Quasi-One-Dimensional Particle Code for Simulation of Magnetic Nozzle Propulsion Systems

Frans H. Ebersohn[1], JP Sheehan[1], Benjamin W. Longmier[1], John V. Shebalin[2]
1. Aerospace Engineering, University of Michigan, 2. Exploration Integration and Science Directorate, NASA Johnson Space Center

Introduction

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

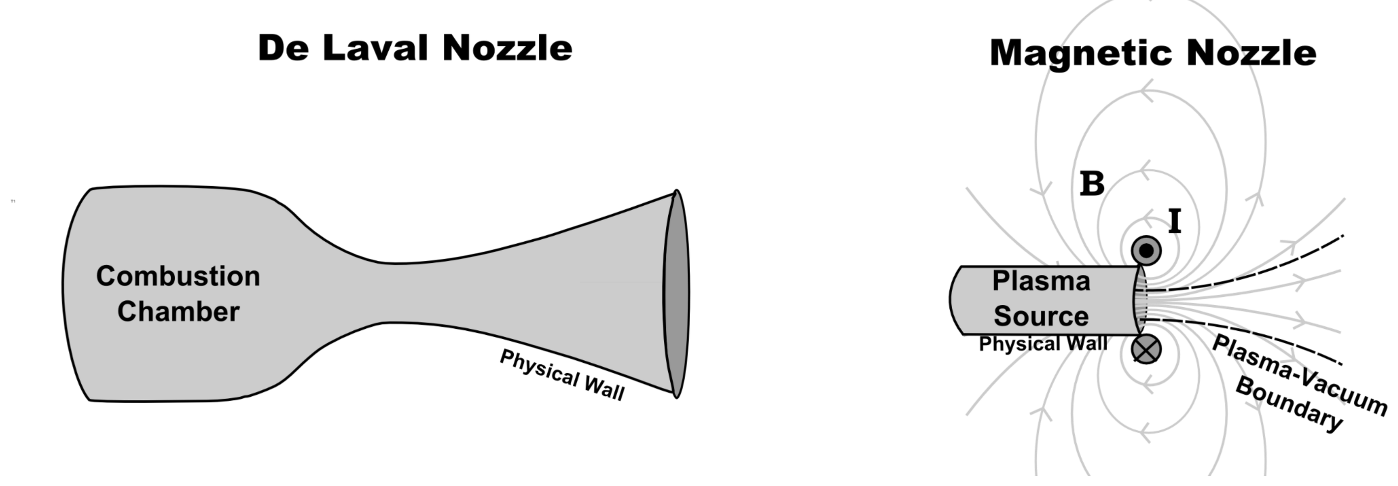

Figure 1: Comparison of De Laval nozzle to magnetic nozzle [1].

Figure 2: A rendering of the CubeSat Ambipolar Thruster.

Objectives

1. Formulate a novel quasi-one-dimensional particle-in-cell code for the simulation of magnetic nozzles.
2. Validate code with known computational solutions and theory.

Methodology

A novel quasi-one-dimensional electrostatic particle-in-cell (PIC) method is developed which focuses on studying energy exchange and thermalization. Electrostatic PIC is outlined in Figure 3 below.

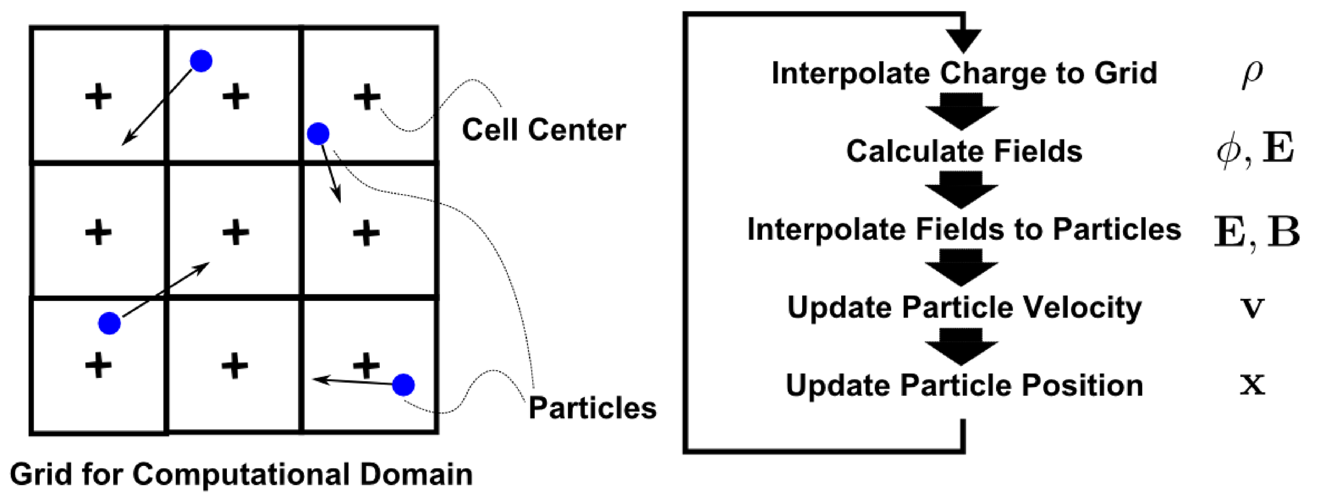

Figure 3: Basics of a electrostatic Particle-In-Cell code.

The centerline axis of the magnetic nozzle, shown in Figure 4, is modeled and three velocity dimensions are resolved.

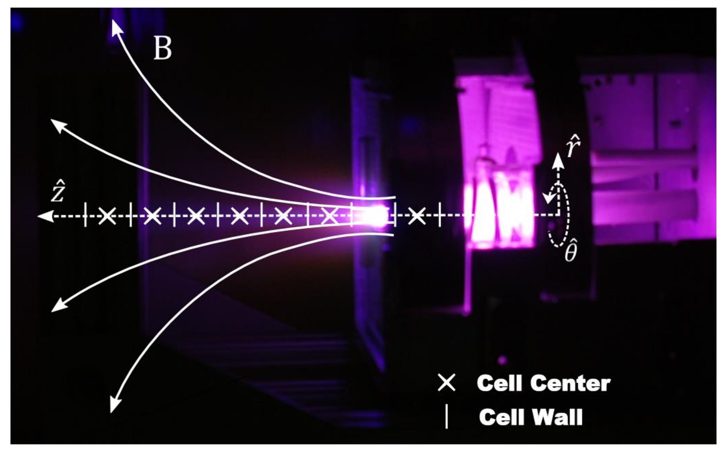

Figure 4: Simulation domain over the CAT experiment plasma plume.

Magnetized particles are assumed to be displaced from the axis by their Larmor radii to incorporate axial magnetic forces and 2D effects. The cross sectional area is varied by assuming that particles approximately follow magnetic field lines.

$$B_r = -\frac{r_L}{2}\frac{\partial B_z}{\partial z} \qquad A = \frac{B_{z,in}}{B_z} A_{in}$$

The motion of the charged particles is governed by:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{v} \qquad m\frac{d\boldsymbol{v}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Results and Discussion

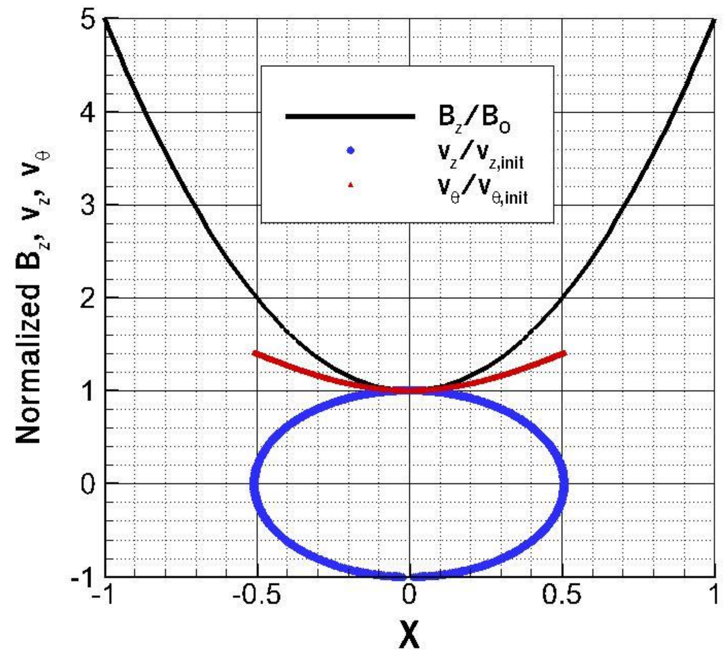

Figure 5: Velocities of a particle trapped by a strong magnetic field.

Simulations of a particle in a strong magnetic field are performed to validate the code. The results of this simulation are shown in Figure 5. The particle is trapped in the region of low magnetic field strength due to Lorentz forces as predicted by theory. The energy of the particle is also conserved, which along with other test cases validates the algorithms implemented.

Additional simulations of a Maxwellian velocity distribution of particles in a magnetic field are performed to compare with magnetic mirror theory. According to magnetic mirror theory, only particles with certain velocities are trapped within the mirror. Particles lost fall within what is known as the loss cone which is shrunk as the magnetic field strength increases. Figure 6 shows the initial and final velocity space of particles and the analytical loss cone as the magnetic field strength is increased.

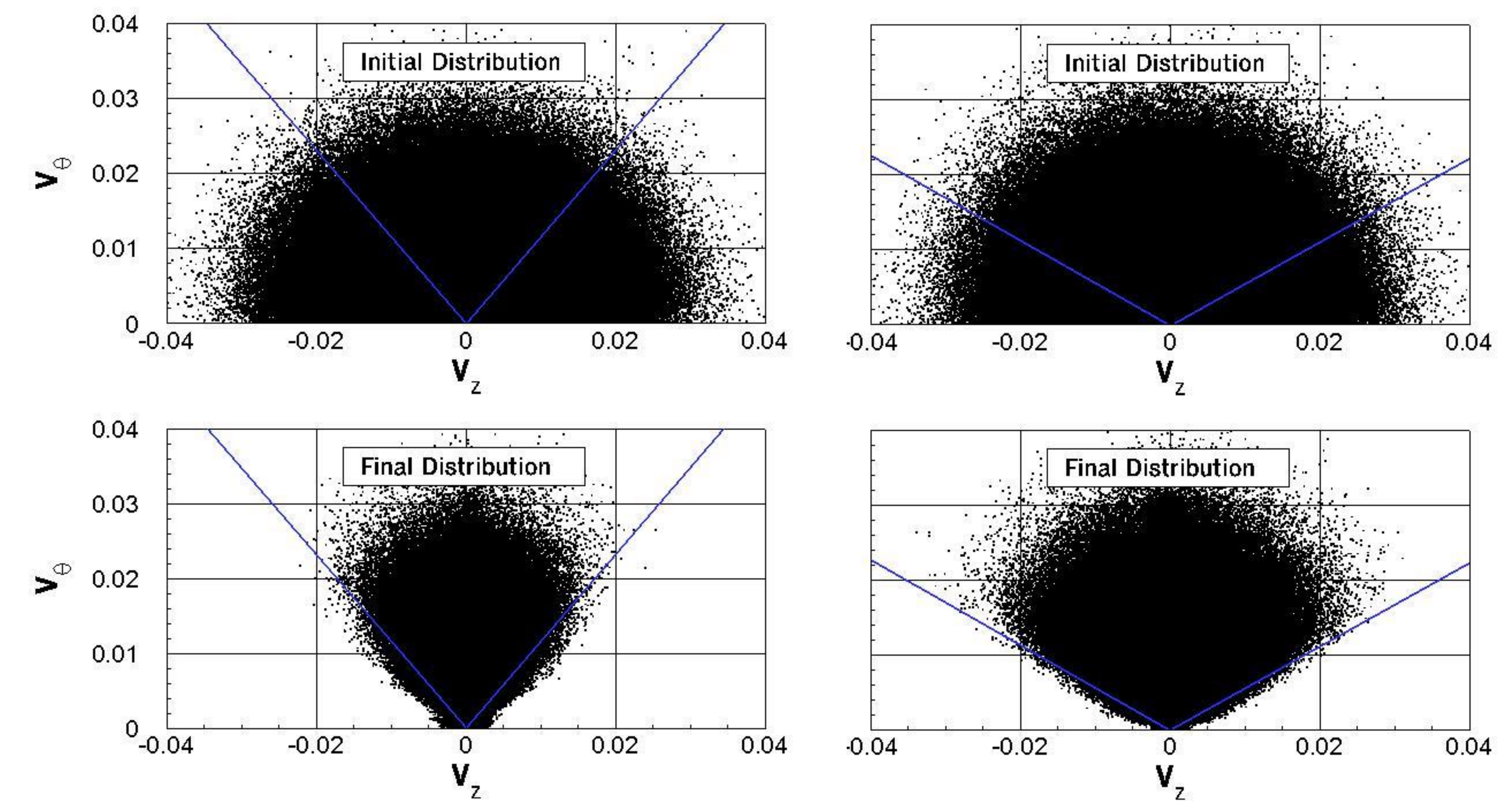

Figure 6: Velocity space in a magnetic mirror. The blue line represents the analytical loss cone. Left: B_{max}/B_0 = 1.75, Right: B_{max}/B_0=4.0.

Conclusions

A quasi-one-dimensional method for magnetic nozzle simulation is developed and its implementation shows promising results for magnetic mirror test cases.

Acknowledgements

This research is funded by a NASA Space Technology Research Fellowship. Thank you to my lab mates at PEPL for their support.

References

[1] Ebersohn, F.H., et al. "Magnetic nozzle plasma plume: review of crucial physical phenomena." AIAA paper 4274 (2012): 2012.
[2] Boris, J. P. "Relativistic plasma simulation-optimization of a hybrid code." Proc. Fourth Conf. Num. Sim. Plasmas, Naval Res. Lab, Wash. DC. 1970.
[3] Birdsall, C.K., and A.B. Langdon. "Plasma physics via computer simulation." CRC Press, 2004.

Symposium Gold Sponsors