GPU Accelerated Simulations of Channel Formation for LWFA

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Motivation

- Low-Z plasma waveguides improve consistency of high energy electrons (10’s of GeV) from laser wakefield accelerators
- Short, medium-intensity laser pulse ionizes gas creating low density plasma usable as waveguide
- Simulation (EM/ES PIC) can provide insight into the stability, pressure, uniformity, etc. of the plasma channel - but expensive!

- **Motivation**: Plasma channels can be useful waveguides for laser wakefield acceleration
  - How do the channel properties depend on the laser pulse and neutral density?

We will show our efforts towards answering this question, *focusing on performance*

GPU Acceleration

Goal: utilize all available hardware for simulations

Design:

- All data structures and updaters are **agnostic**

PIC needs:

- Fields, particles (depositers and interpolaters), reactions
  - Particles naturally independent/parallel but unordered
  - Fields require neighbor info, but ordered
  - Reactions independent and can be ordered

Let's look at each of these components

GPU Acceleration Fields

Fields can exist in any combination of memory spaces

Need curl calculation for Maxwell's equations

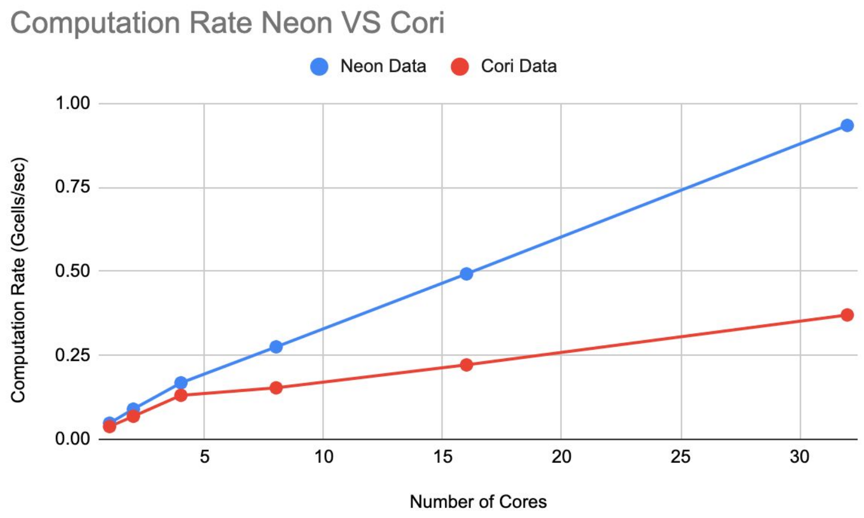
- We include ability to model dielectrics and PEC embedded boundaries (cut-cells)
- Applications beyond LWFA including photonics, SRF cavities, antennas, etc.

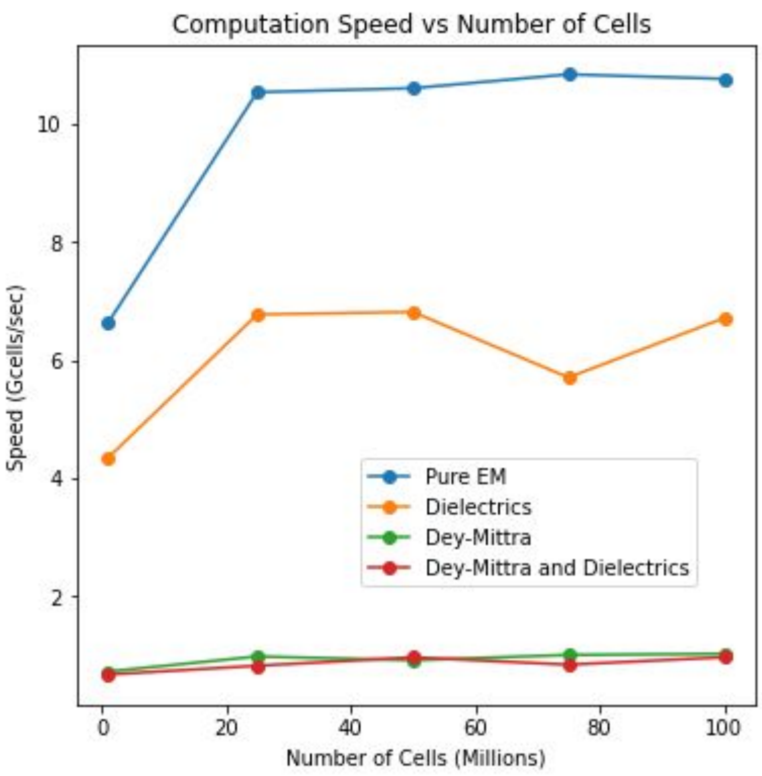
GPU techniques:

- Thread over fast direction within each kernel
- Align/coalesce memory access
- Reuse accessed memory while in cache

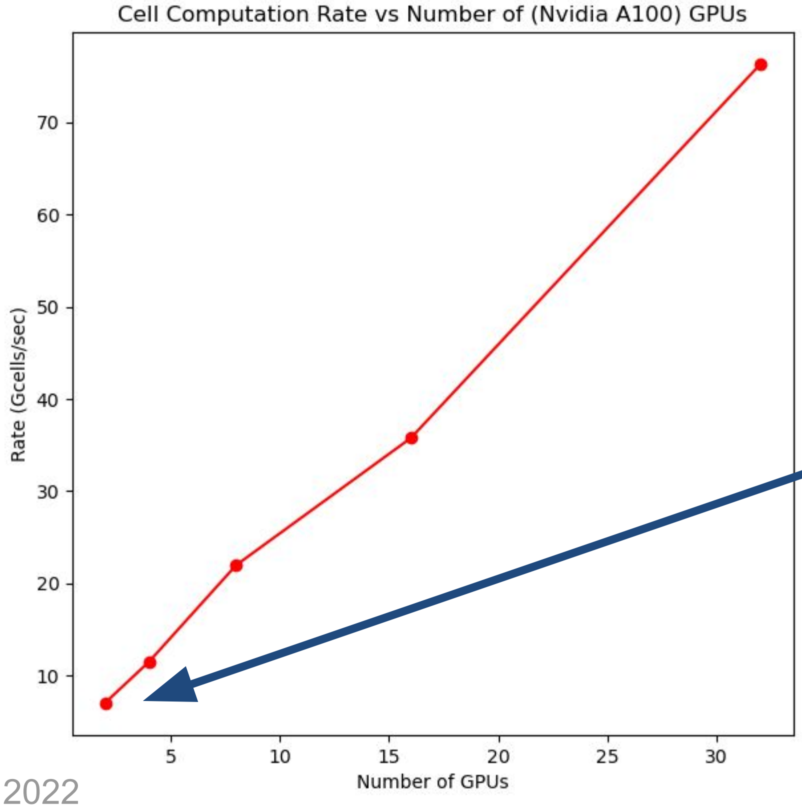
GPU Acceleration Fields

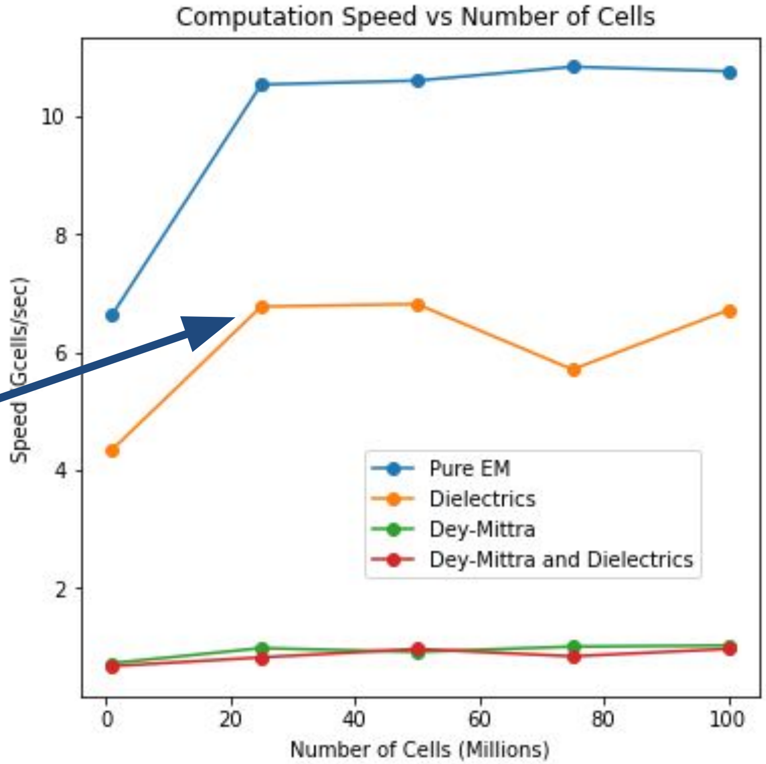
- CPU speeds up to 1 Gcell/s with 32 cores on Neon (AMD Epyc)
- A100 GPU speed >10 Gcell/s





GPU Acceleration Fields





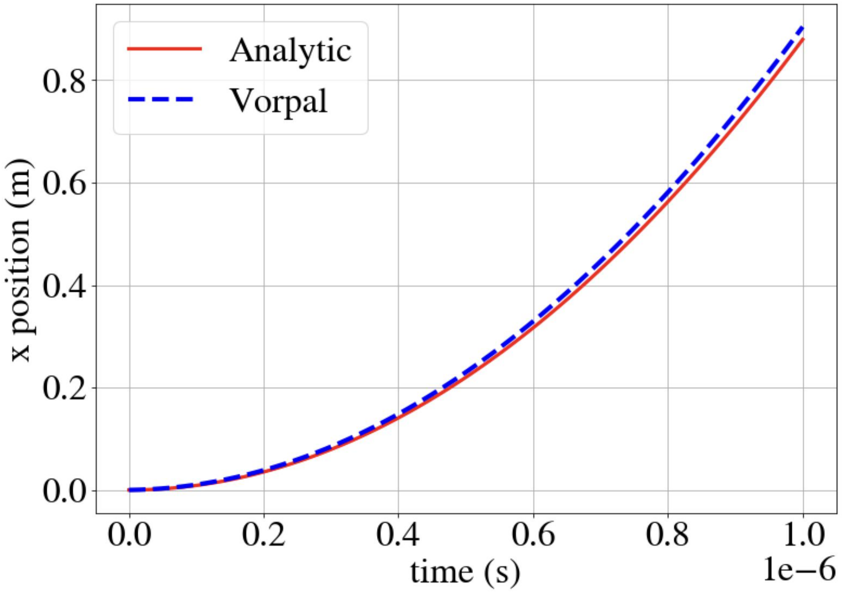
GPU Acceleration Particles

Recently implemented EM particles, these are *preliminary results*

Validate results:

- **<u>Constant E</u>**
- Constant B
- Beam spreading

Correct results across a range of problems



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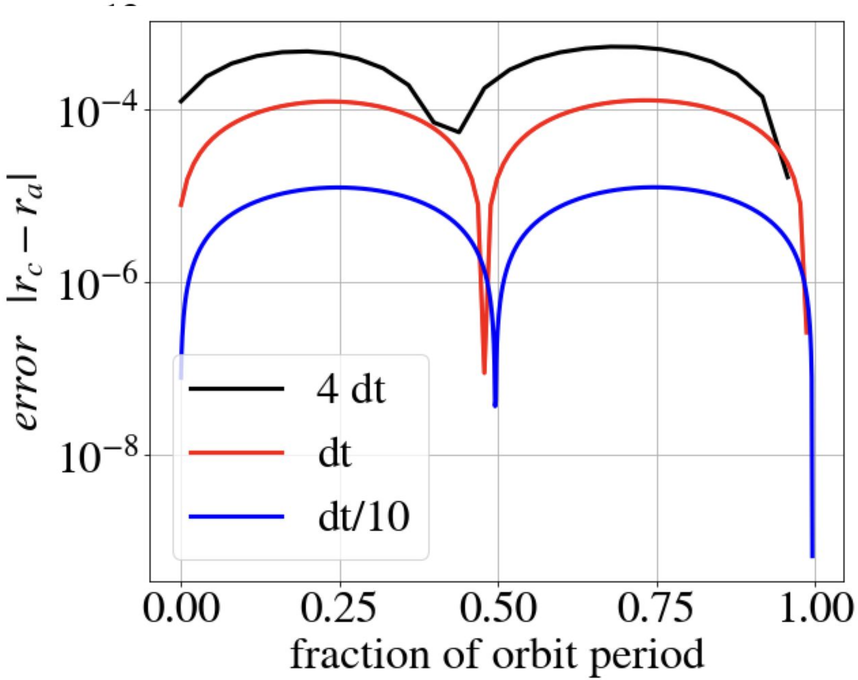

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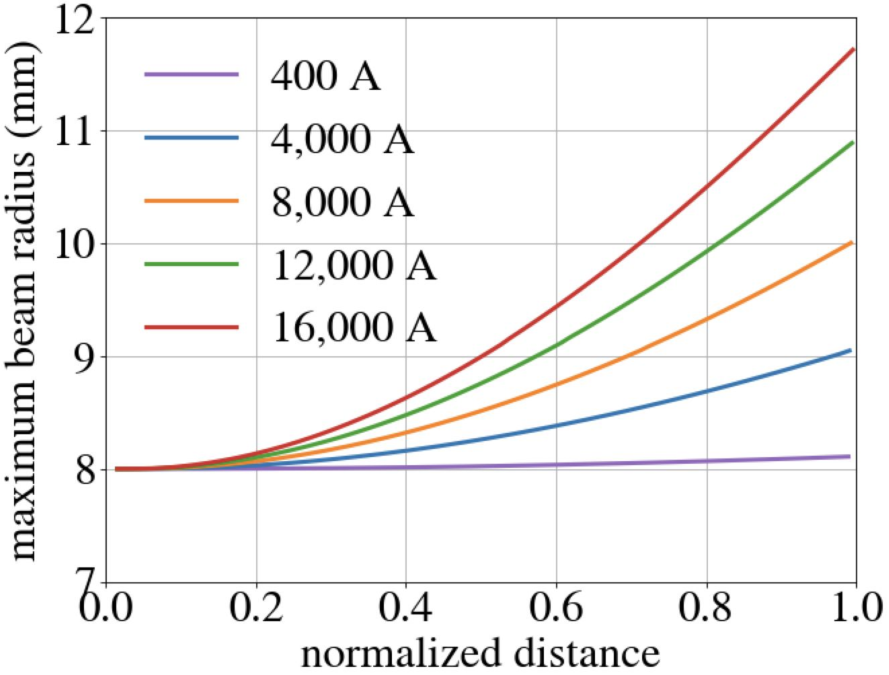

GPU Acceleration Particles

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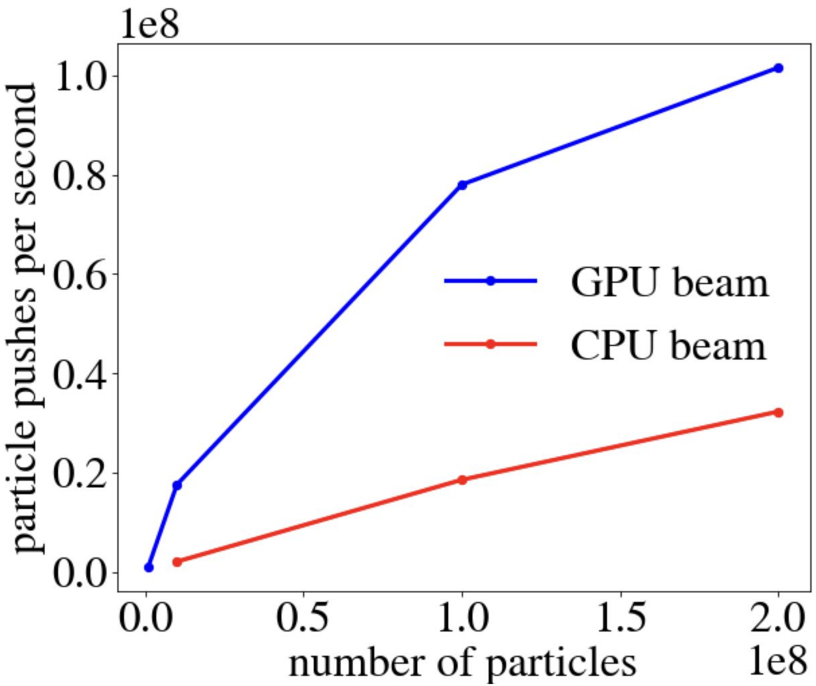
- Compare speed on AMD Epyc 7302 (16 cores) with A100 GPU
- Optimizations still to be done to get faster particle pushes
- Adding reactions will slow particle performance due to extra sorting



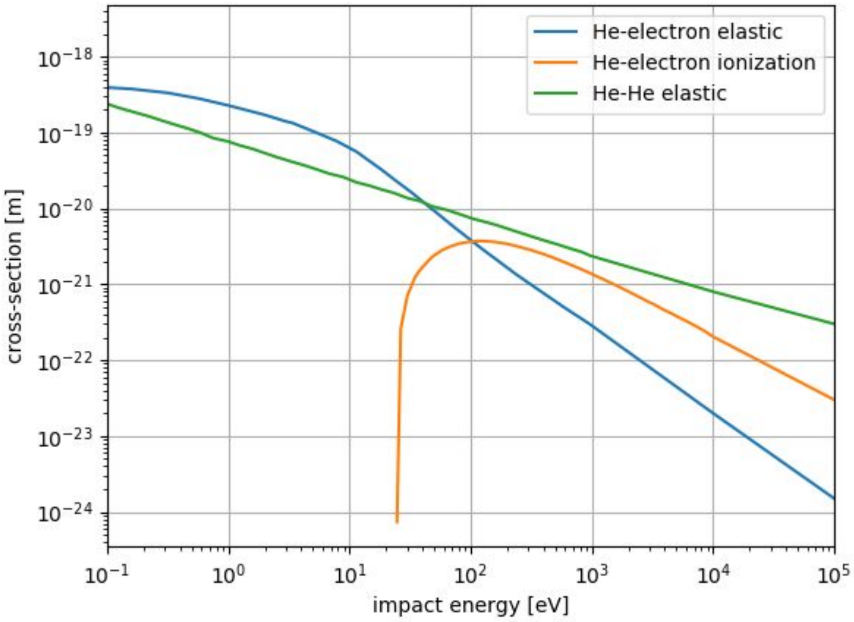
GPU Acceleration Reactions

GPU reactions design:

- Flexible - reactants/products can be any combination of field, fluid, particle

- Specify reactants, products, cross-section, reaction type

- Table filled with relevant info, probabilities calculated, product generator does physics



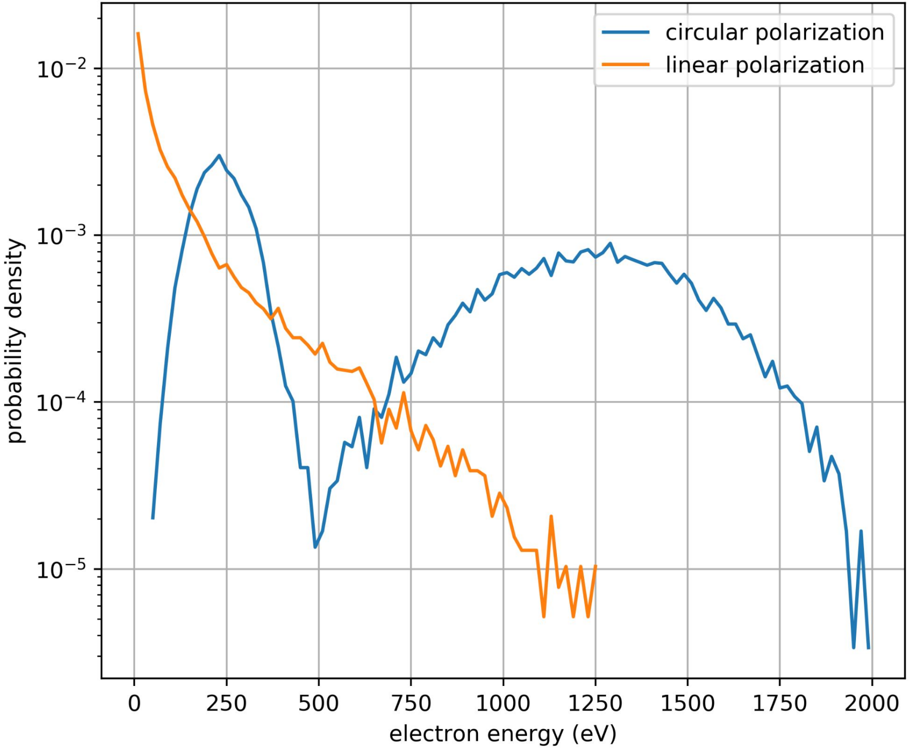
GPU Acceleration Reactions

Benchmarks:

- DSMC neutral heat transport
- Turner cases
- Field ionization eedf correct

Speed:

- GPU > 20x faster than single core CPU with better scaling



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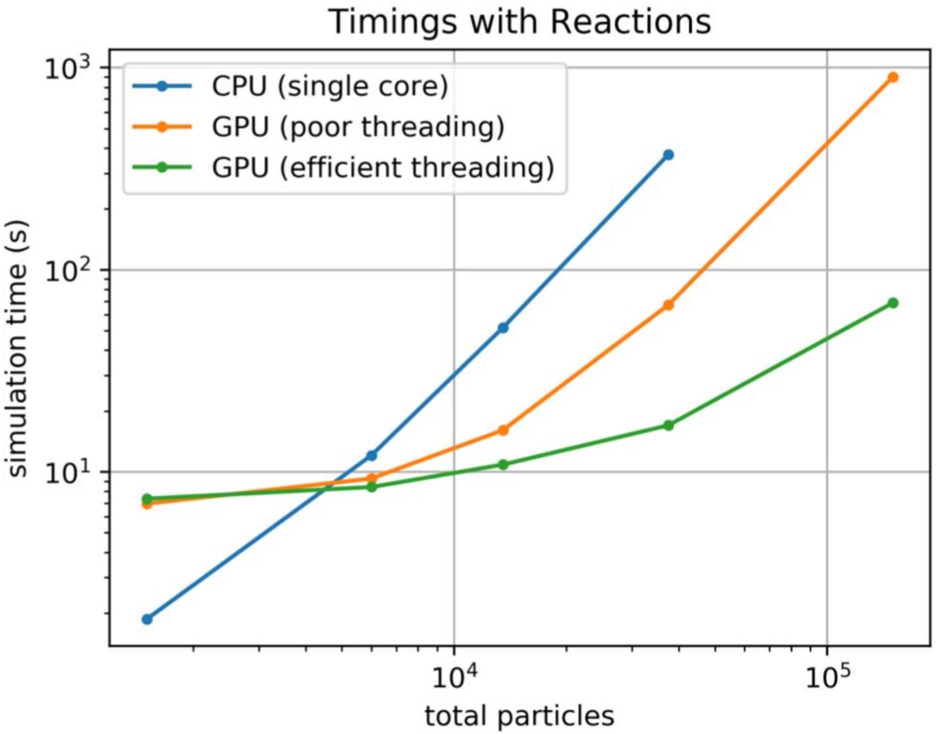


Simulation

Disparate time scales:

- Ionization occurs in femtoseconds
- Expansion occurs in nanoseconds

Separate into **electromagnetic** and **electrostatic** simulations

Electromagnetic dx and dt limited by EM wave

Electrostatic dx limited by Debye length, dt by electron velocity

Simulation

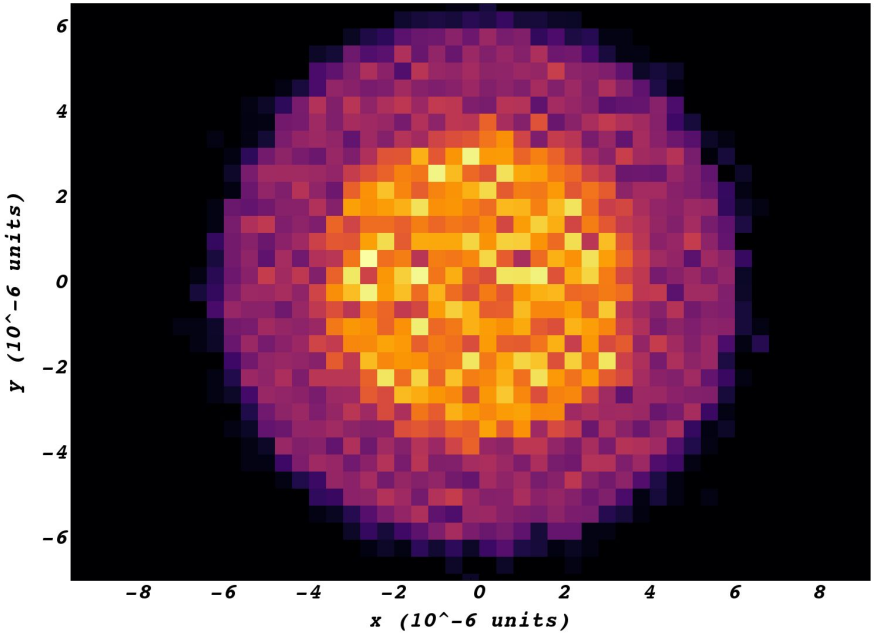
Laser parameters:

- Wavelength: 800nm (f=374 THz)
- Gaussian pulse with σ_x = 5μm and σ_t = 12.7fs
- Intensity: 2.1x10^{16} W/cm
- Amplitude: E_0 = 4x10^{11} V/m
- Linearly polarized in *y*

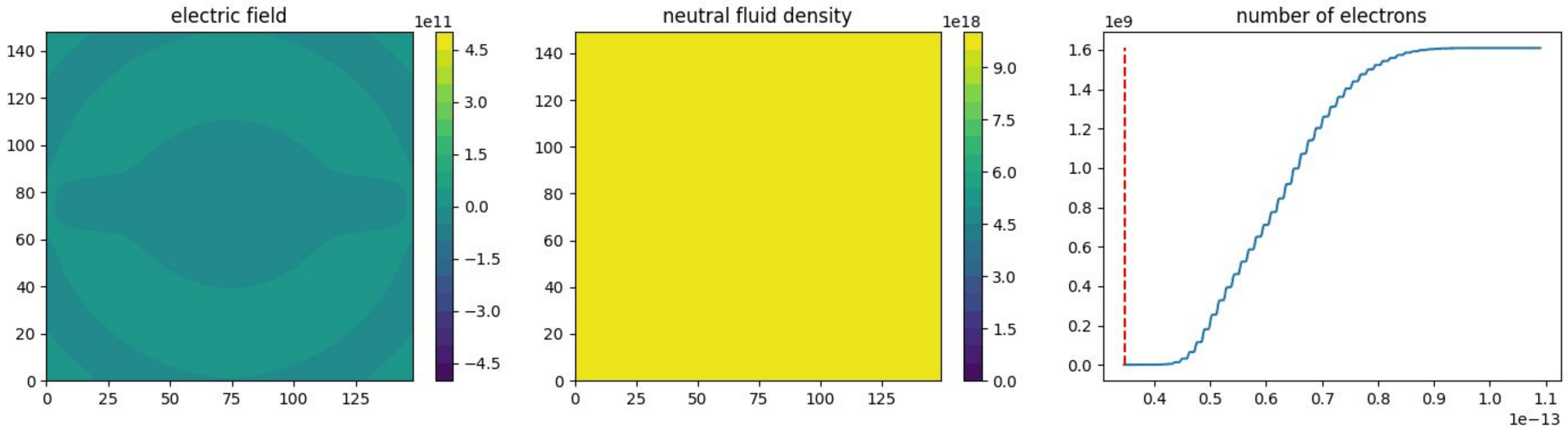
$$E_y(x,y,t) = \mathrm{E}_0 \sin(\omega t)\, e^{-(t-3\sigma_t)^2/2\sigma_t^2}\, e^{-(x^2+y^2)/2\sigma_x^2}$$

Channel ionization

- Laser interaction with fluid requires EM-PIC
- Setup:
  - ADK ionization model
  - Fluid Helium
  - Kinetic He^{+}, He^{2+}, e^{-}
- Helium neutral results in two ionization states after laser passthrough
- Creates electron density step down (see image)
- 4x faster on GPU than 32 core CPU, more optimization on the way



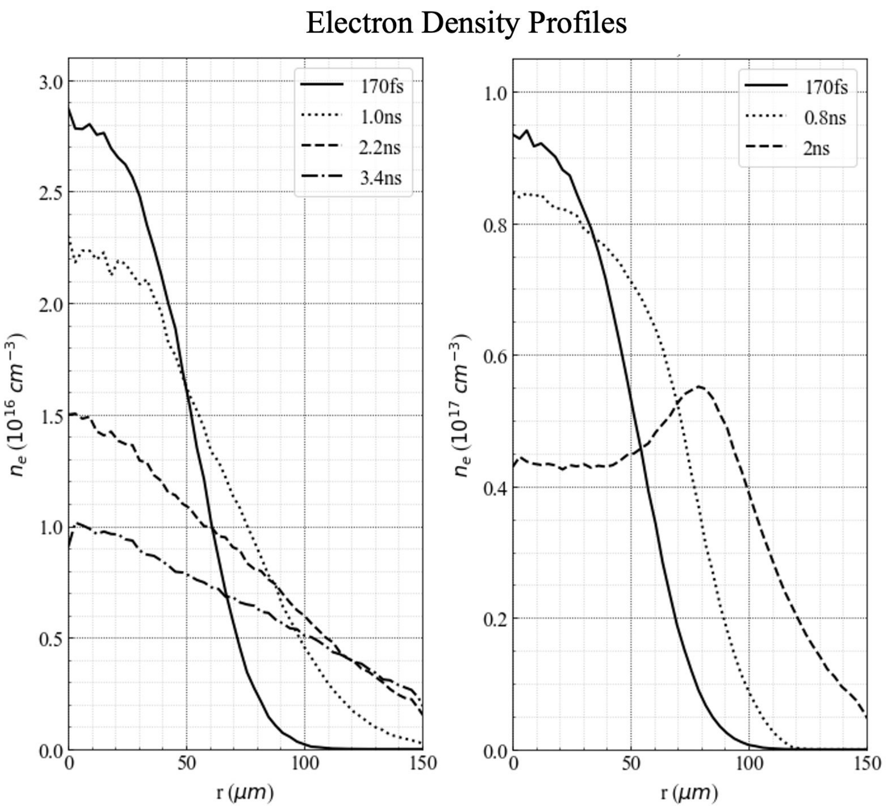
Channel ionization



Channel expansion

Electrostatic PIC not limited by EM timescales or wavelength

- Use energy conserving ES-PIC
- Channel expansion due to electron thermal distribution
- Impact ionizations of expanding electrons leads to more electron/ion generation
- At higher densities, shock forms
- See Kathryn Wolfinger poster tomorrow for more physics results/discussion

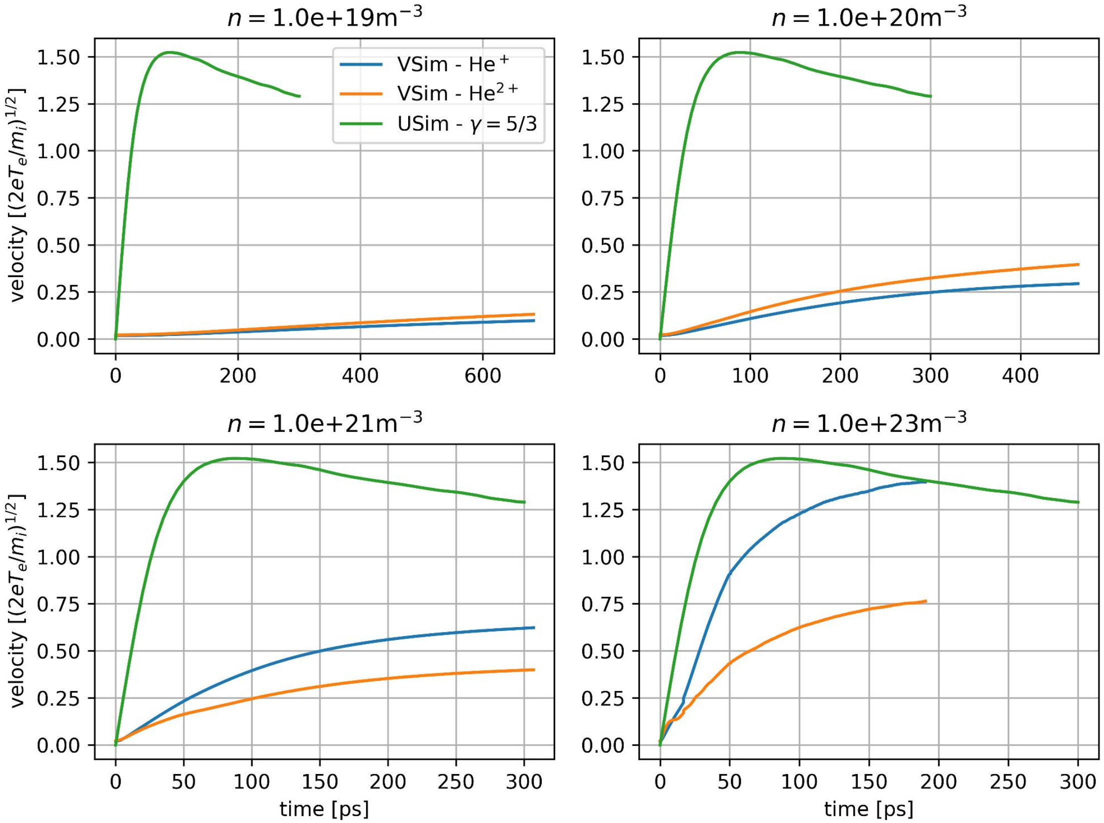


Summary

- Simulation of channel formation at lower densities needs EM/ES PIC
- Simulations are expensive, GPU acceleration can help
- Fields, particles, and reactions implemented in Vorpal for use on GPUs
- Performance significantly improves for fields and reactions, marginal improvement so far for particles
- Channel formation and expansion physics shown, see more at Kathryn’s poster

Extra Slides

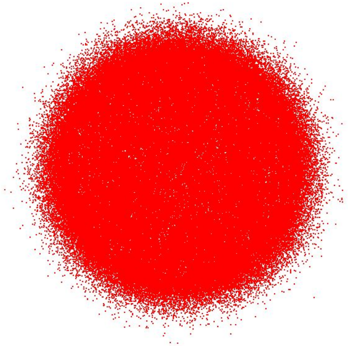
Fluid vs PIC

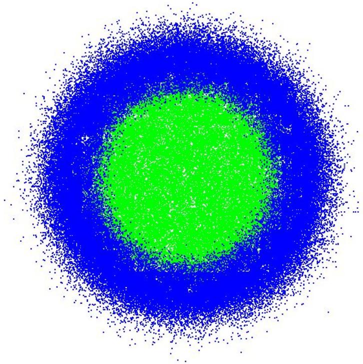


$n = 1.0e{+}19 m^{-3}$
$n = 1.0e{+}20 m^{-3}$
$n = 1.0e{+}21 m^{-3}$
$n = 1.0e{+}23 m^{-3}$
VSim - He^{+}
VSim - He^{2+}
USim - $\gamma = 5/3$
velocity $[(2eT_e/m_i)^{1/2}]$
time [ps]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
0
200
400
600
100
300
50
150
250

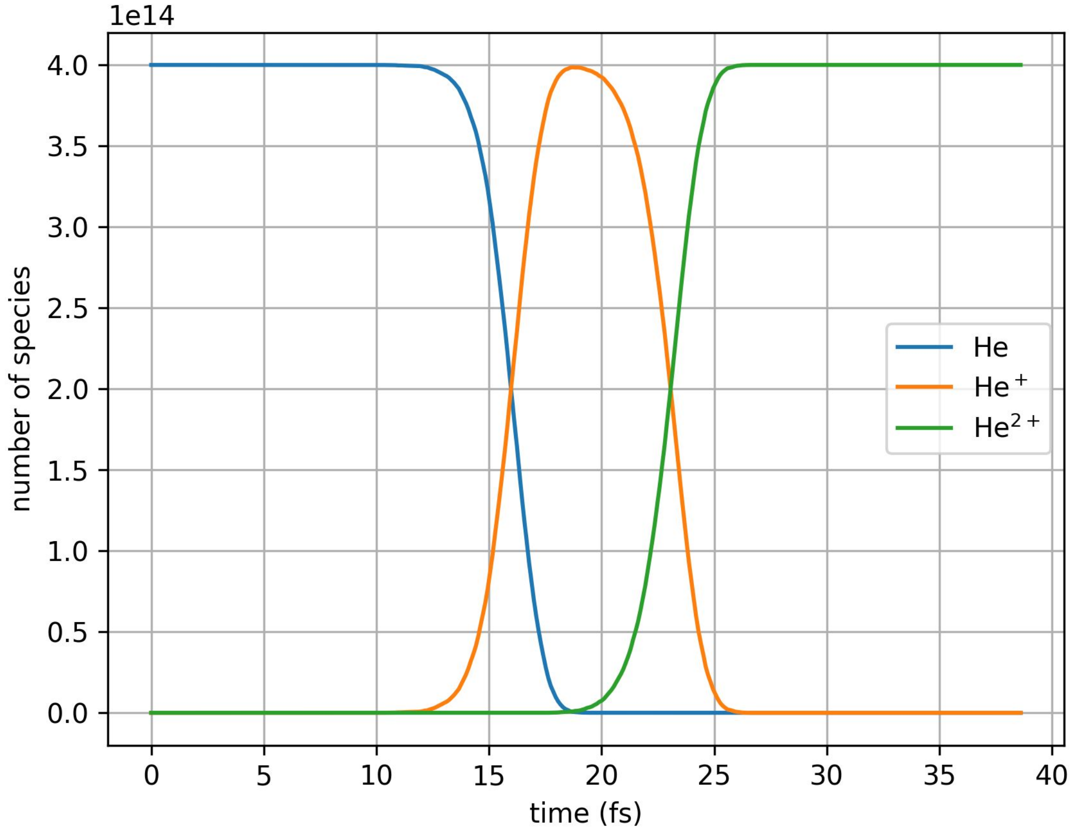
Channel ionization

- Laser interaction with fluid requires EM-PIC
- Helium results in two ionization states after laser passthrough
- Results in electron density step down (see image)





Channel ionization



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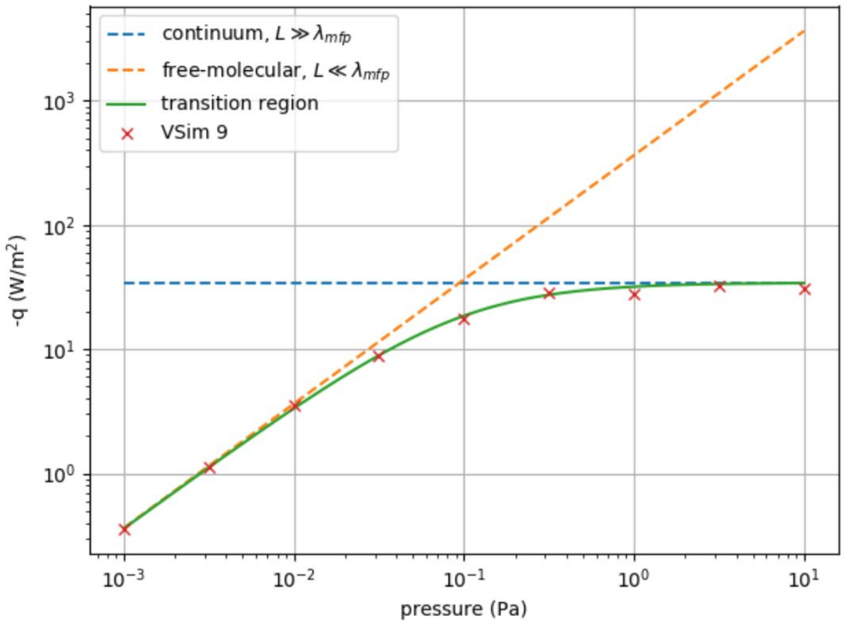

GPU Acceleration Particles