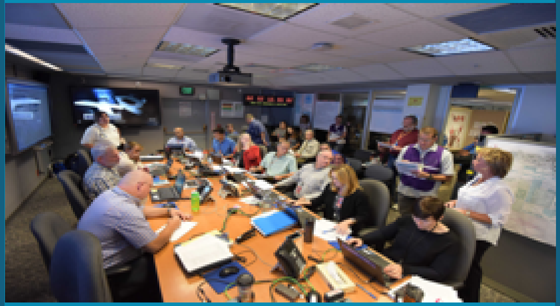
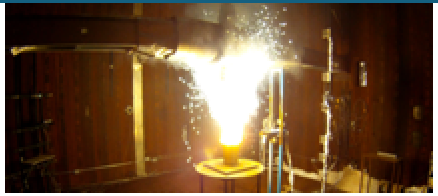
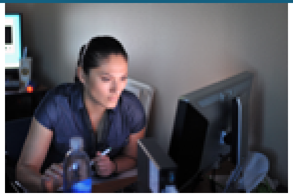
SAND2022-12197C

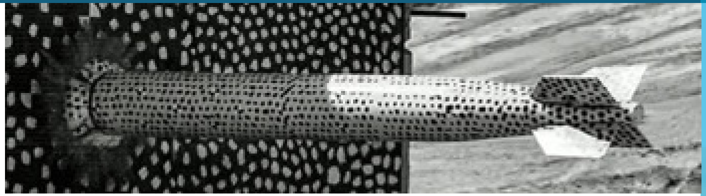
Sandia National Laboratories

Simulations of Cathode Plasma Expansion in Vacuum









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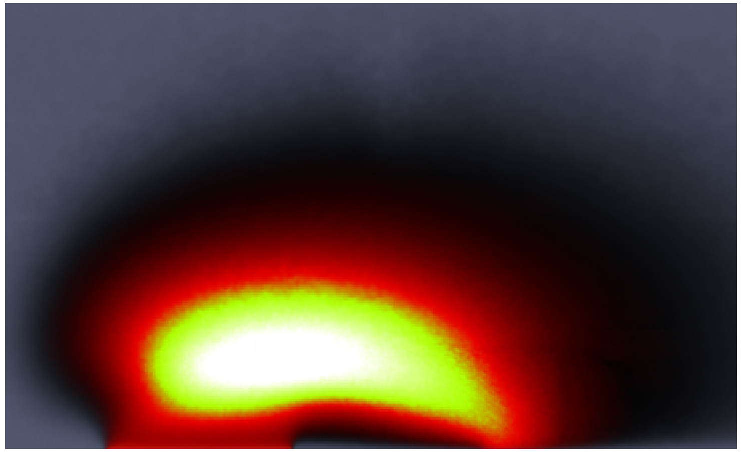
Motivation



Vacuum arcs have been studied for many years, but many phenomena are still missing a satisfactory answer.

There are multiple hypothesized models, including unipolar arcs, thermofield runaway with whisker/protrusion growth, and explosive electron emission (ectons).

Many of these processes have been simulated, but the costs can become enormous.

Most models begin with a cathode plasma that grows to the anode.

As part of an effort to better understand the expansion properties of a purported cathode plasma (generated by any of the above mechanisms), we study some aspects of this vacuum plasma expansion.

Our study is intentionally a simplification of a full vacuum arc – we are interested only in expansion of a model cathode plasma.

Experimental Observations

The experiment in [1] describes a set of gap lengths and operating conditions. The experiments support:

1. The anode material does not influence breakdown time (voltage collapse).
2. Breakdown times across multiple gap sizes indicate a cathode plasma expansion speed of ~20,000 m/s.
3. Electron impact on the anode is not sufficient to thermally desorb/ablate anode material.
4. Anode material is provided through sputtering due to ions from the cathode plasma.

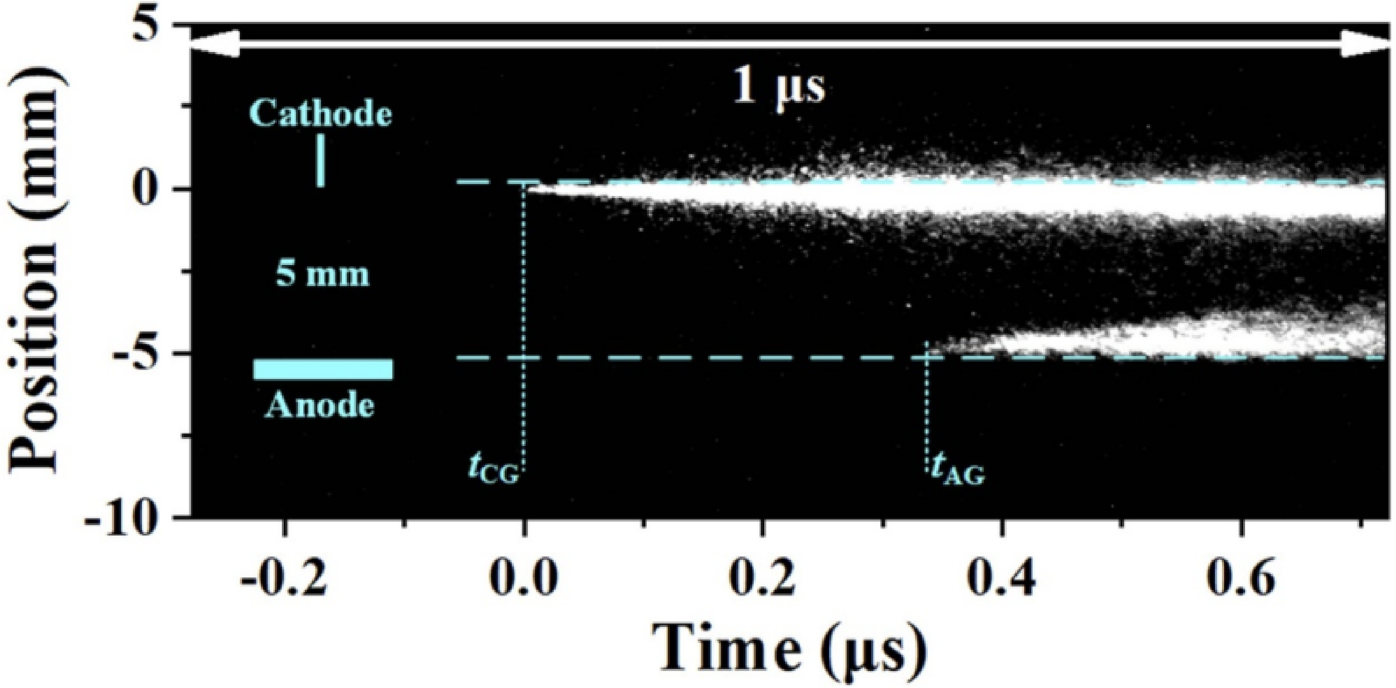
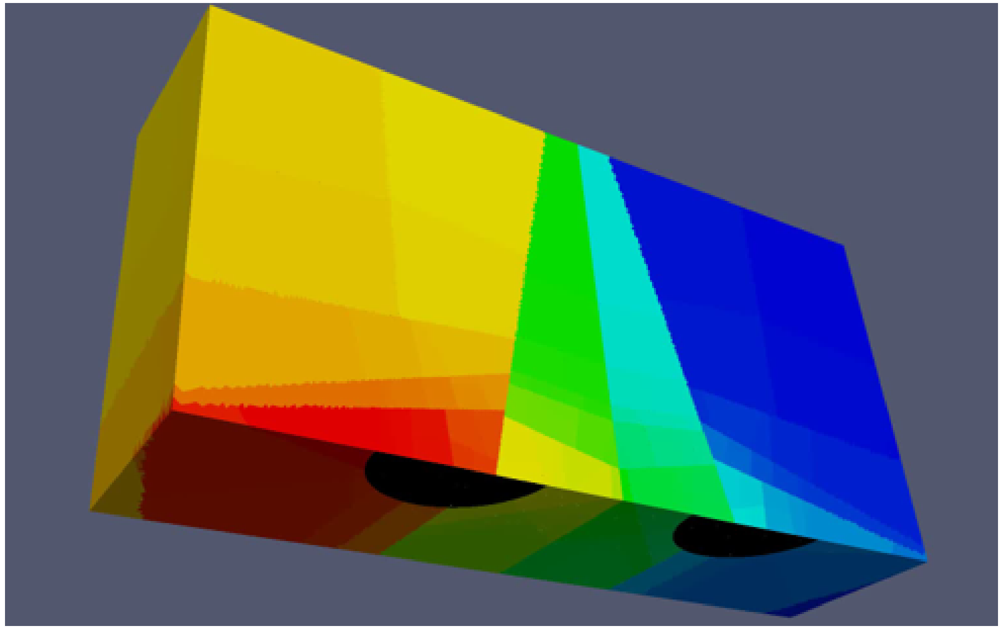


Image reproduced from [1]. Pulse voltage is 40 kV for 5 μs. $t_{AG} - t_{CG}$ ~300 ns.

[1] Z. Zhou, et al., "Effect of the anode material on the evolution of the vacuum breakdown process", J. Phys. D: Appl. Phys. **54** (2021)

Aleph Simulation Tool



- 1, 2, or 3D Cartesian
- Unstructured FEM (compatible with CAD)
- Massively parallel
- Hybrid PIC + DSMC (PIC-MCC)
- Electrostatics
- Fixed B field
- Solid conduction
- Advanced surface (electrode) models
- e- approximations (quasi-neutral ambipolar, Boltzmann)
- Collisions, charge exchange, chemistry, excited states, ionization
- Photon transport, photoemission, photoionization
- Advanced particle weighting methods
- Dual mesh (Particle and Electrostatics/Output)
- Dynamic load balancing (tricky)
- Restart (with all particles)
- Agile software infrastructure for extending BCs, post-processed quantities, etc.
- Currently utilizing up to 64K processors (>200M elements, >1B particles)

Aleph Simulation Tool

Basic algorithm for one time step of length Δt:

1. Given known electrostatic field $\mathbf{E}^n$, move each particle for $\frac{\Delta t}{2}$ via:

$$v_i^{n+1/2} = v_i^n + \frac{\Delta t}{2}\left(\frac{q_i}{m_i}\mathbf{E}^n\right)$$

$$x_i^{n+1} = x_i^n + \Delta t v_i^{n+1/2}$$

2. Compute intersections (non-trivial in parallel).
3. Transfer charges from particle mesh to static mesh.
4. Solve for $\mathbf{E}^{n+1}$,

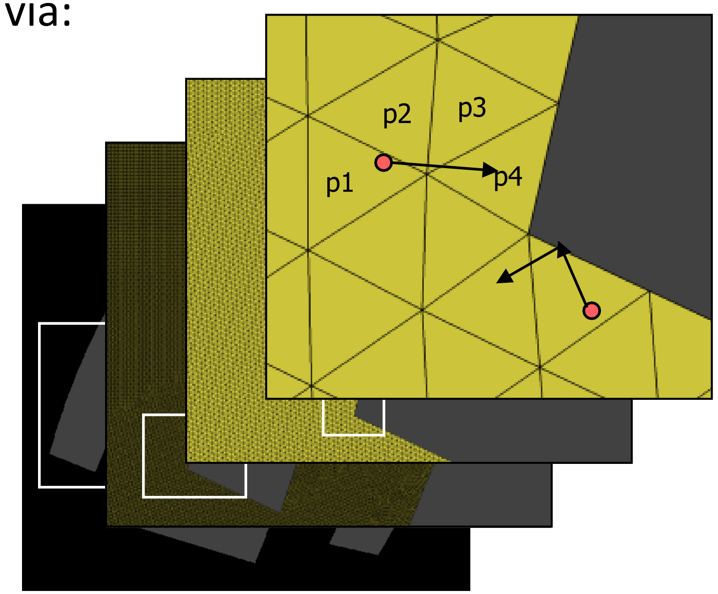
$$\nabla \cdot \left(\epsilon \nabla V^{n+1}\right) = -\rho(\mathbf{x}^{n-1})$$

$$\mathbf{E}^{n+1} = -\nabla V^{n+1}$$

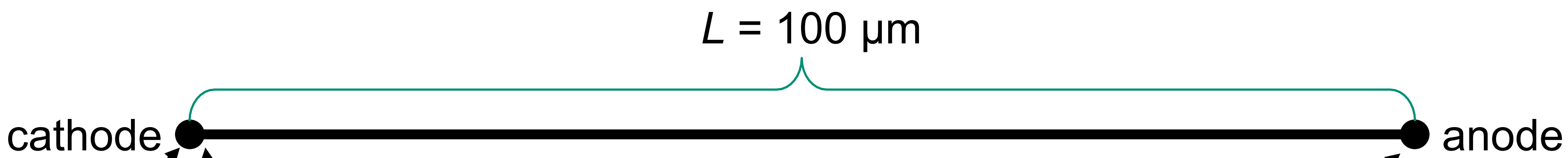
5. Transfer fields from static mesh to dynamic mesh.
6. Update each particle for another $\frac{\Delta t}{2}$ via:

$$v_i^{n+1} = v_i^{n+1/2} + \frac{\Delta t}{2}\left(\frac{q_i}{m_i}\mathbf{E}^{n-1}\right)$$

7. Perform DSMC collisions: sample pairs in element, determine cross section and probability of collision. Roll a digital die, and if they collide, re-distribute energy.
8. Perform chemistry: for each reaction, determine expected number of reactions. Sample particles of those types, perform reaction (particle creation/deletion).
9. Reweight particles.
10. Compute post-processing and other quantities and write output.
11. Rebalance particle mesh if appropriate (variety of determination methods).



1D Model Description



- $V = 0$
- Reflecting boundary for all species

- Nanbu collisions: e- + e-, e- + Cu+, Cu+ + Cu+ (ln(Λ) = 4.0 to 7.6)

- $V = 6{,}000\ \mathrm{V} - I_A R$
- I_A from Shockley-Ramo model
- $R = 1{,}000\ \Omega$
- Assumed arc radius = 25 μm
- Absorbing boundary for all species

- Plasma source region is 1 μm wide
- Plasma repopulated every timestep
- $n_e = n_i = 0.2 \times 10^{22}/\mathrm{m}^3$,
  $1.0 \times 10^{22}/\mathrm{m}^3$, or
  $5.0 \times 10^{22}/\mathrm{m}^3$ (factors of 5x and 25x)
- $T_e = 5$ eV, $T_i = 8{,}000$ K

Simulation Parameters

Assuming maximum density $n_e = 5 \times 10^{22}/m^3$, and $T_e = 5$ eV,

Plasma electron period = 79.3 fs, and

Debye length = 74.3 nm.

Used $\Delta x = 50$ nm (100 nm for $n_e = 1 \times 10^{22}/m^3$ and $n_e = 0.2 \times 10^{22}/m^3$).

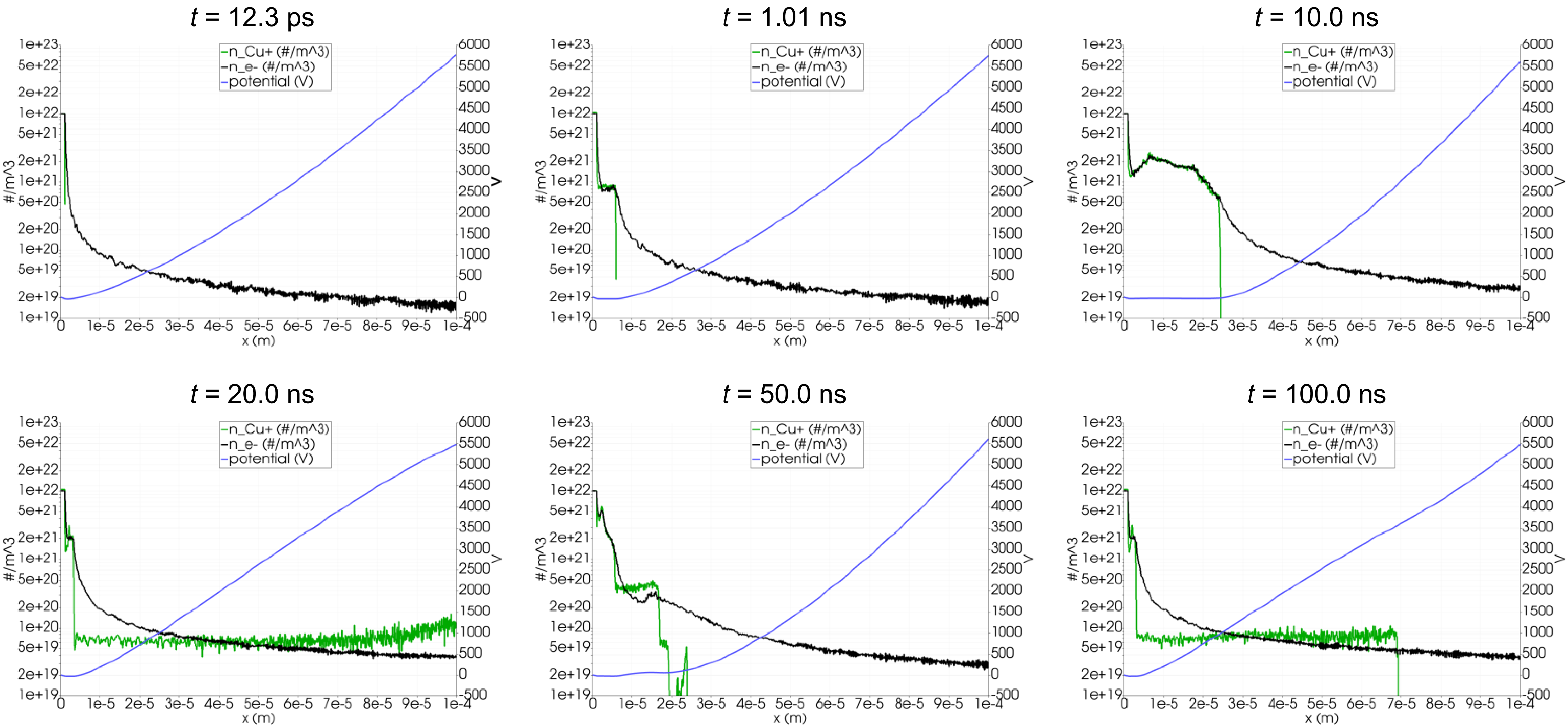
Used $\Delta t = 6.5$ fs.

Used particle weight of 5×10^{11} yielding 5,000 particles/cell at highest density and 400 particles/cell at lowest density.

CFL satisfied for e- energy <= 667 V. This is violated but only in the non-interacting low density expansion region.

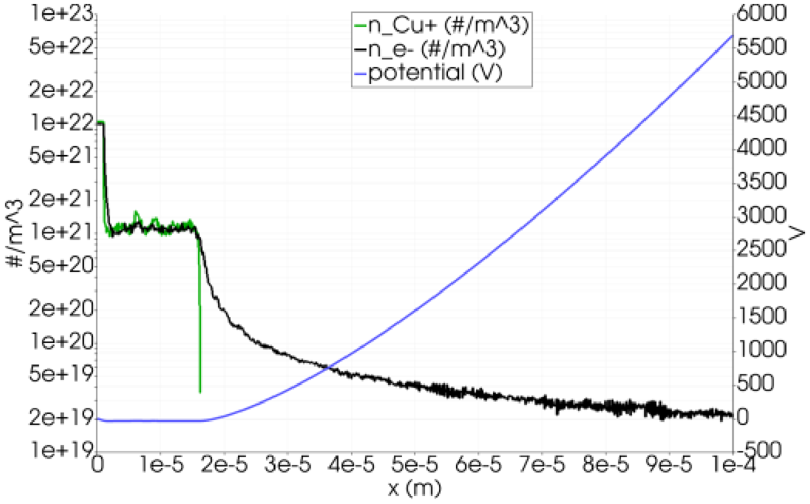
48 hours on 144 MPI cores for $n_e = 5 \times 10^{22}/m^3$ simulation. 32 and 72 cores for the smaller scenarios.

Results: Base Case, $n_e = 1 \times 10^{22}/m^3$

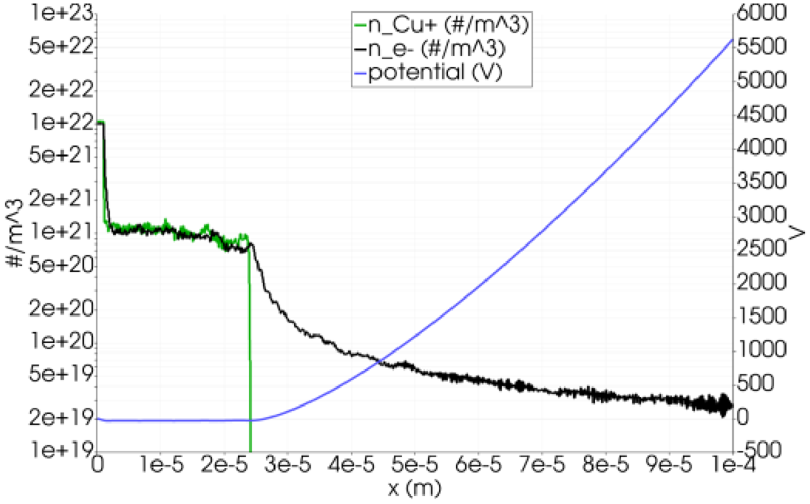


Results: Base Case, $n_e = 1 \times 10^{22}/m^3$

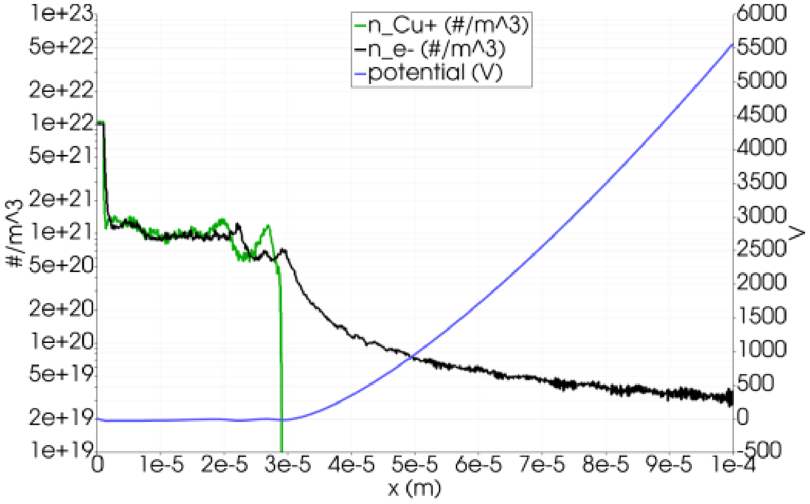
t = 82.5 ns



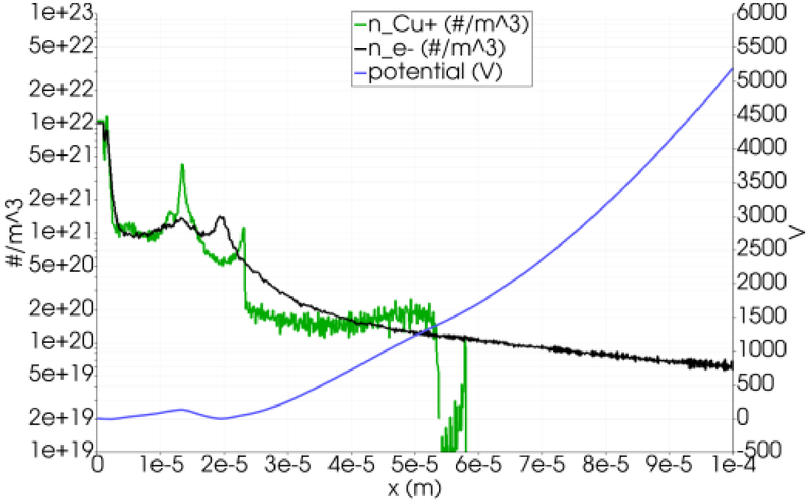
t = 84.0 ns



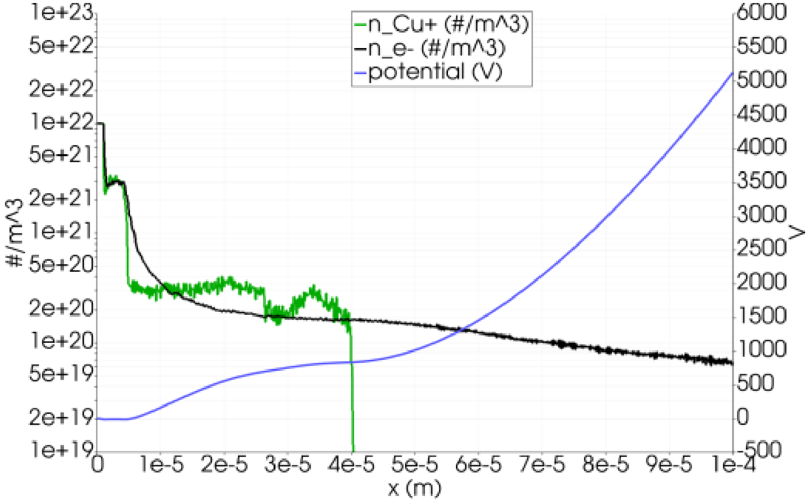
t = 85.0 ns



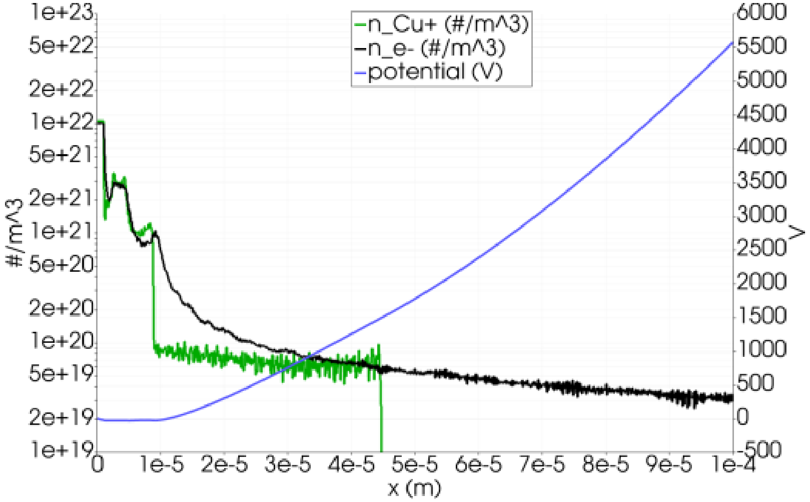
t = 87.0 ns



t = 88.0 ns

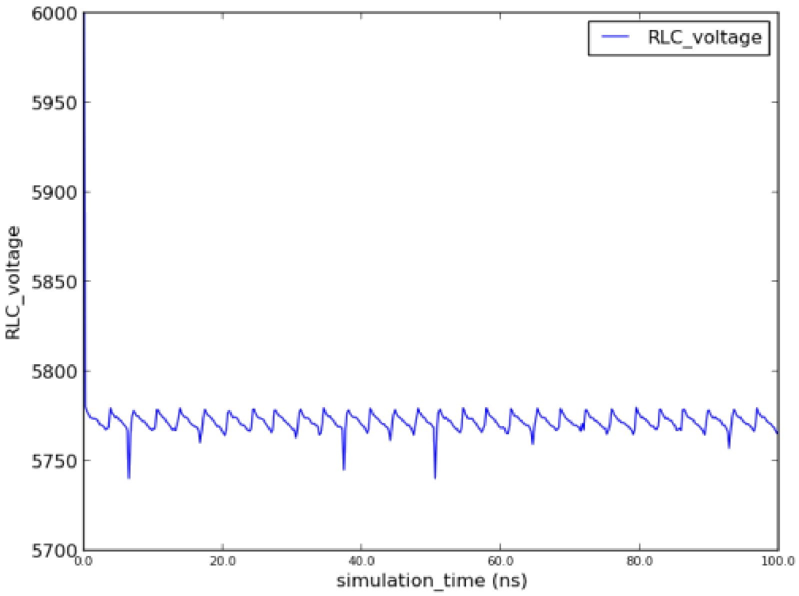


t = 89.0 ns

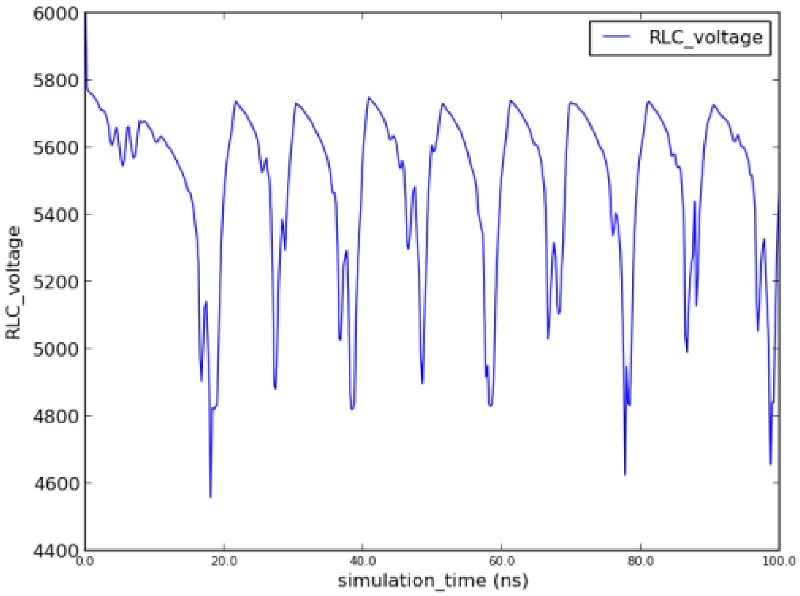


Voltage Oscillations (V = 6 kV – $I_A R$)

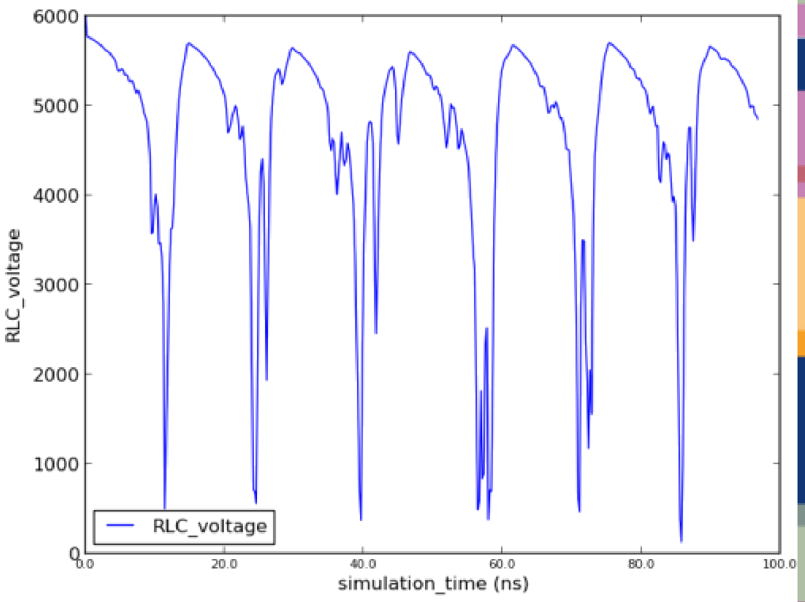
$n_i = n_e = 0.2 \times 10^{22}/m^3$



$n_i = n_e = 1.0 \times 10^{22}/m^3$



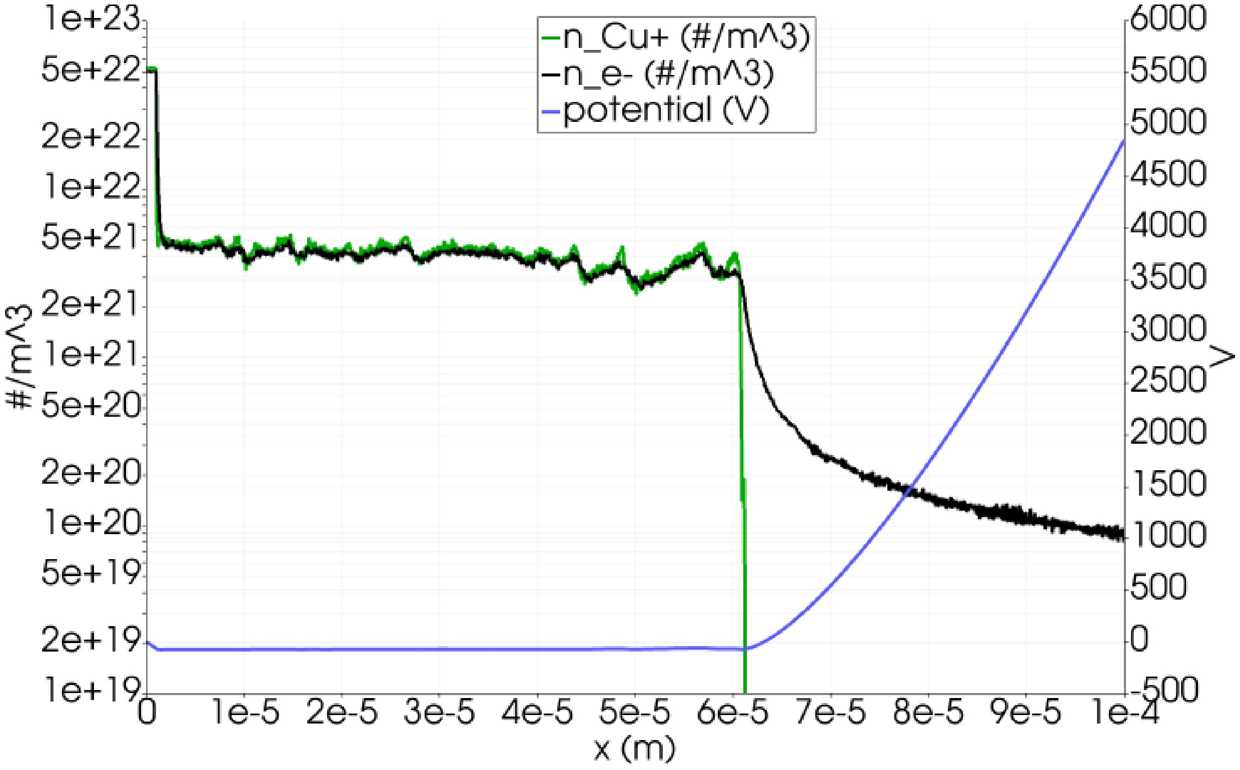
$n_i = n_e = 5.0 \times 10^{22}/m^3$



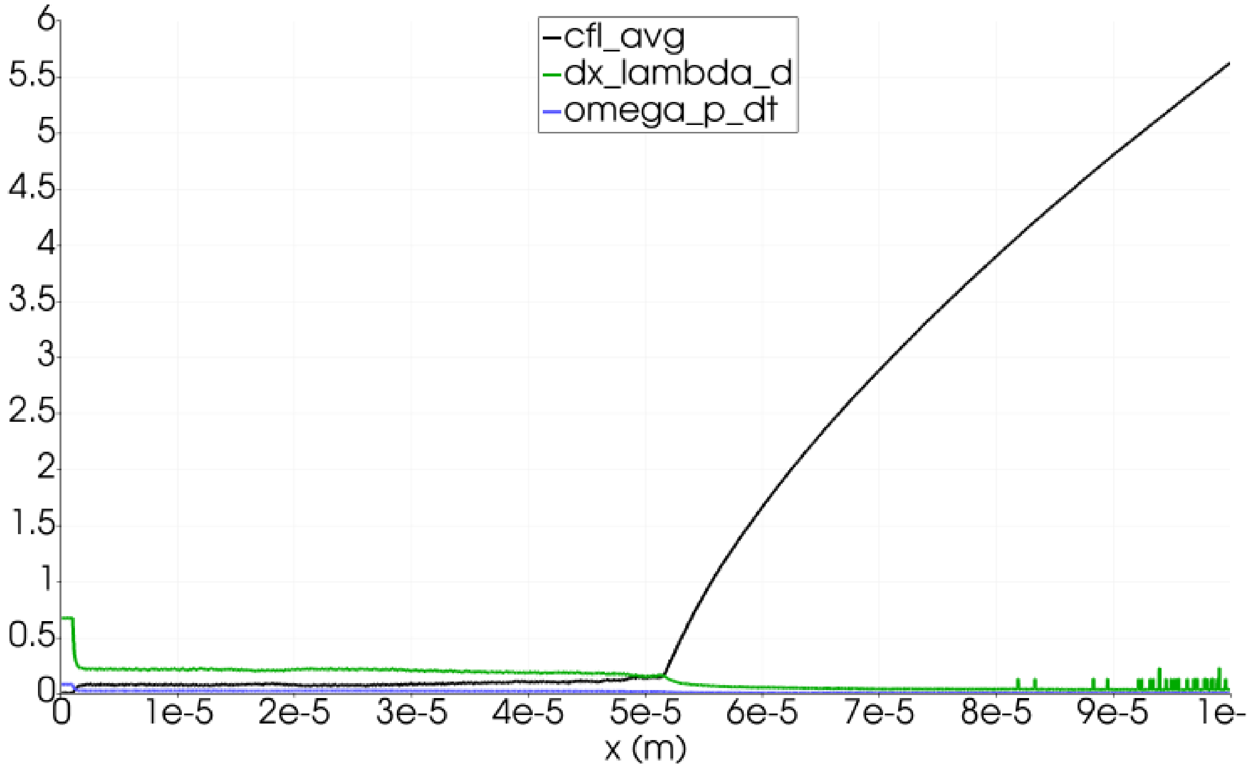
Resolution Results

Most challenging simulation is n_e = 5 x $10^{22}/m^3$,

t = 96.8 ns



t = 96.8 ns



Summary

Have simulated simple scenario of a constant density cathode plasma expanding in vacuum.

Results show a periodic solution with oscillations. Oscillations are sometimes seen in vacuum arc initiations, but no claims are made as to the realism of the simulations presented here.

Next steps:

- Include sputtering and other boundary behaviors at the anode
- Go to higher densities – as high as $10^{28}/m^3$ perhaps

Want to collaborate on models or experiments? Go to https://www.sandia.gov/prf/.

Upcoming conference: 30th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV 2023). Go to http://isdeiv2023.w3.kanazawa-u.ac.jp/.

Contact: mmhopki@sandia.gov