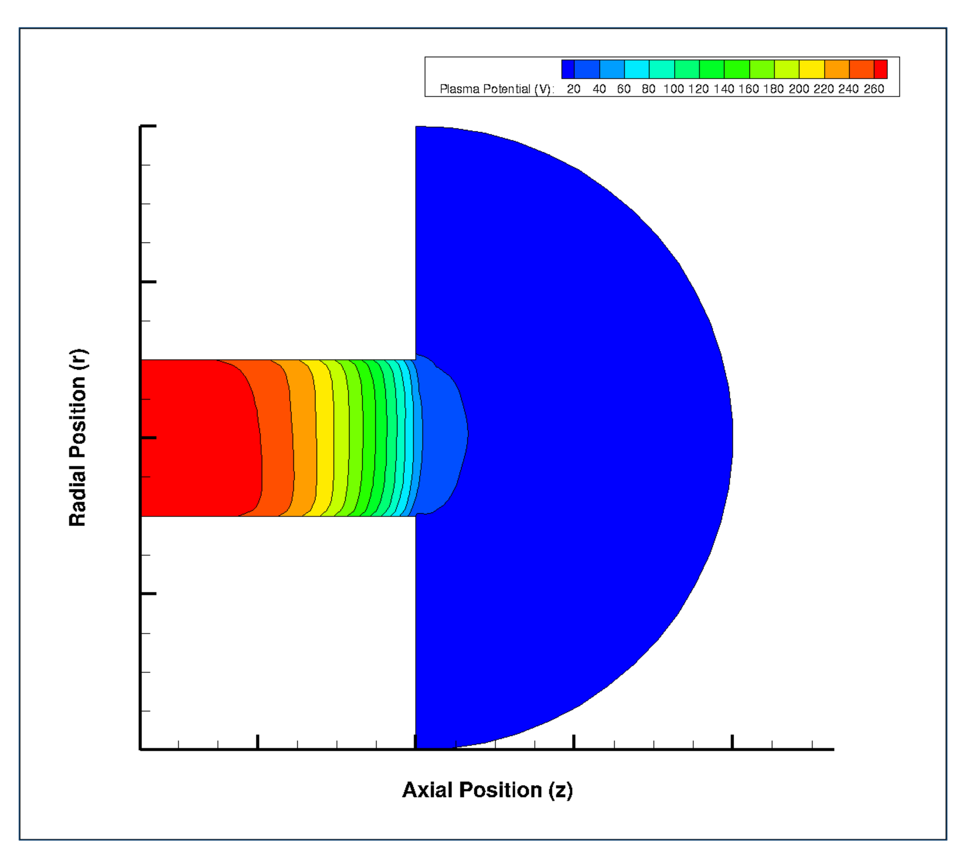

Fig. 5: Plasma Potential (V)

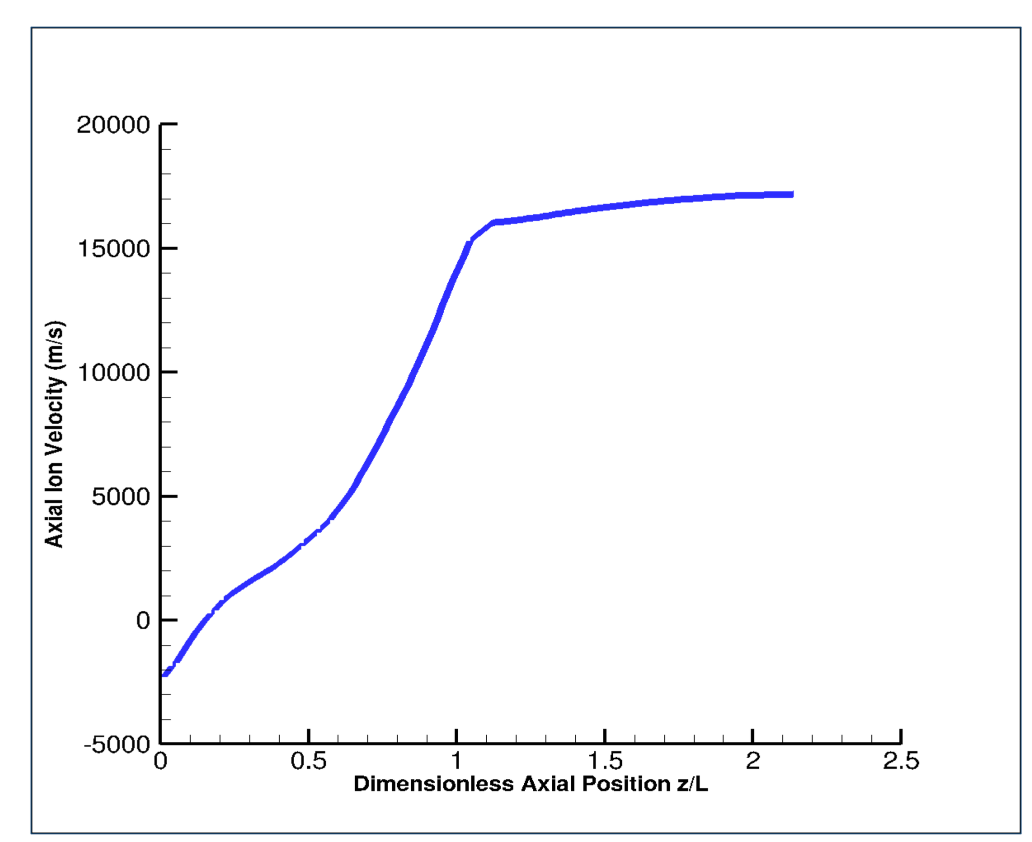

Fig. 6: Axial Ion Velocity at Discharge Channel Centerline (m/s)

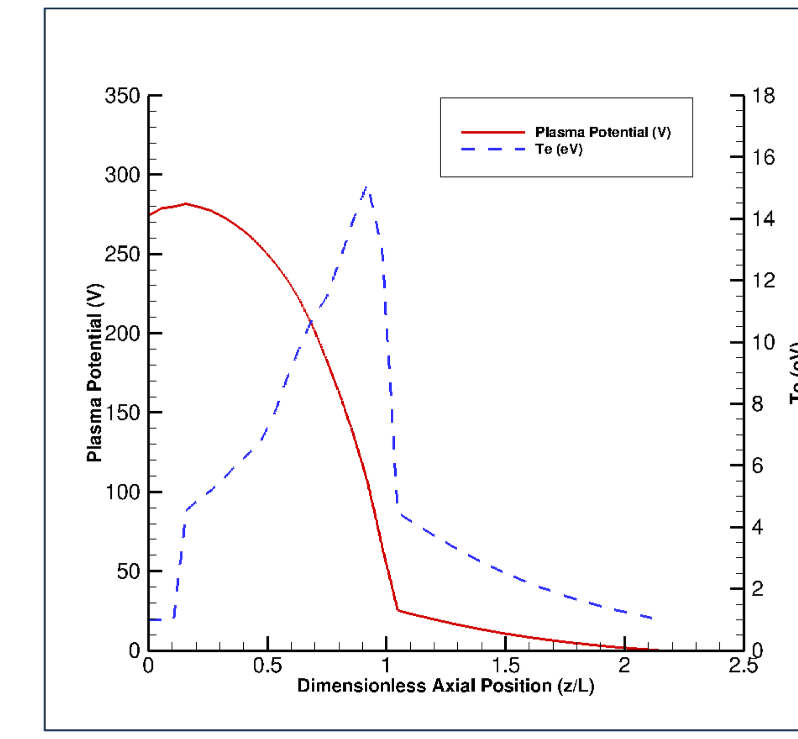

Fig. 7: Plasma Potential and Electron Temperature at Discharge Channel Centerline

Discussion

- The electron temperature contour exhibits unexpected curvature outside of the channel, indicating that the domain may not be large enough to capture the flow field properties.
- The plasma potential decreases to zero in the near field thruster plume, which is not realistic.
- Since the axial ion velocity is still increasing at the edge of the domain, it is likely that the acceleration region has not been fully simulated.
- The magnetic field lines extend past the thruster walls (Fig. 2), indicating that the upper magnet location requires modification.

Conclusion

- Qualitatively, simulation results agree with experimentally observed behavior.
- Macroscopic quantities including thrust, discharge current, and ion current do not yet agree with expected measured properties.
- Discrepancies in the model may be due to the following:
  - Results are sensitive to the magnetic field topology. [3] The simulation uses a mathematically possible magnetic field topology that has not been compared to the entire experimental field.
  - The simulation domain may not be large enough to capture thrust occurring outside the thruster channel.

Acknowledgements

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References

[1] Giuliano, P.N., Boyd, I.D., "Spectral Analysis of simulated Hall thruster discharge oscillations,"IEPC-2009-084, 31st International Electric Propulsion Conference, Sept 2009, Ann Arbor, MI.
[2] Fife, J., *Hybrid-PIC Modeling and Electrostatic Probe Survey of Hall Thrusters*, Ph.D. thesis, Massachusetts Institute of Technology, 1999.
[3] Nikolay, V.B., Gorshkov, O.A. & Shagayda, A.A., "Experimental Investigation of Magnetic Field Topology Influence on Structure of Accelerating Layer and Performance of Hall Thruster," IEPC-2005-033, Princeton, NJ, 2005.