GPU-Accelerated 2D Kinetic Modeling of Transport in a Hall Thruster Channel

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Abstract

The causes of anomalous electron transport across the magnetic barrier in Hall thrusters is an area of ongoing research. An understanding of the mechanisms causing this transport would allow for the development of turbulence models for this process. Since the transport is kinetic, the 2D particle-in-cell code LTP-PIC serves as a fitting numerical tool to carry out this study. Such simulations may also be used to study dominant modes using a spectral diagnostic. The simulation is extended azimuthally to observe periodic structures. Given that PIC codes are computationally expensive, requiring a large number of particles and time steps, adapting this MPI + OpenMP portable code to GPU using the OpenACC standard decreases runtime while maintaining a single code base.

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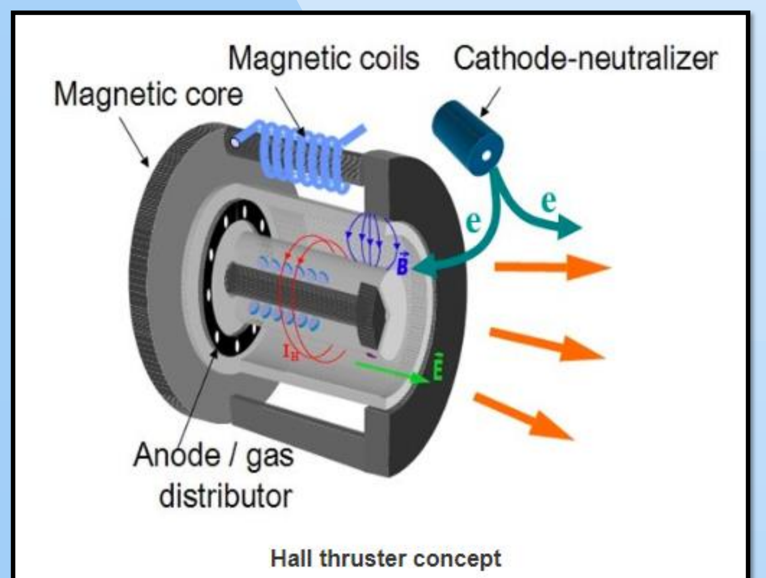
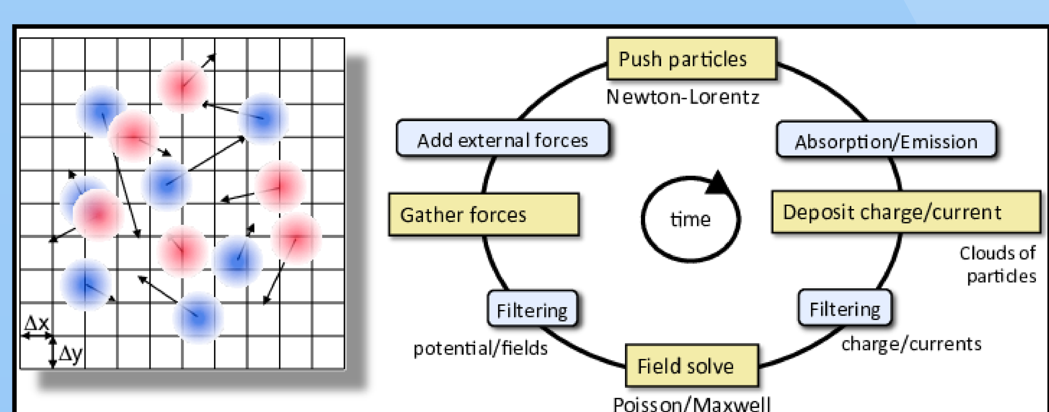
BACKGROUND

- Hall thrusters are a popular form of electric propulsion, used for:
  - satellite orbit maintenance
  - deep space travel



Hall thruster diagram showing the flow of electrons [1]

  - Issue: The mechanism by which electrons cross the magnetic field lines to reach the anode is unknown – "anomalous electron transport"
- Low temperature Hall thruster plasma simulated via Particle-in-Cell (PIC) modelling
- Our group designs low-temperature plasma PIC, or LTP-PIC

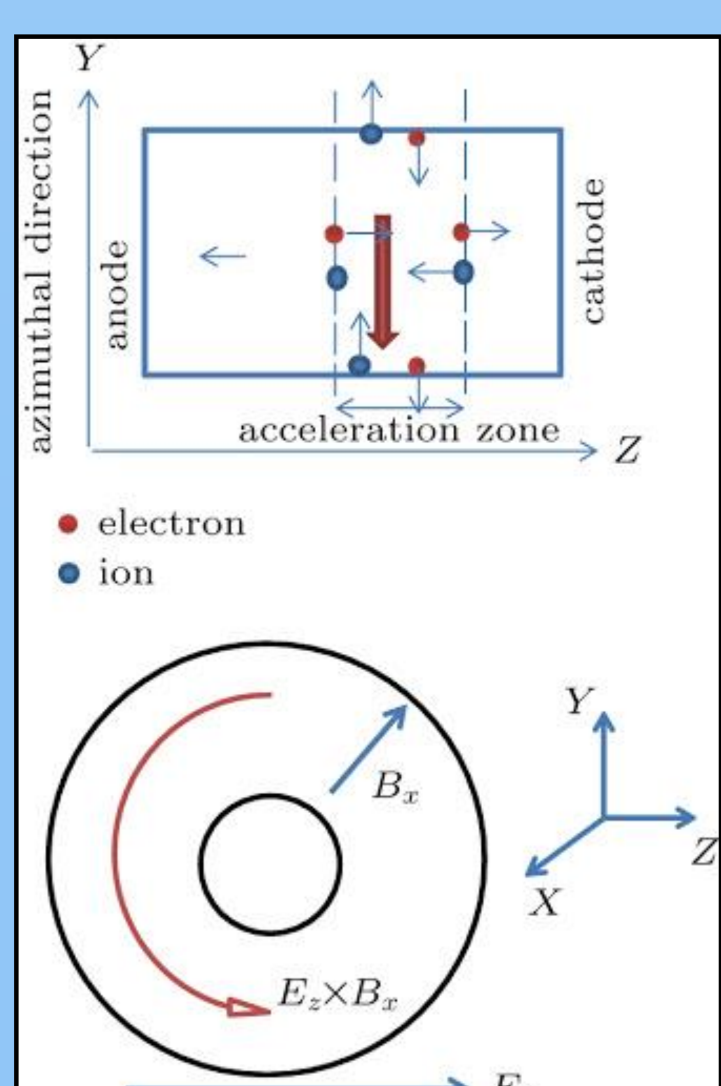


Flowchart of fundamental Particle-in-Cell operation [2]

  - Issue: PIC can take days to run

OBJECTIVES

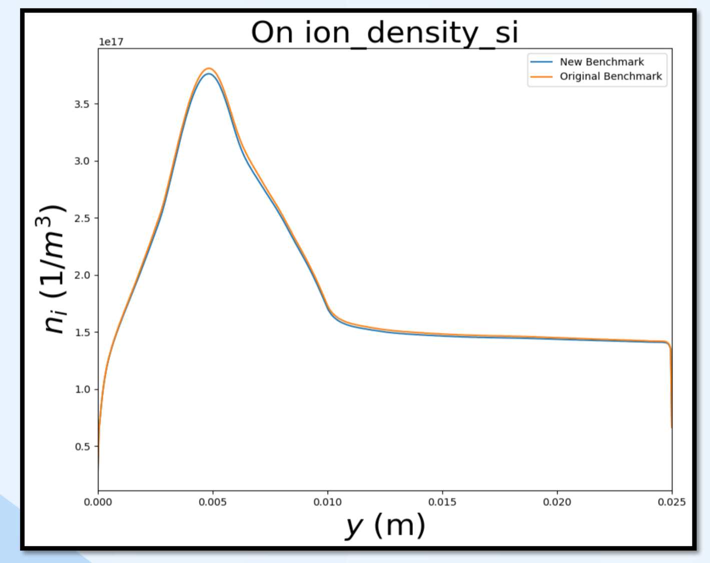
- Investigate anomalous electron transport
- Electron Cyclotron Drift Instability (ECDI)
- azimuthal wave
- most likely explanation of transport
- Study scaling behavior of PIC code
- OpenACC standard for GPUs
- MPI + OpenMP portable code



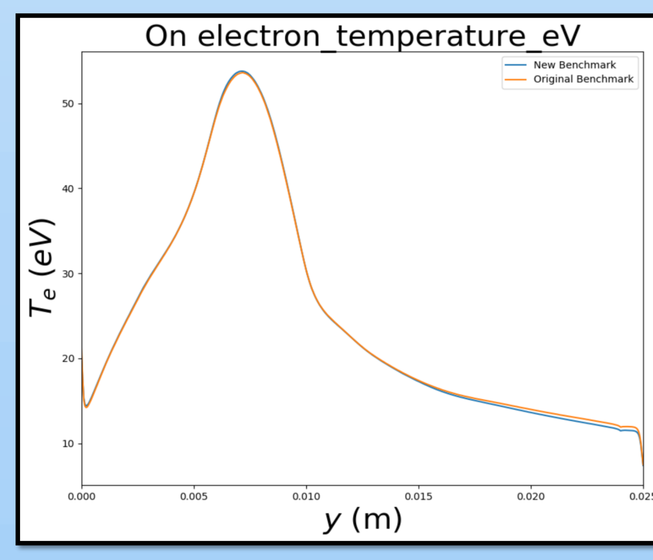
Diagrams showing the simulation plane (above) and the electron cyclotron drift instability (below) [3]

SIMULATIONS

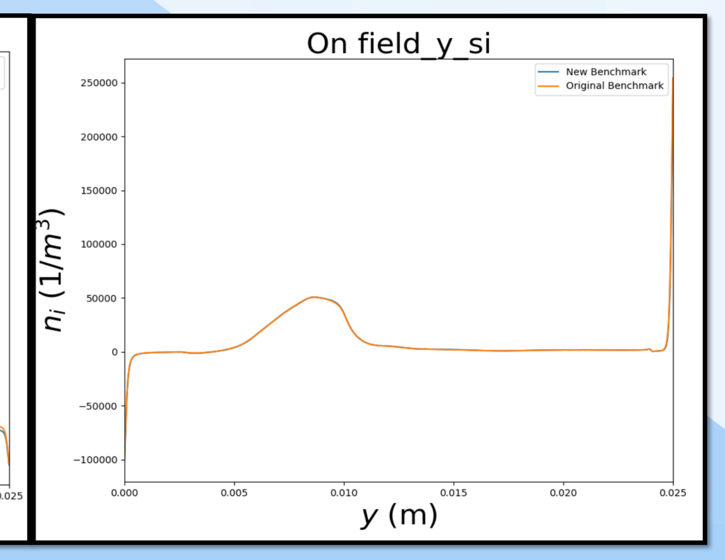
- Reran the Benchmark simulation [4], which was updated to include GPUs
- Indicates that GPU code does not yield different results compared to CPU code
- Bottleneck in decreasing runtime is the Poisson field solver
  - Using Hypre library



Percent difference: 1.3%



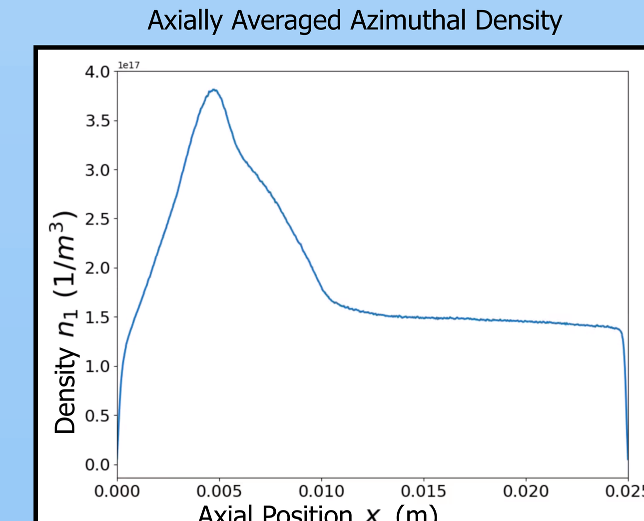
Percent difference: 0.9%



Percent difference: 3.9%

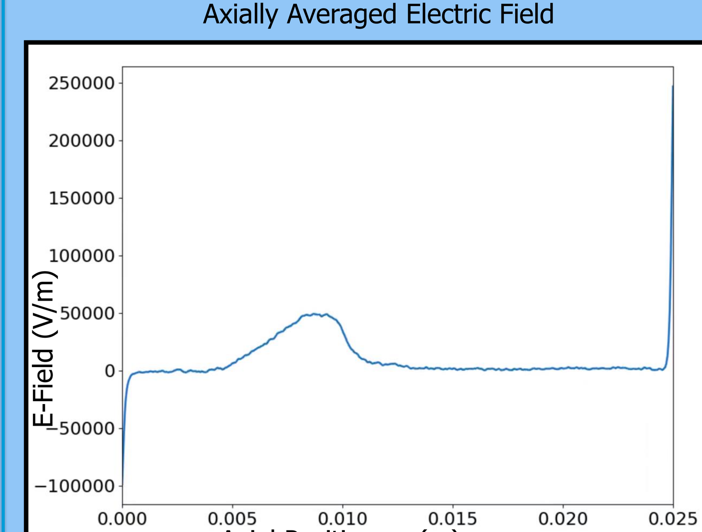
- Benchmark simulates 20 μs over 4 million steps
- Images below are stills from animations during quasi-steady-state
- Use the QR code under References to see these and other animations

Axially Averaged Azimuthal Density

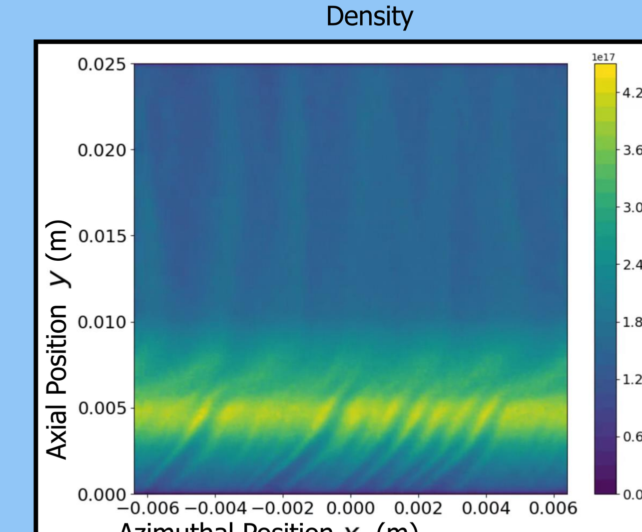


- Simulation reaches quasi-steady-state after about 16 ms
- The axial electric field local peak lags the plasma density peak by about 0.4 cm
- In the density animation, waves form in the azimuthal direction
  - A suspected cause of anomalous electron transport
- Note that the peak in the Axially Averaged Azimuthal Density plot above matches with the 2D density plot below, at 0.5 cm.

Axially Averaged Electric Field

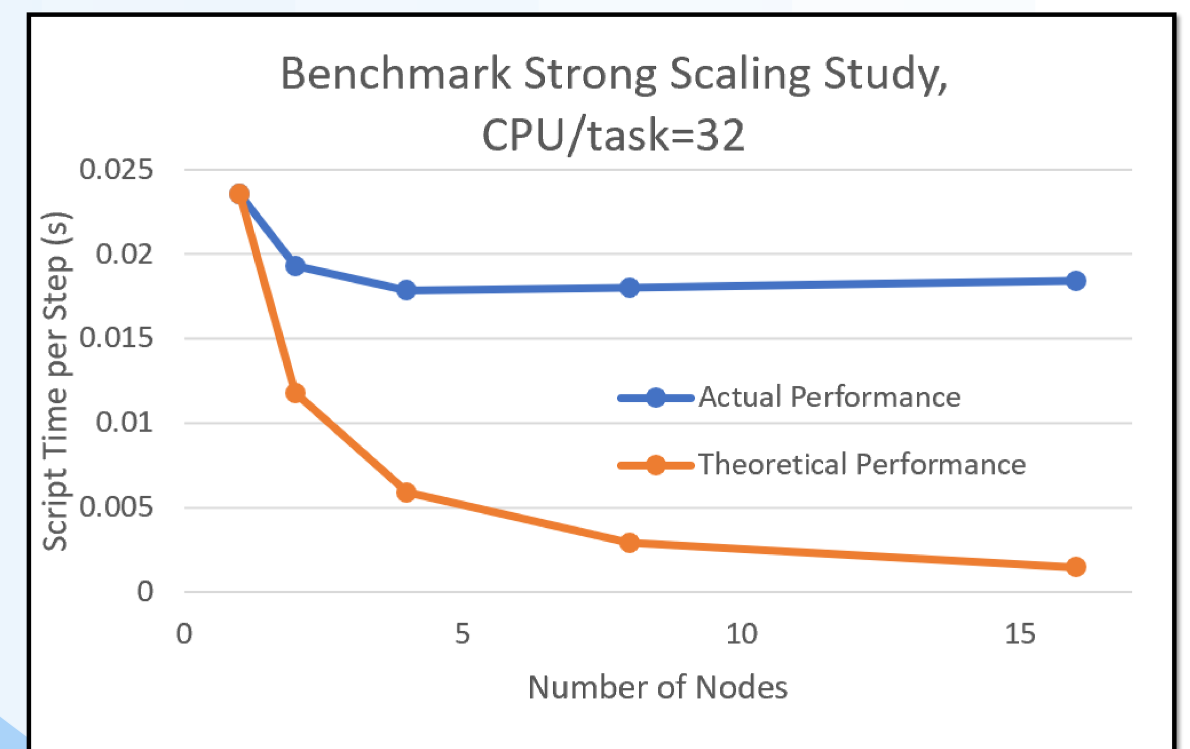


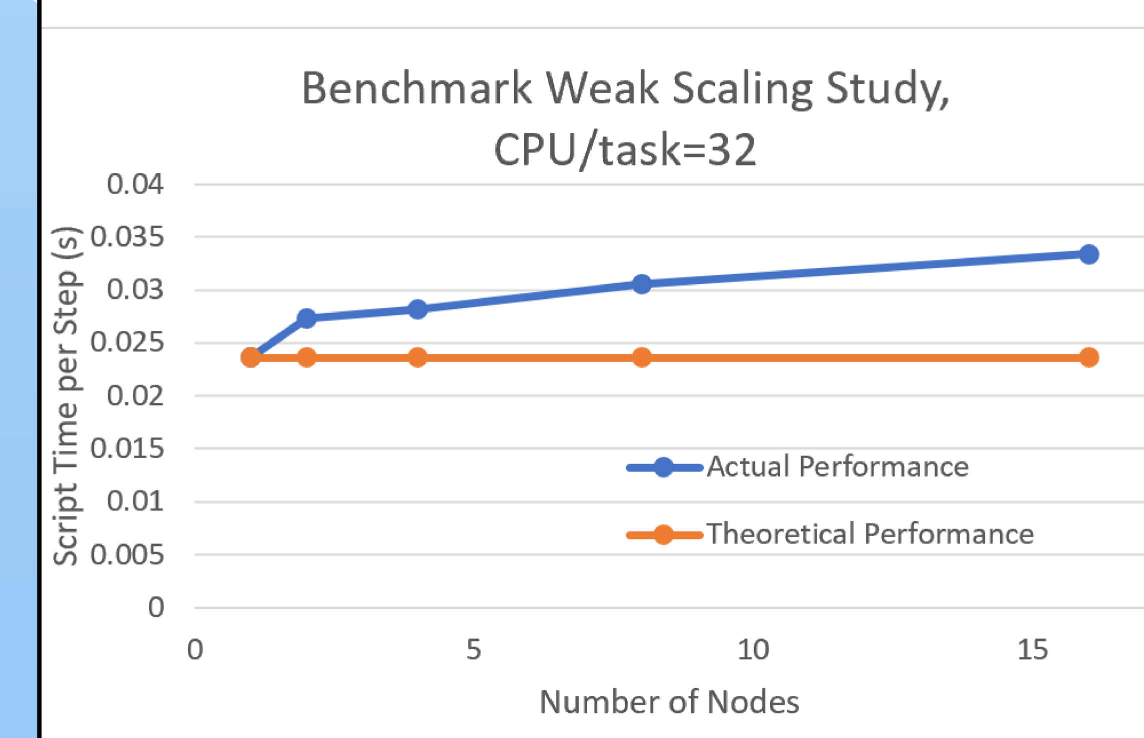
Density



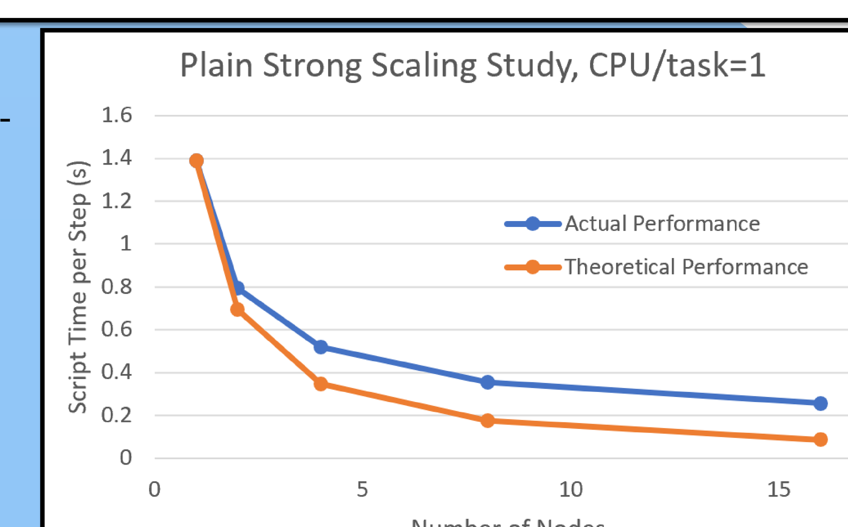
SCALING

- Observe how LTP-PIC runtime change with different simulation sizes and resources
  - Strong scaling: Increasing system resources while keeping simulation size constant
    - Typically more rigorous and difficult to achieve
  - Weak scaling: Increasing the simulation size in proportion to the increase in system resources
    - LTP-PIC currently satisfies weak scaling, but not strong scaling
    - Studies done on the Traverse cluster

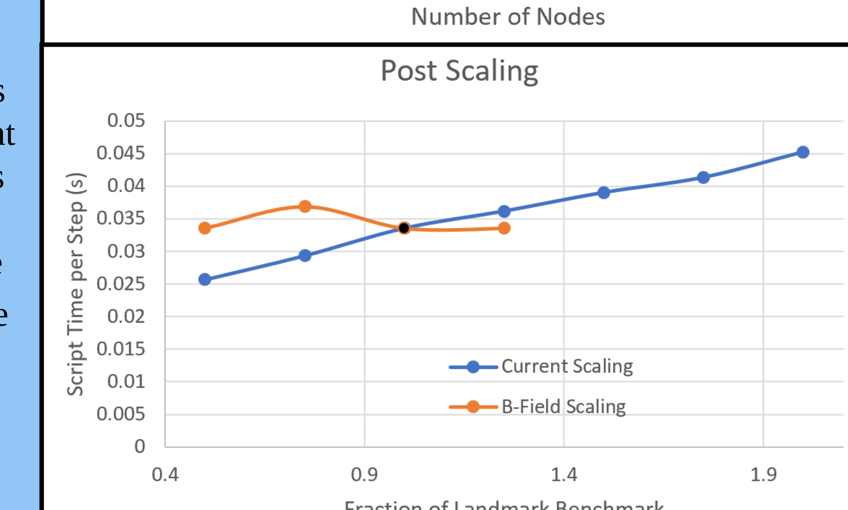




- However when LTP-PIC is not compiled as a benchmark, it comes much closer to achieving strong scaling

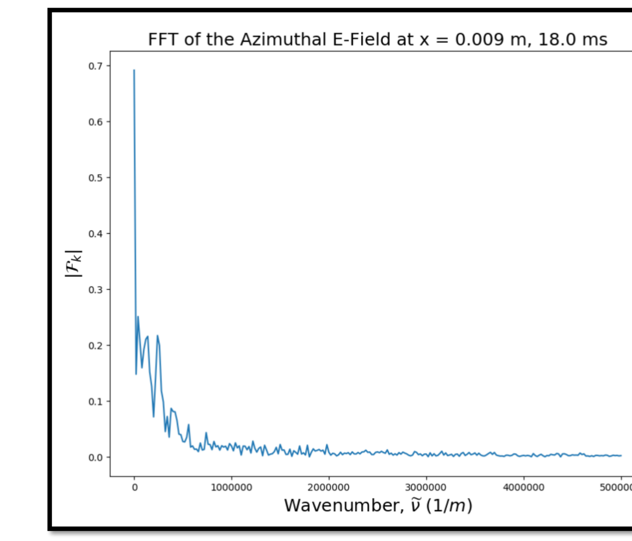


- Preliminary analysis of scaling the current and B-field suggests that the B-field has no effect on runtime
- Possibly because the current affects the number of particles, while the B-field does not

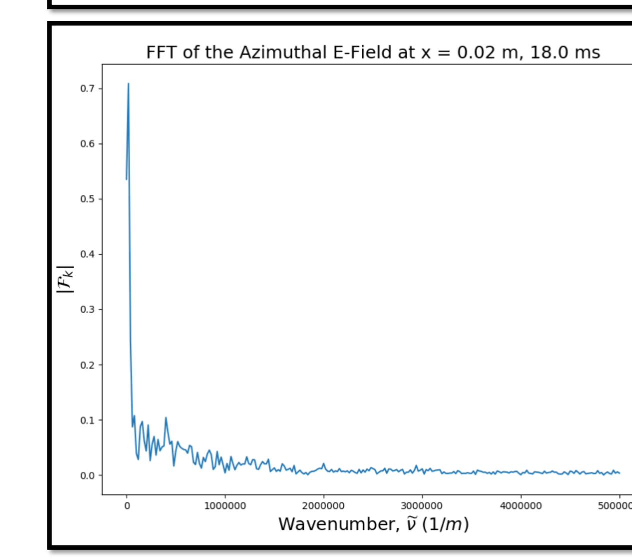


DISCUSSION

- The fast Fourier transforms are normalized and sampled at varying axial locations
- At x = 0.9 cm, the Axially Averaged Electric Field plot local maximum can be seen by having larger peaks on lower wavenumbers



- At x = 2 cm, the Axially Averaged Electric Field plot is more uniform
  – greater periodicity



FUTURE WORK

- Make LTP-PIC a 3D code from its current 2D grid
- A bottleneck in reducing runtime is the field solver and particle-push
  - Use Ampere's law to evolve E-field
- Study the effect of scaling the E-field on runtime
- Add an anode to the simulation and observe the effects its bias would have
- Scale the code with nearest grid point interpolation
  - Compare to bilinear interpolation
- Conduct a Fourier analysis over time
- Analyze the total current through the Hall thruster system

REFERENCES

For animations and citations:

https://suliposter.weebly.com/

ACKNOWLEDGEMENTS

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