Simulation of Magnetic Field Guided Plasma Expansion

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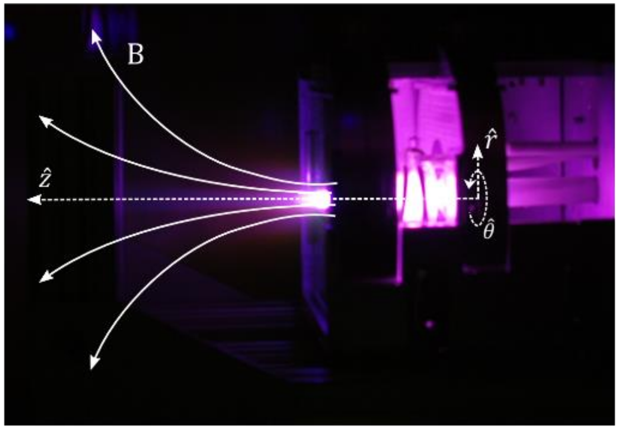
This research is funded by a NASA Space Technology Research Fellowship and DARPA contract number NNA15BA42C.

Magnetic field guided plasma expansions show up in the laboratory and in nature.

- Plasma thrusters (electrode-less, magnetic nozzle)
- Solar phenomena
- Astrophysical plasma jets
- Aurora Borealis



CubeSat Ambipolar Thruster

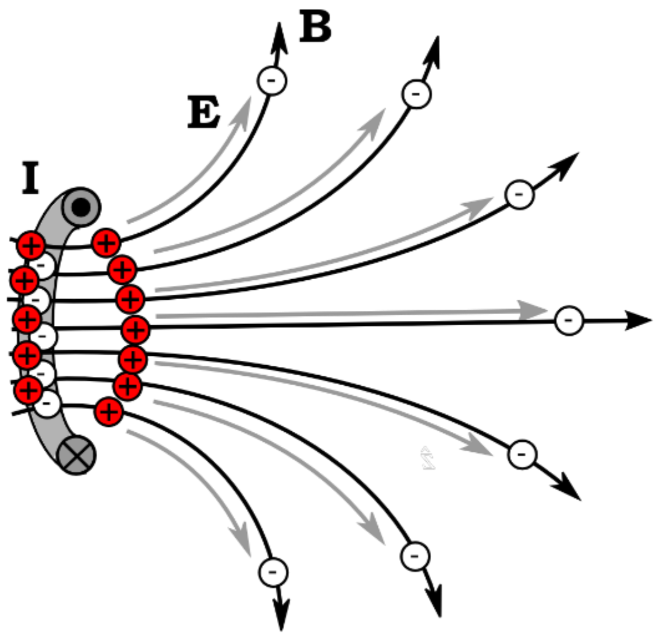

Aurora borealis

Ions can be accelerated during the expansion.

How are ions accelerated in these magnetic field expansions?

Ions can be accelerated by the electric field created by fast expanding electrons.

Quasi-neutral plasma



Vacuum

The magnetic dipole force can accelerate ions along magnetic field lines.

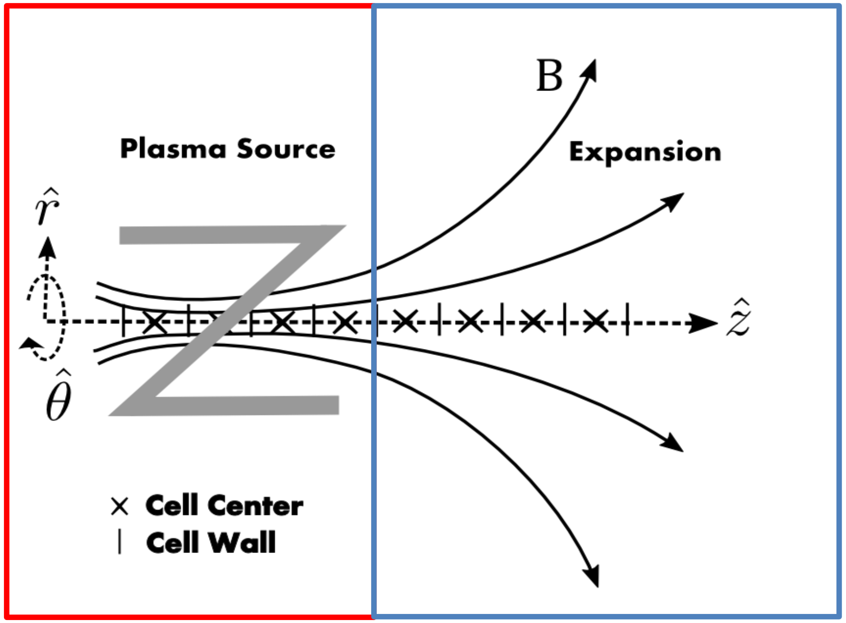
- Particles accelerated by magnetic dipole force. (μ = magnetic moment)

$$\boldsymbol{F}_d = \nabla(\boldsymbol{\mu} \cdot \boldsymbol{B})$$

- Quantity $(\boldsymbol{\mu} \cdot \boldsymbol{B})$ acts like a magnetic potential

The Quasi-1D PIC code incorporates 2D effects to a 1D electrostatic PIC code without 2D costs.

- Ion and electron particles
- Constant background neutral density
- Ion and electron collisions with neutral background
- Constant magnetic field in source region (1D)
- Decreasing magnetic field in expansion region

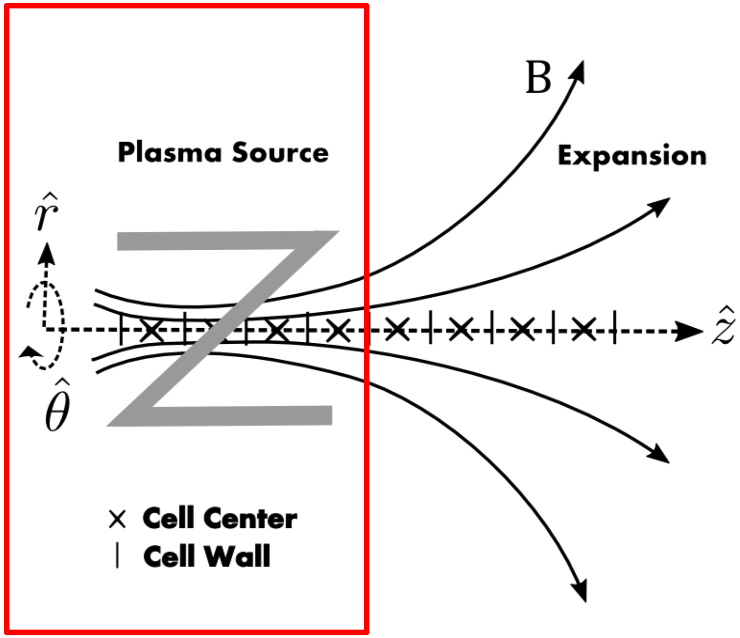


The plasma is heated by an oscillating electric field. Heated electrons collide with neutral background.

$$J_{y,tot} = \epsilon_0 \frac{\partial E_y}{\partial t} + J_{conv}$$

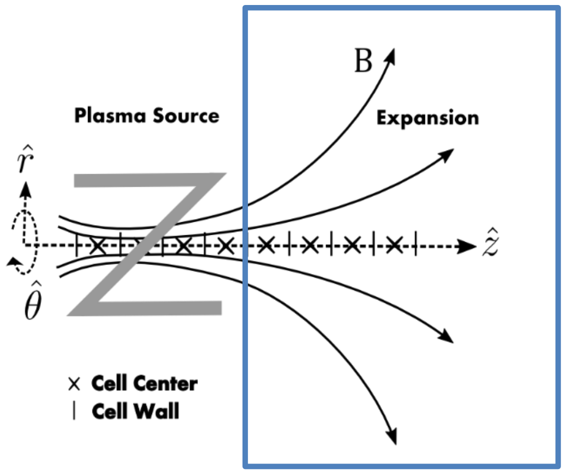
$$J_{y,tot} = \mathrm{J}_0 \sin(2\pi \times f \times t)$$

$$f \ = 10\ Mhz$$

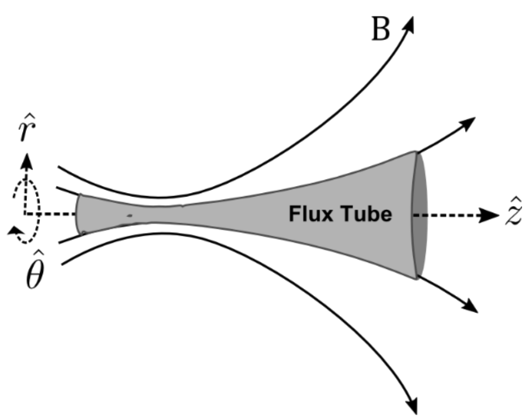


Based on Meige (2005)

The cross-sectional area variation is found by assuming particles follow field lines.



Cross-section variation



Magnetic field forces

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

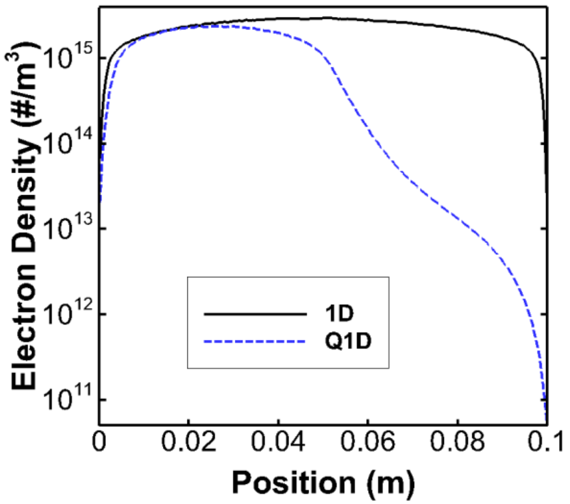
$$\frac{\partial v_{\perp}}{\partial t} = \frac{1}{2B}\frac{\partial B}{\partial s} v_{\parallel} v_{\perp}$$

Simulation parameters are chosen to compare with previous simulations.

Parameter	Value
Length	10 cm
Grid Cells	250
Time Step	5×10^{-11} s
Total Time	25 μs
Heating Current	100 A/m^2
Heating Frequency	10 MHz
Macroparticle Weight	2×10^8 Particles/Macroparticle
Neutral Pressure	1.23 mTorr
Neutral Temperature	293 K
Gas	Argon
Magnetic Field (B_0)	300 G

Similar to parameters used by Meige (2005) and Baalrud (2013)

Incorporation of two-dimensional effects leads to capturing ion acceleration.



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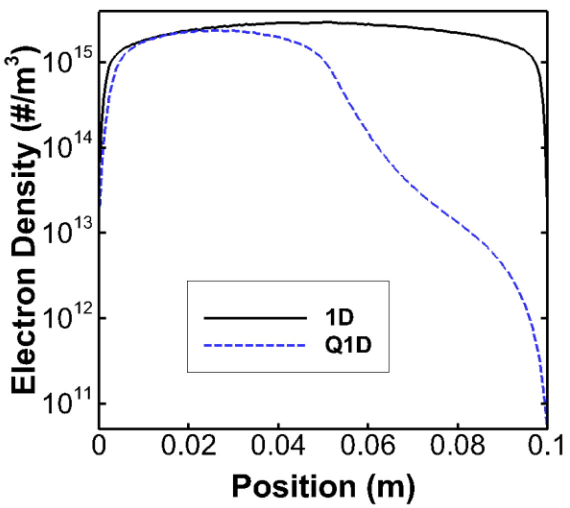

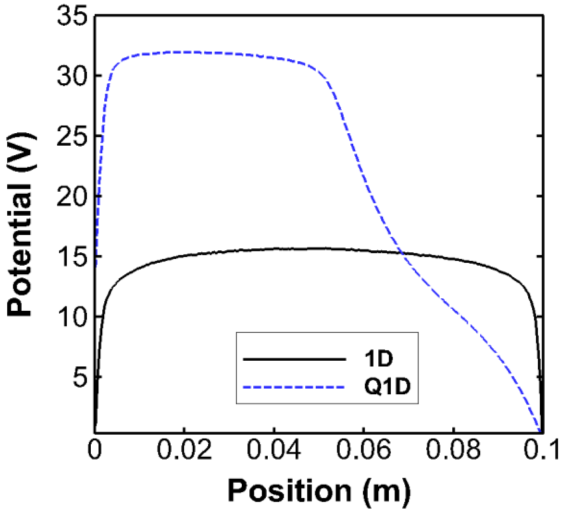

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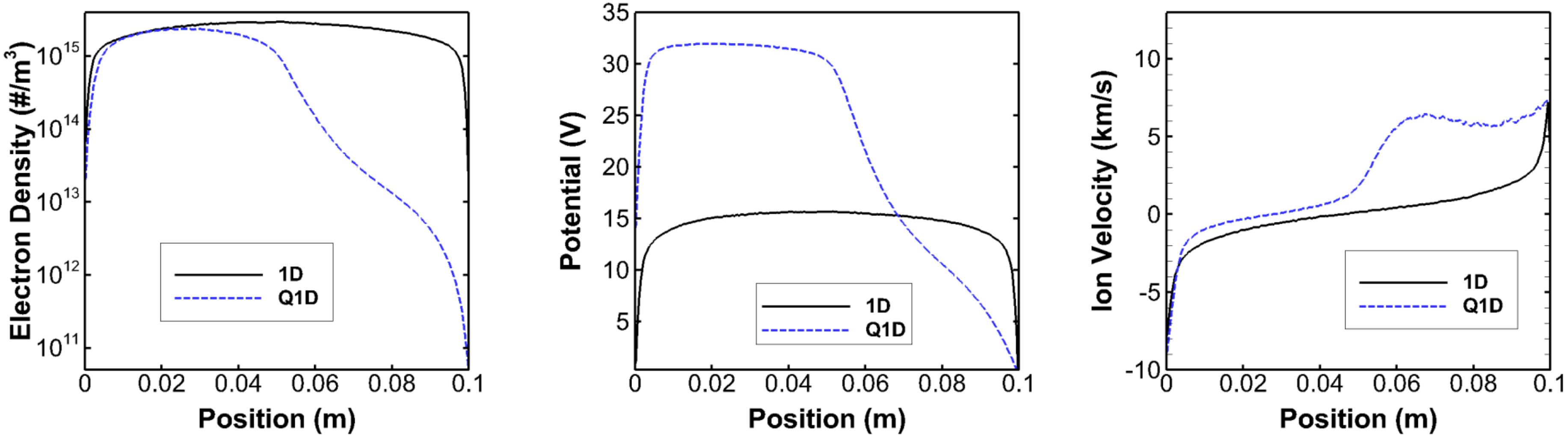
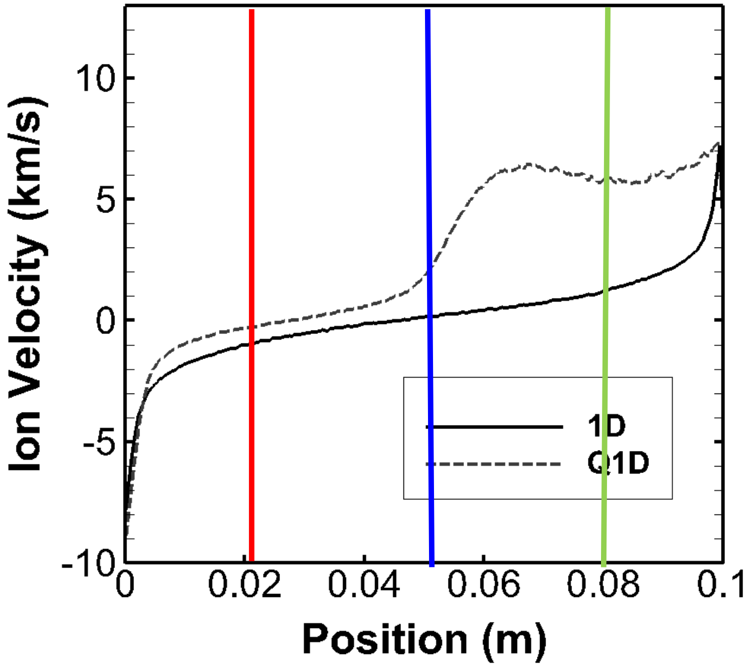
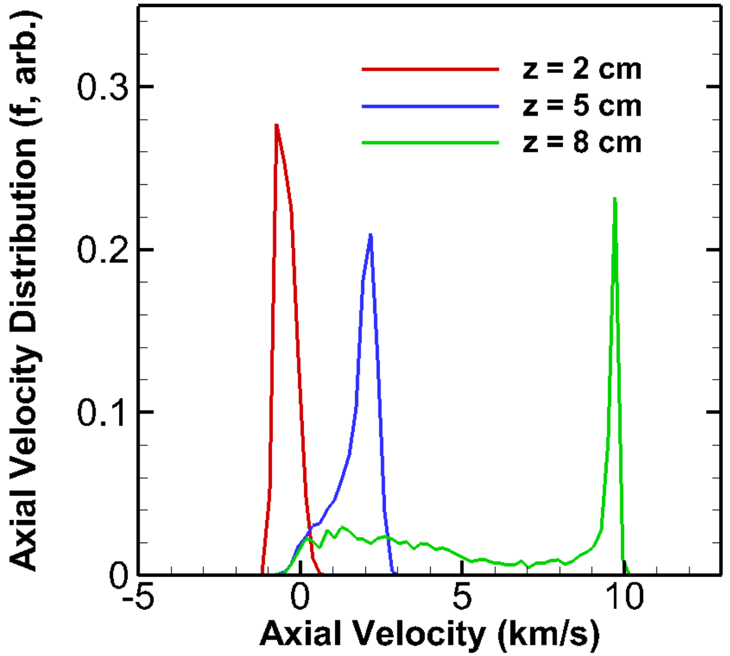


Ions develop into a beam with some lower energy particles.





Magnetic field effects on electrons leads to the acceleration of the ions.

The light electrons are heated in the heating region

⇩ $v_{\perp,e} \uparrow$

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Charge imbalance leads to the formation of an electric field which accelerates the ions out with the electrons

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Ion beam formation

Conclusions and future work.

- Electrons driven by magnetic field forces create potential drops which result in ion acceleration.
- Future simulations will investigate HDLT, CAT, and VASIMR ion acceleration mechanisms.
- Perform further parametric study with this test problem. (Additional magnetic field topologies, heating currents, etc)

Acknowledgements

Thank you for your time!

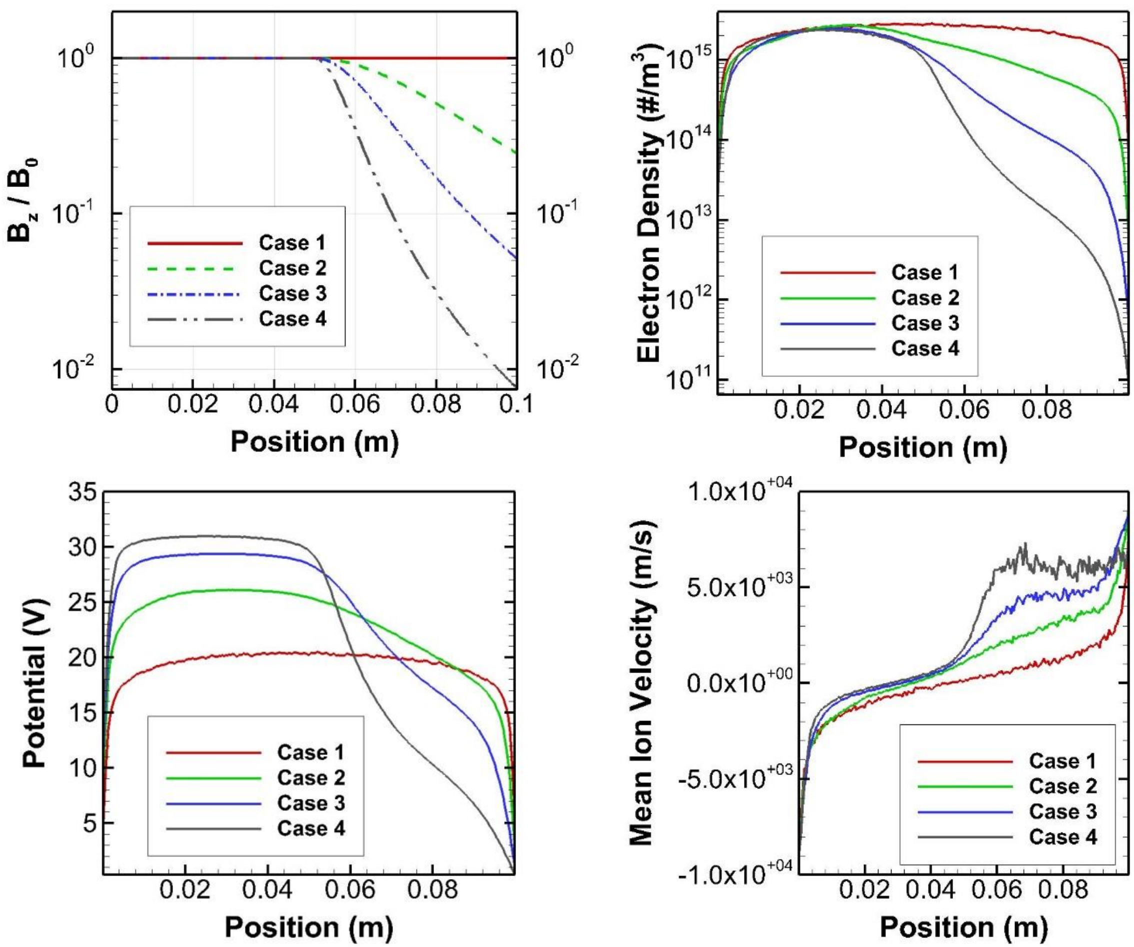
Questions?

This research is funded by a NASA Office of the Chief Technologist Space Technology Research Fellowship and the DARPA contract number NNA15BA42C. Simulations were performed on the NASA Pleiades and University of Michigan ARC FLUX supercomputers.

Thank you to the members of PEPL and NGPDL for their discussions about this research.

BACKUP SLIDES

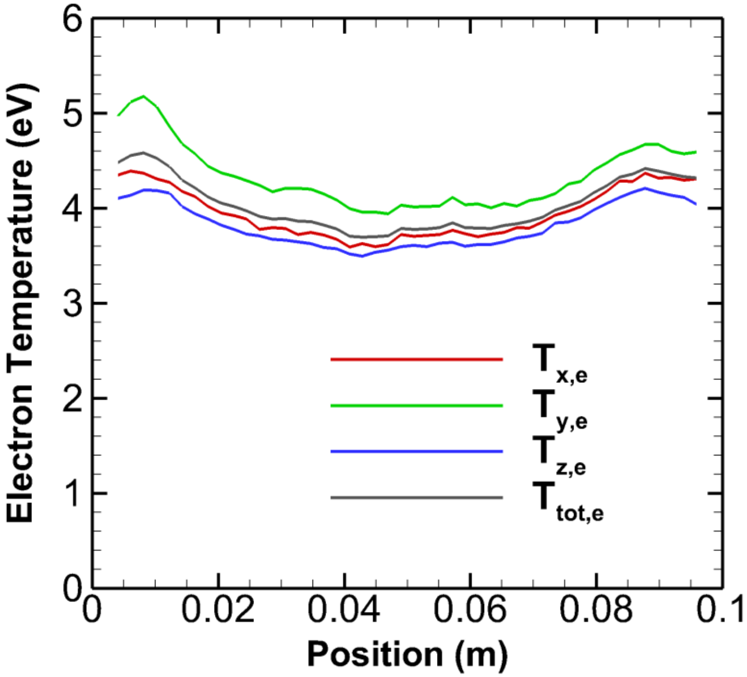
Rapid expansion leads to rapid potential drop and more ion acceleration.



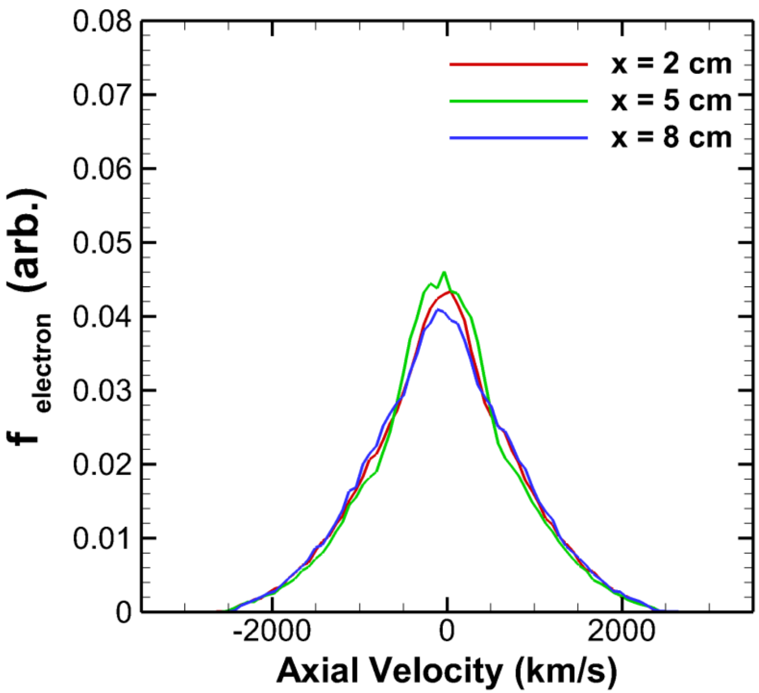
Kinetic simulations are necessary to capture important ion acceleration physics.

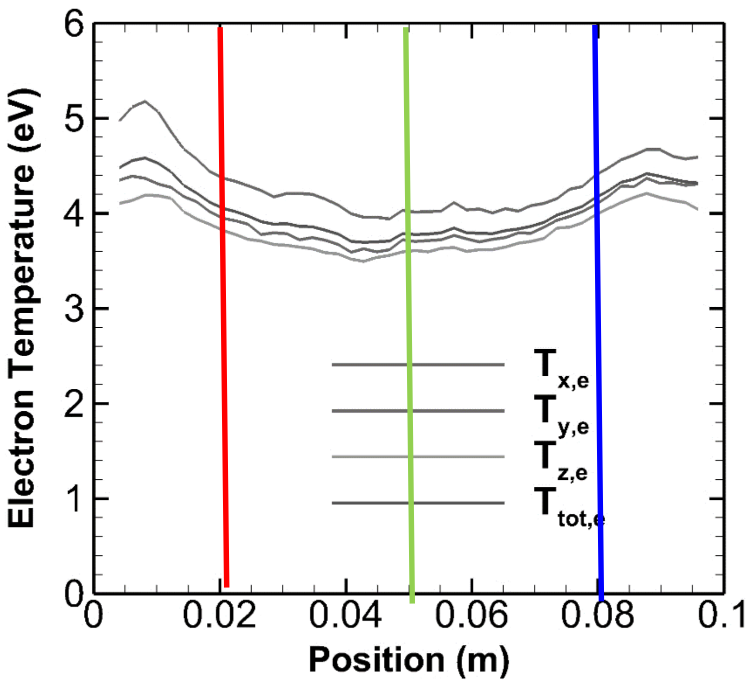
- Evolution of the ion and electron energy distribution functions
- Instabilities in the plasma
- Potential structures which form in the plasma plume
- Capture most fundamental physics for ion acceleration

Electron temperatures are around 4-5 eV

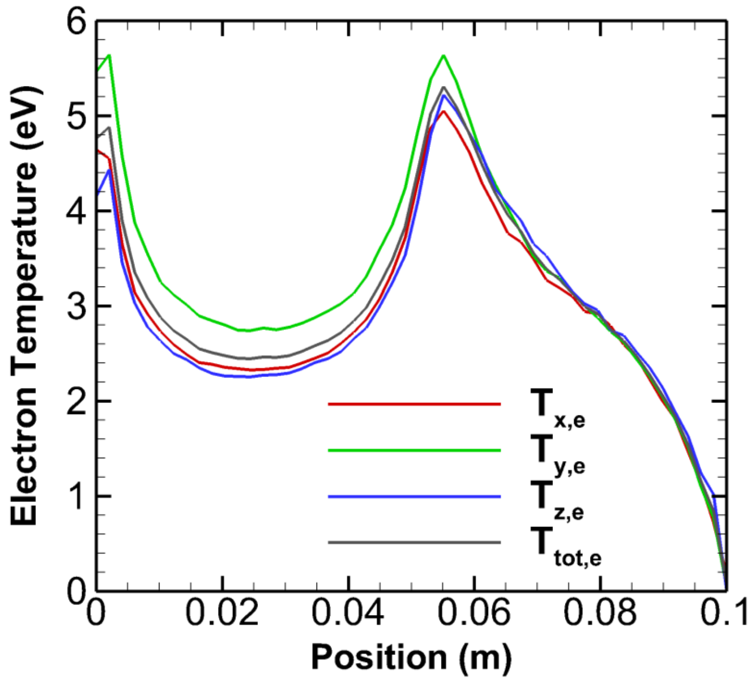


Electron distribution only varies slightly spatially.

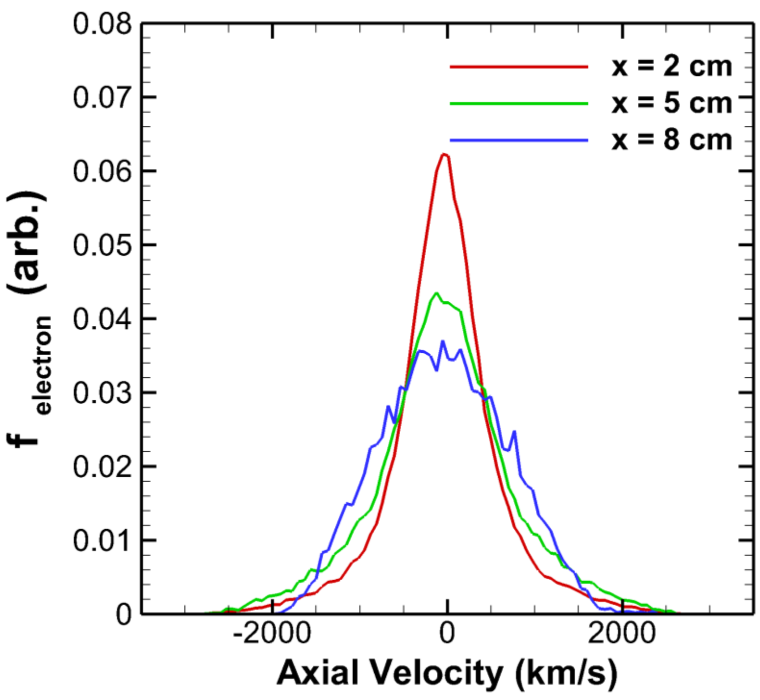


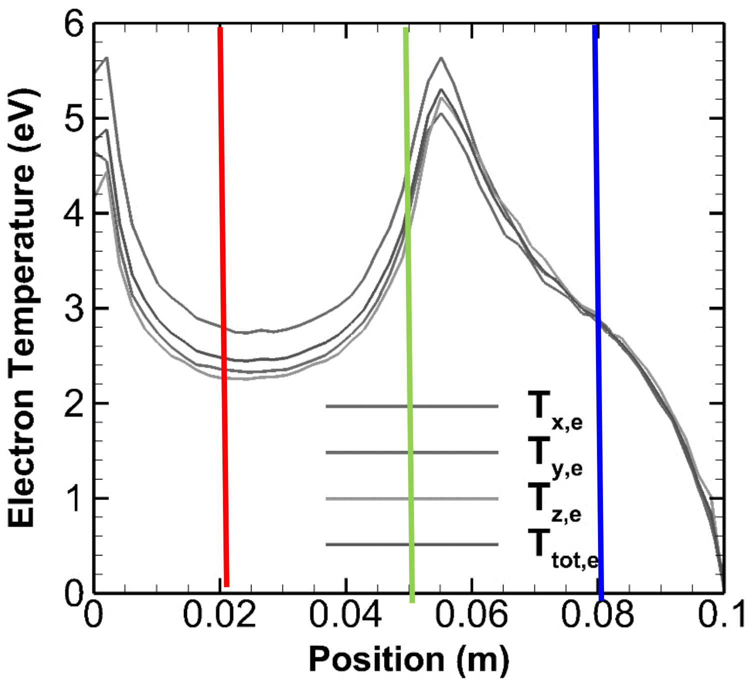


Electron temperatures vary greatly through domain when including two-dimensional effects

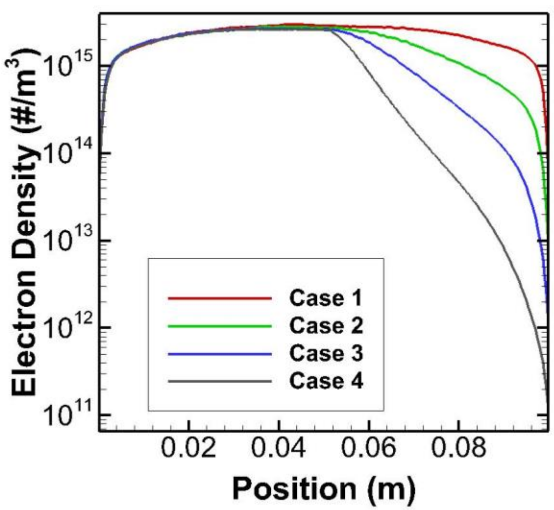


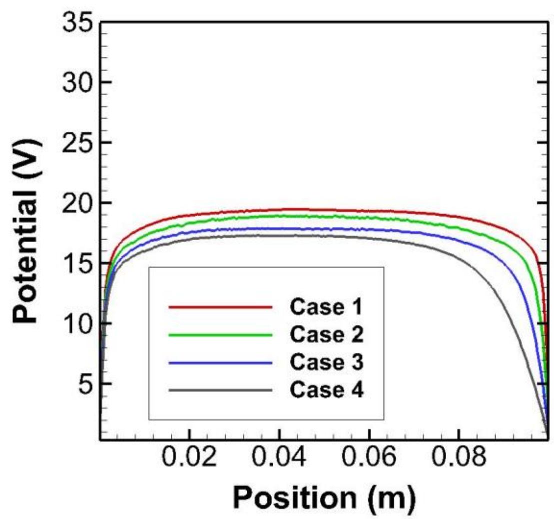
Electron distribution shows significant variation through the domain.

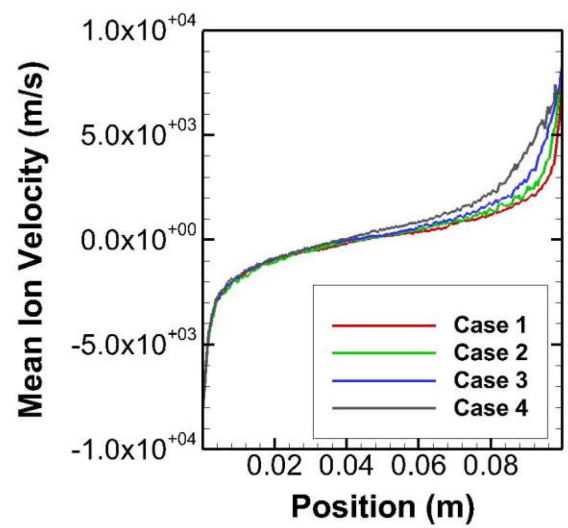




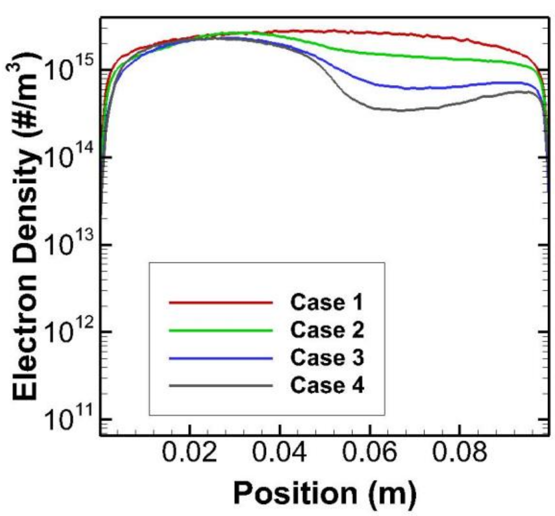
Cross-sectional area variation changes density, but no major ion acceleration is seen.

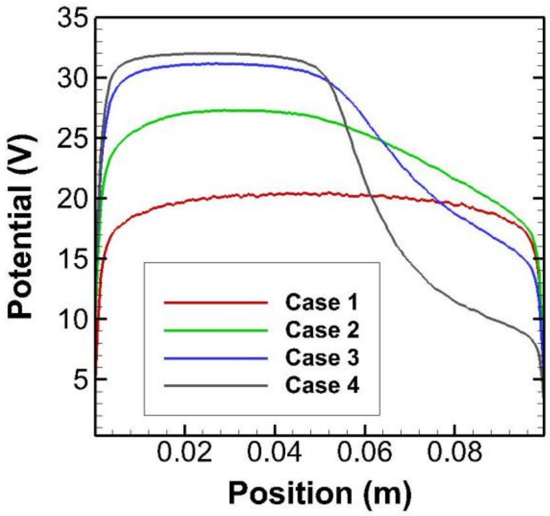


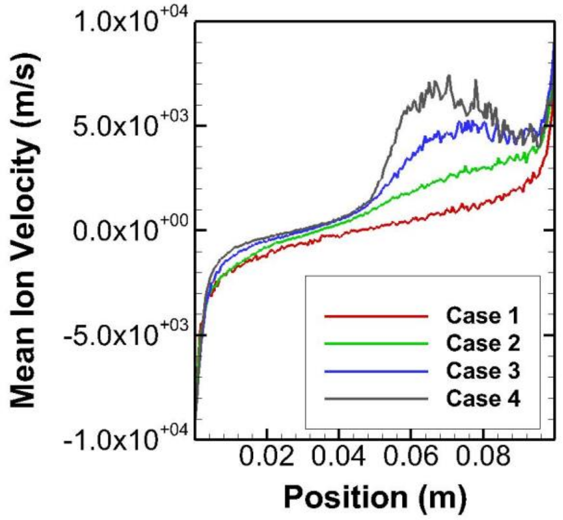




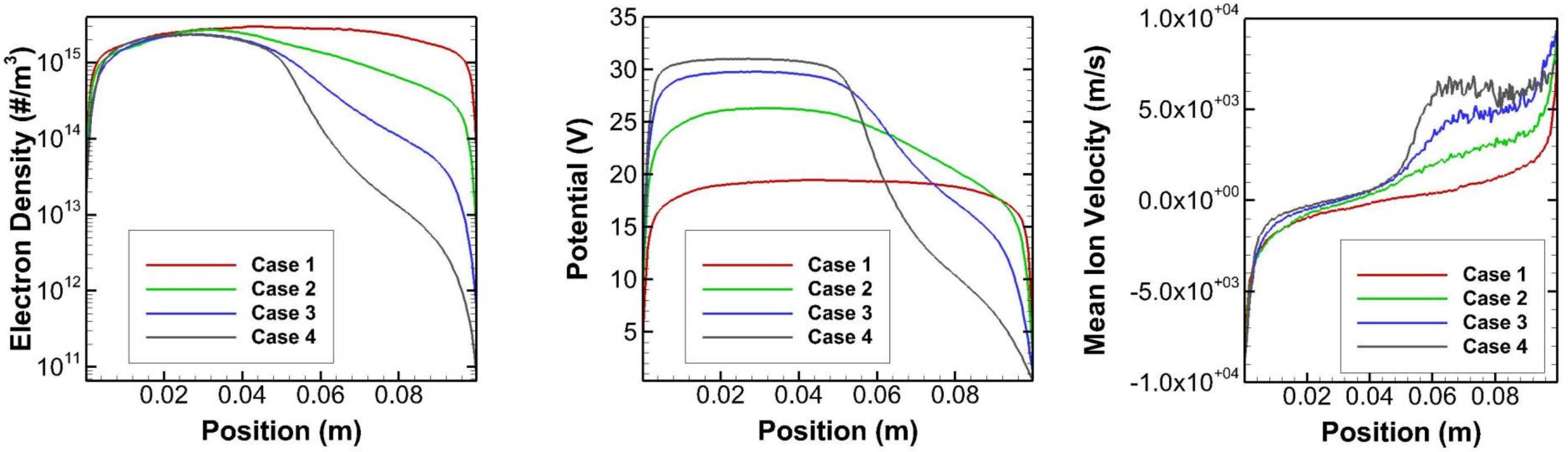
Magnetic field forces result in ion acceleration.







Full simulations shows characteristics of both effects.

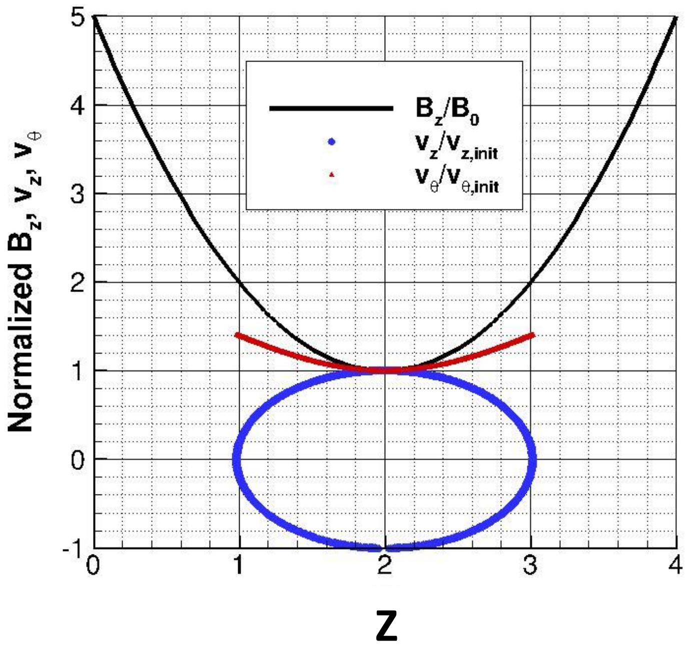


Magnetic mirror simulation setup

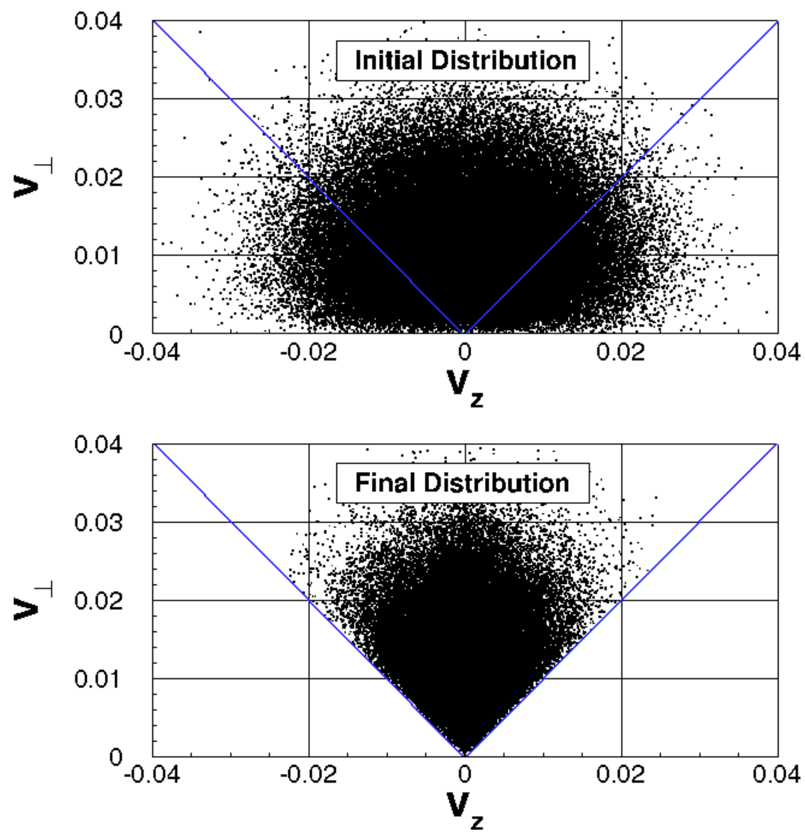
Goal:
- Validate magnetic field forces

Physics:
- Charged particles moving from weak magnetic field to strong magnetic field region are confined for certain conditions.

Setup:
- One-dimensional domain
- Particles loaded Maxwellian velocity distribution at center of domain.
- Ignore electric field forces, uncoupled particle motion.



Code correctly reproduces analytical loss cone



Magnetic mirror velocity distribution
and loss cone (blue)

$$\frac{B_{max}}{B_{min}} = 2.0$$

Conditions for trapped particles:

$$\frac{v_\perp^2}{v_\parallel^2 + v_\perp^2} > \frac{B_{min}}{B_{max}}$$

Loss Cone:

$$\frac{v_{\parallel,0}}{v_{\perp,0}} = \sqrt{\frac{B_{max}}{B_{min}} - 1} = 1.0$$

The fraction of particles trapped agrees well with theory

$$\gamma = \sqrt{1 - \frac{B_{min}}{B_{max}}} = \frac{\sqrt{2}}{2}$$

$Initial\ Particles$: $10^5\ Particles$

$Predicted$: $7.0710 \cdot 10^4\ Particles$

$Simulation$: $7.0733 \cdot 10^4\ Particles$

$Error$: 0.033%

Quasi-neutral plasma expansion simulation setup

Goal:

- Validate cross-sectional area variation

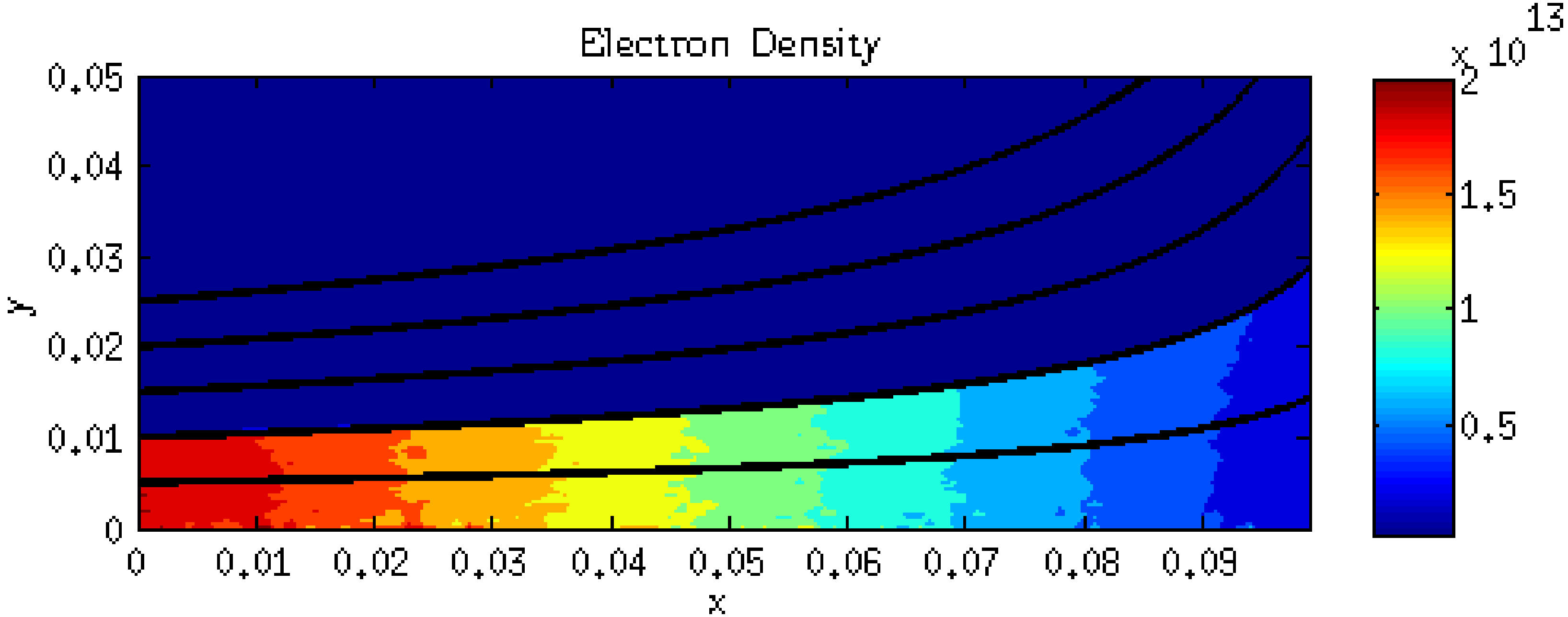
Physics:

- A quasi-neutral plasma beam expansion is controlled by a strong magnetic field.

Setup:

- Hydrogen ions and electrons are injected into a domain with a diverging applied magnetic field.
- Simulations are compared between a 2D r-z simulation (OOPIC) and QPIC.

OOPIC simulation of quasi-neutral jet expansion following magnetic field lines



Results from QPIC agree well with the centerline number density from OOPIC