Simulation of Magnetic Nozzle Plasma Thruster Expansion

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Abstract

Simulations of a helicon plasma thruster are presented. Ion acceleration is shown to occur due to potential structures created by magnetic field effects on electrons.

Introduction

Strong guiding magnetic fields known as magnetic nozzles are key components in the design of electrode-less plasma thrusters. The operating regime of many magnetic nozzle devices (ex. CubeSat Ambipolar Thruster) lie near the edge of the continuum regime, making numerical simulation challenging.[1]

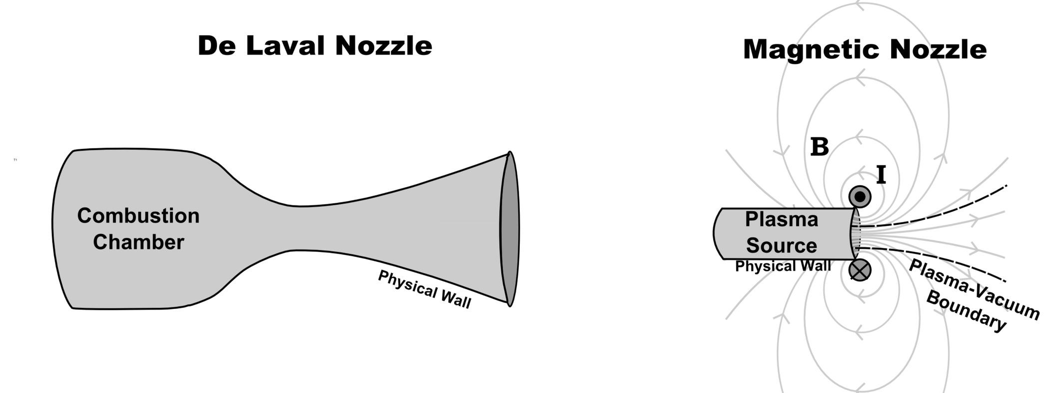

Figure 1: Comparison of magnetic nozzle to De Laval nozzle.[1]

Methodology

A new quasi-one-dimensional electrostatic particle-in-cell method was developed to study ion acceleration in magnetic nozzles.[2]

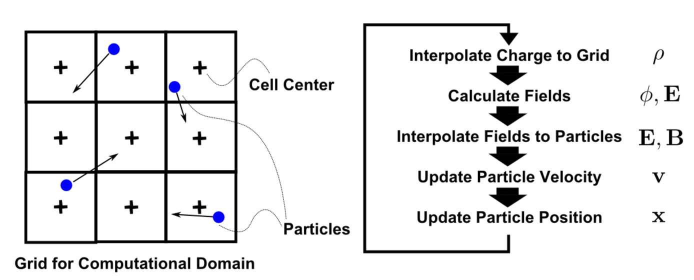

Figure 2: Electrostatic Particle-In-Cell algorithm.

The centerline axis of the magnetic nozzle was resolved and the two-dimensional effects of the plasma expansion and magnetic field forces were modeled.

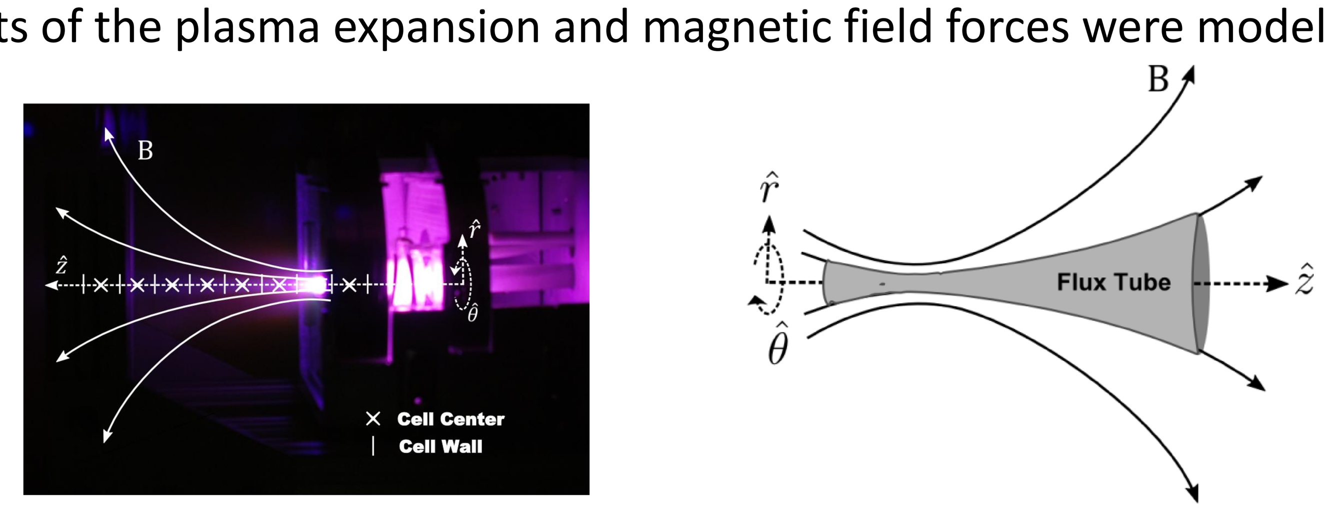

Figure 3: Left, Illustration of the model domain overlaid on a firing of the CubeSat Ambipolar Thruster (CAT). Right, Example of magnetic flux tube modeled.

Magnetized particles were assumed to be displaced from the axis by their Larmor radii to incorporate axial magnetic forces and 2D effects.

$$B_r = -\frac{r_L}{2}\frac{\partial B_z}{\partial z}$$

The cross sectional area of the domain was varied by assuming that particles approximately follow magnetic field lines.

$$A = \frac{B_{z,in}}{B_z} A_{in}$$

Governing equations:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v}$$

$$\frac{\partial v_\parallel}{\partial t} = \frac{q}{m}E_\parallel - \frac{1}{2B}\frac{\partial B}{\partial s}v_\perp^2$$

$$\frac{\partial v_\perp}{\partial t} = \frac{1}{2B}\frac{\partial B}{\partial s}v_\perp v_\parallel$$

$$\nabla^2\phi = -\frac{\rho}{\epsilon_0}$$

Collisions:

Ion-Neutral: Elastic, Charge Exchange

Electron-Neutral: Elastic, Inelastic, Ionization

Simulation Setup

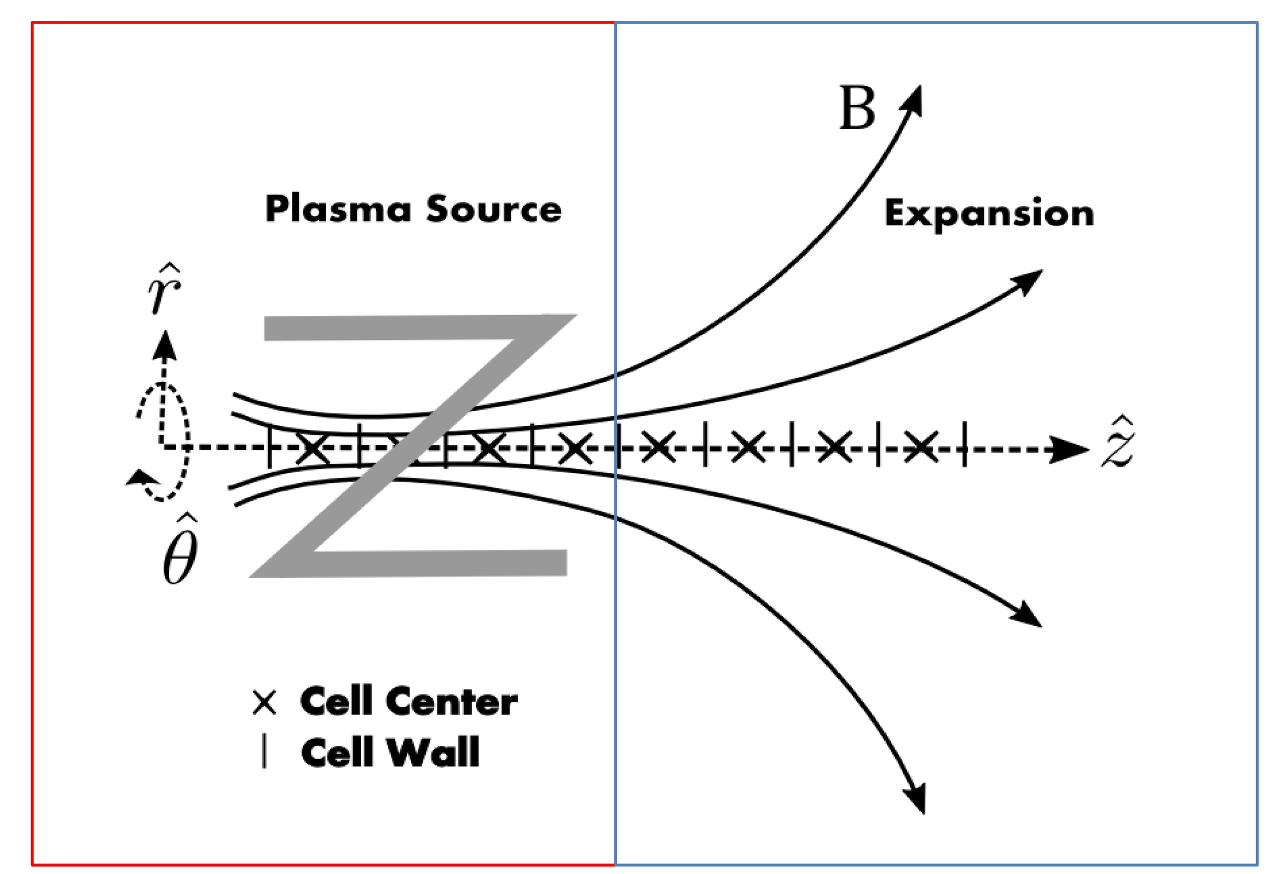

Figure 4: Simulation domain showing heating region and expansion region.

- Time varying perpendicular electric field heats particles in the source region.
- Constant magnetic field applied in the source region . (1D effects only).
- Decreasing magnetic field in the expansion region due to the magnetic field diverging.
- Apply two-dimensional effects to capture magnetic nozzle effects on plasma.

Results

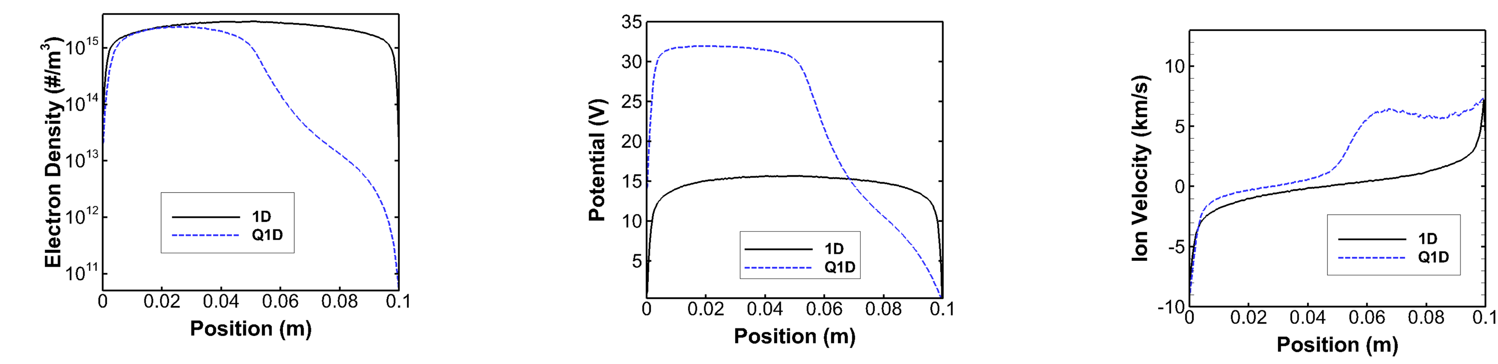

Figure 5: Simulation results for density, potential, and ion velocity demonstrating 2D effects.

The new quasi-1D methods captured important two-dimensional effects. A decrease in plasma density was seen as the plasma expanded as well as the formation of a potential drop which accelerated the ions.[2]

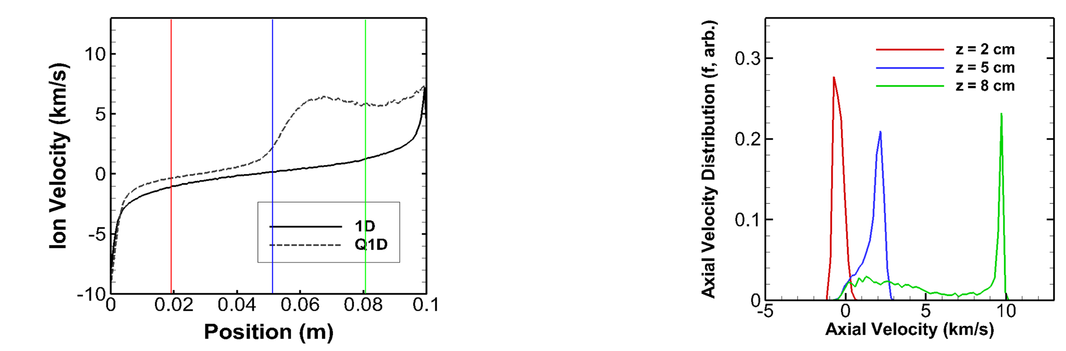

Figure 6: Ion axial velocity distribution demonstrating beam formation.

An ion beam was formed as the ions were accelerated by the potential drop. This is promising for thruster performance. A low energy peak was seen due to charge-exchange collisions.

What is accelerating the ions?

The forces due to the magnetic field rapidly accelerate the light, high-energy electrons out of the plasma source region. This results in a charge imbalance which sets up an electric field that drags the ions out along with the electrons creating an ion beam.[3]

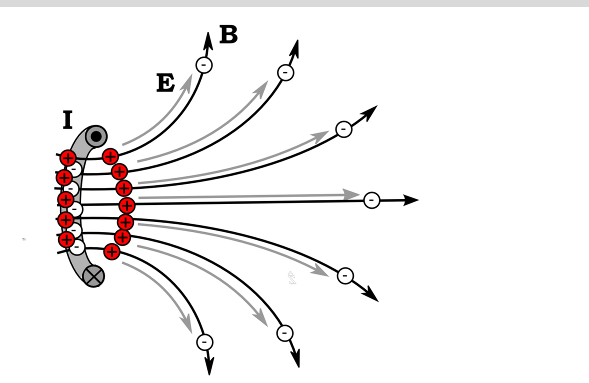

Figure 7: Schematic of ion acceleration mechanism.

Conclusions

The new quasi-1D particle-in-cell code captured important physical processes in magnetic nozzles. Potential structures develop in the magnetic nozzle due to the magnetic field forces axially accelerating electrons in the expansion region. This potential structure accelerates the ions into a beam.

Acknowledgements

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[2] Ebersohn, F.H., Sheehan, J.P., Gallimore, A.D., and Shebalin, J.V., "Quasi-One-Dimensional Particle-In-Cell Simulation of Magnetic Nozzles", IEPC 2015-357 , 34th International Electric Propulsion Conference, Kobe, Japan, July 6-10, 2015.

[3] H.G. Kosmahl. "Three-dimensional plasma acceleration through axissymmetric diverging magnetic fields based on dipole moment approximation." echnical report, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH, 1967.