Quasi-One-Dimensional Simulations of Magnetic Nozzles for Plasma Thruster Applications

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Abstract

A novel quasi-one-dimensional particle-in-cell method for simulation of magnetic nozzles is developed. Preliminary verification and validation simulations for this solver are completed .

Introduction

Strong guiding magnetic fields known as magnetic nozzles (Fig. 1) are key components in the design of electrodeless plasma thrusters. The operating regime of many magnetic nozzle devices (ex. Cubesat Ambipolar Thruster) lie near the edge of the continuum regime, making computational modelling challenging.[1]

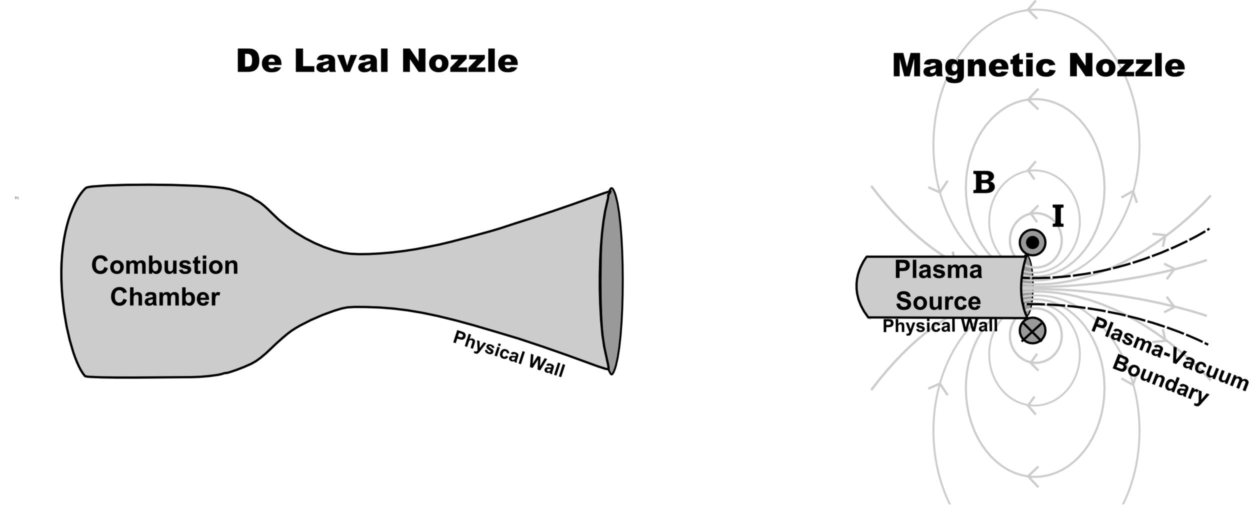


Figure 1: Comparison of magnetic nozzle to De Laval nozzle.[1]

General Methodology

Herein we develop a novel method for the simulation of magnetic nozzles with a quasi-one-dimensional electrostatic particle-in-cell method. The method is developed primarily to study energy exchange and thermalization in the plasma and is summarized below:

- The centerline axis of magnetic nozzle is modeled and three velocity dimensions are resolved.

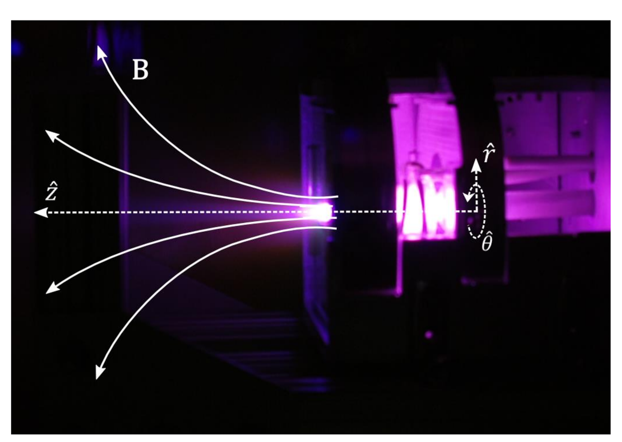


Illustration of the model domain overlaid on a firing of the Cubesat Ambipolar Thruster (CAT).

- Magnetized particles are assumed to be displaced from the axis by their Larmor radii to incorporate axial magnetic forces.

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

- Cross sectional area varies assuming that particles approximately follow magnetic field lines.

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

Quasi-one-dimensional particle mover

Governing equations:

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

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

Particle Movers:

- Standard Boris Algorithm for Axisymmetric Coordinates[2],[3]
- Modified Semi-Implicit Q1D Boris Algorithm

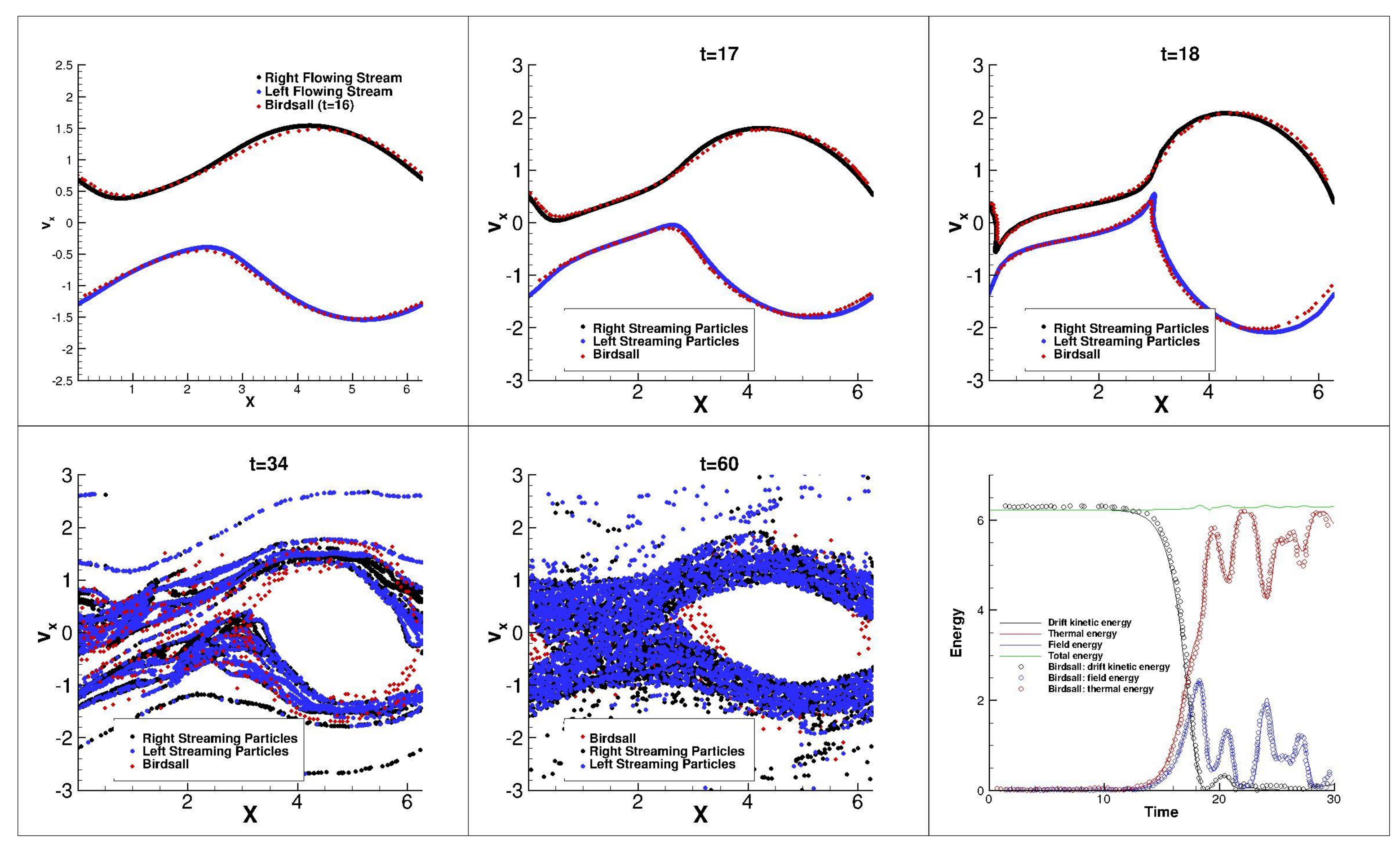
$$\frac{v^{n+\frac{1}{2}} - v^{n-\frac{1}{2}}}{\Delta t} = \frac{q}{m}\left[\boldsymbol{E} + \frac{\left(v^{n+\frac{1}{2}} + v^{n-\frac{1}{2}}\right)}{2}\times\boldsymbol{B}\right] + \frac{\left(\boldsymbol{a}_{cent}^{n+\frac{1}{2}} + \boldsymbol{a}_{cent}^{n-\frac{1}{2}}\right)}{2}$$

$$\boldsymbol{a}_{cent}^{n+\frac{1}{2}} = \frac{\left(v_\theta^{n+\frac{1}{2}}\right)^2}{r_L}\hat{r} - \frac{v_r^{n+\frac{1}{2}} v_\theta^{n+\frac{1}{2}}}{r_L}\hat{\theta}$$

$$r_L = \frac{m v_\theta}{q B_z}$$

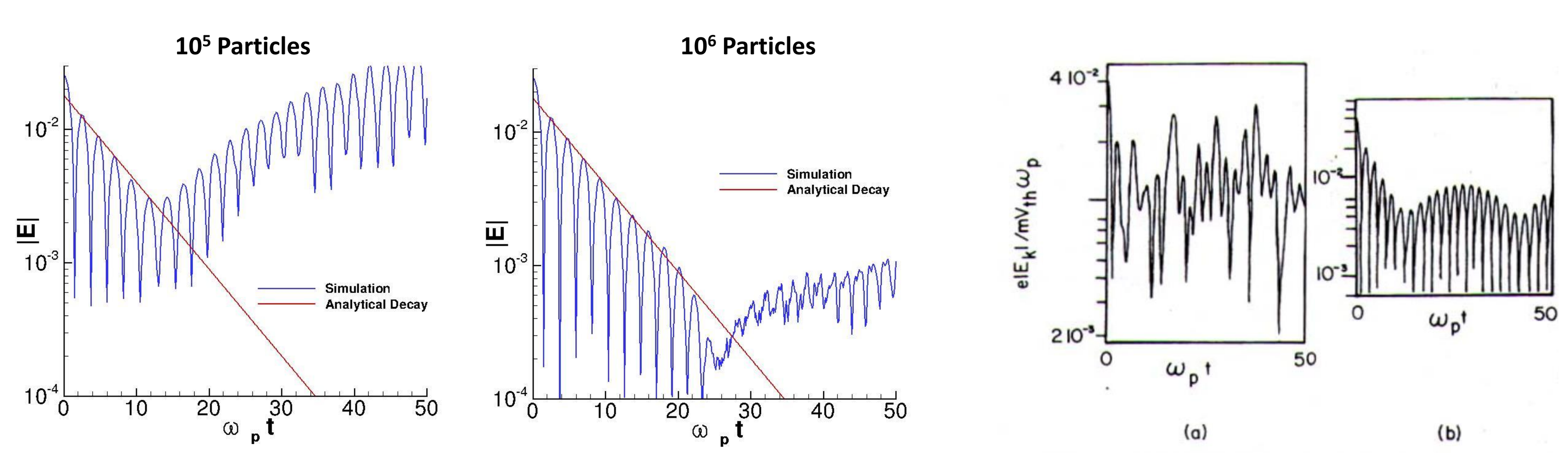
Validation Results

Electron-Electron Two Steam Instability



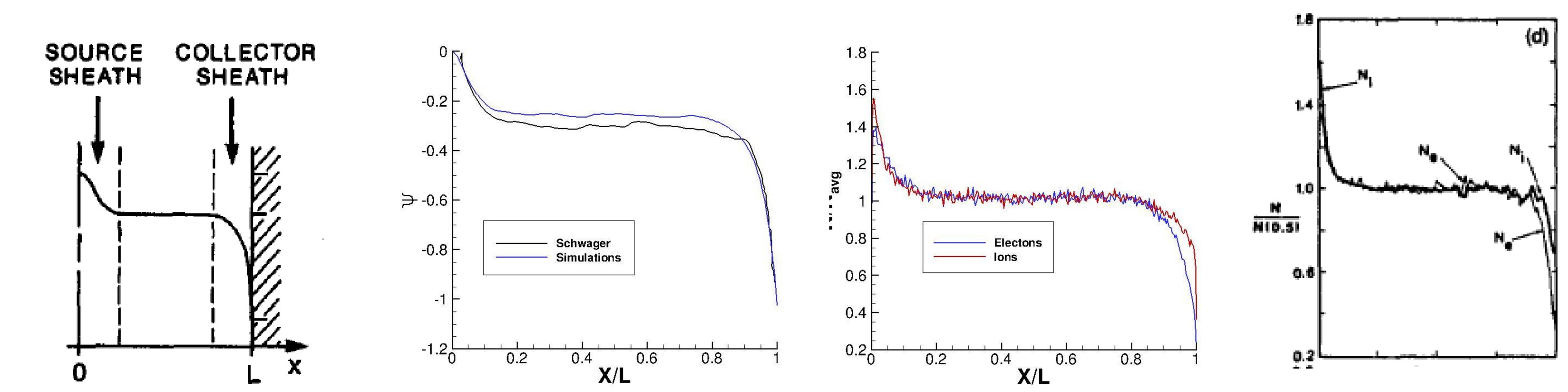
Velocity phase space and energy time history comparisons with results of Birdsall.[3]

Landau Damping



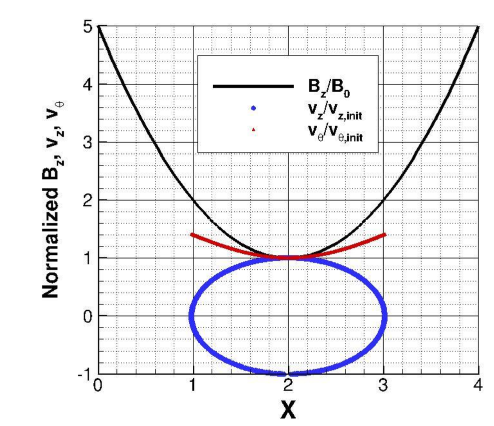
Electrostatic energy time history comparison with Denavit.[4]

Collector Plasma Sheath

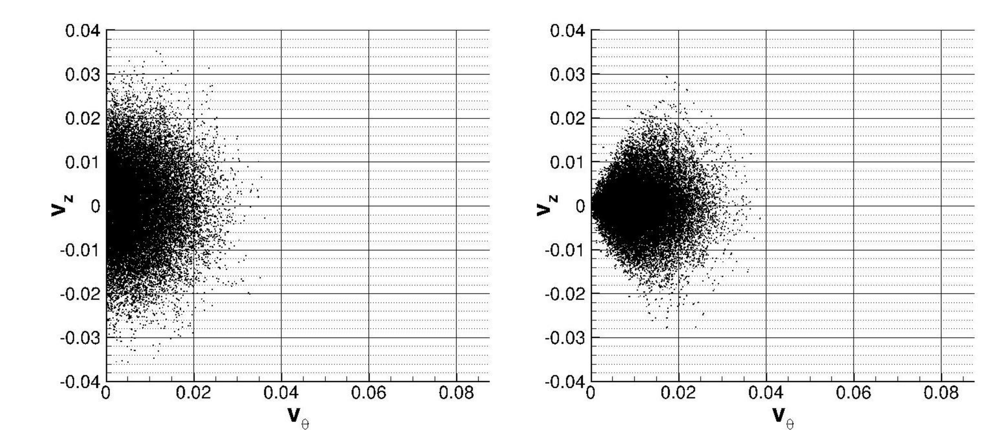


Comparison between our simulations and those of Schwager[6] for a collector sheath.

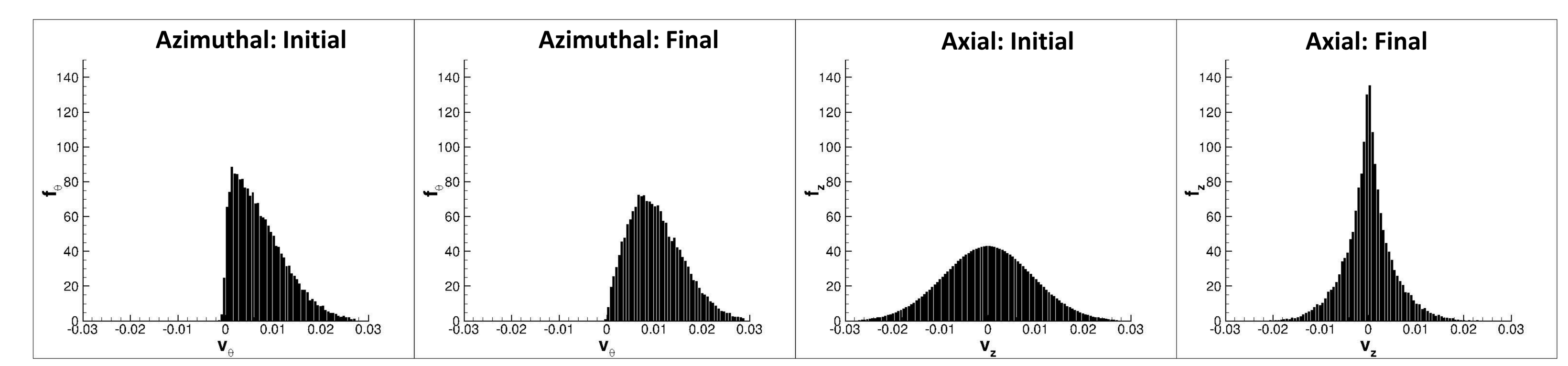
Magnetic Mirror (Preliminary)



Particle motion in a magnetic bottle.



Loss cone in a magnetic mirror.



Initial and final magnetic mirror distribution functions.

Conclusion

Code is validated with standard one dimensional test cases. Quasi-one-dimensional model for magnetic nozzle simulation is developed and its implementation shows promising results for initial test cases. Further evaluation of Q1D algorithm and implementation will be done in the future.

Acknowledgements and References

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