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# Current Loss in the Vacuum Section of the Refurbished Z Accelerator

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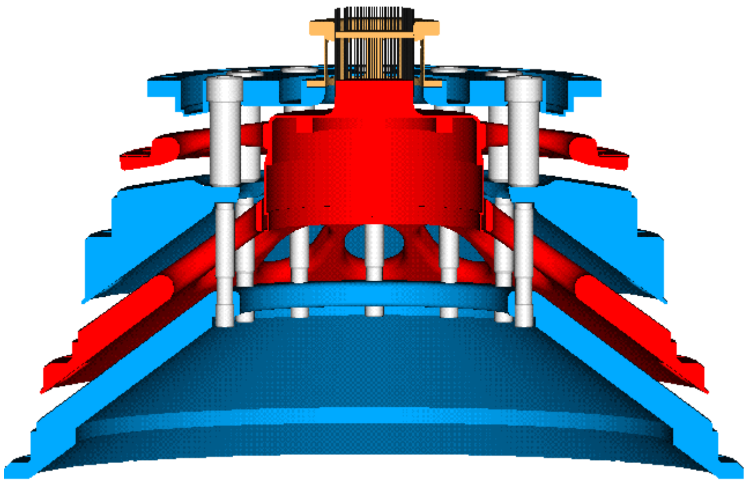

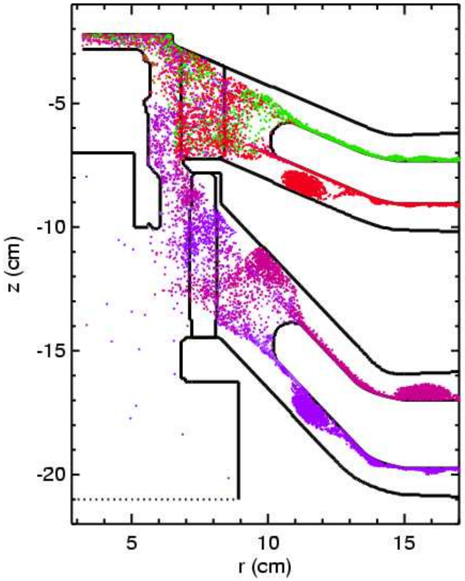


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# Abstract

The refurbishment of the Z accelerator at Sandia National Laboratories was completed in September 2007. The vacuum section is topologically similar to the original Z design, but with new hardware for the insulator stack, the four magnetically insulated transmission lines (MITLs), and the double post-hole convolute. The current loss in the vacuum section consists of two parts. Early in time, electrons flowing into the convolute from the MITLs and lost to the convolute anode surfaces account for the current loss. Late in time, the observed current loss is higher than vacuum electron flow losses predicted by 2-D and 3-D particle-in-cell (PIC) simulations. This additional loss is attributed to dense plasma effects in the convolute. This loss could be due to cathode plasmas, anode plasmas formed by deposition heating of the anode, or a combination of the two. There are no detailed diagnostics for guidance, so PIC simulations currently provide the only insight into the source of the additional convolute current loss. We believe that anode plasmas created at magnetic null regions of the convolute play a significant role. To accurately compute the time at which anode plasmas form due to electron deposition heating, accurate modeling of the electron flow into the convolute is required. We use high-resolution 2-D PIC simulations of the exact MITL geometry out to large radius to compute this flow. 3-D simulations of the convolute necessarily use coarser resolution, but with modified MITL geometry reproducing the 2-D flow into the convolute. We have simulated a range of Z shots with time-accurate drive voltage and load impedance. The goal is to characterize the time for the onset of anode plasma formation as a function of MITL current and voltage, as a first step towards creating more realistic models of convolute current loss for use in circuit codes. We are also developing new methods to model dense electrode plasmas in our PIC simulations.



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# Acknowledgements


- We thank the contribution of the following:
  - Mike Cuneo, Jean-Paul Davis, Mike Desjarlais, Chris Jennings, Brent Jones, Marcus Knudson, William Langston, Ray Lemke, Scot Lewis, Paul Mix, Albert Owen, Michael Pasik, Greg Rochau, Dustin Romero, Daniel Sandoval, Mark Savage, Larry Schneider, Marcelino Vigil




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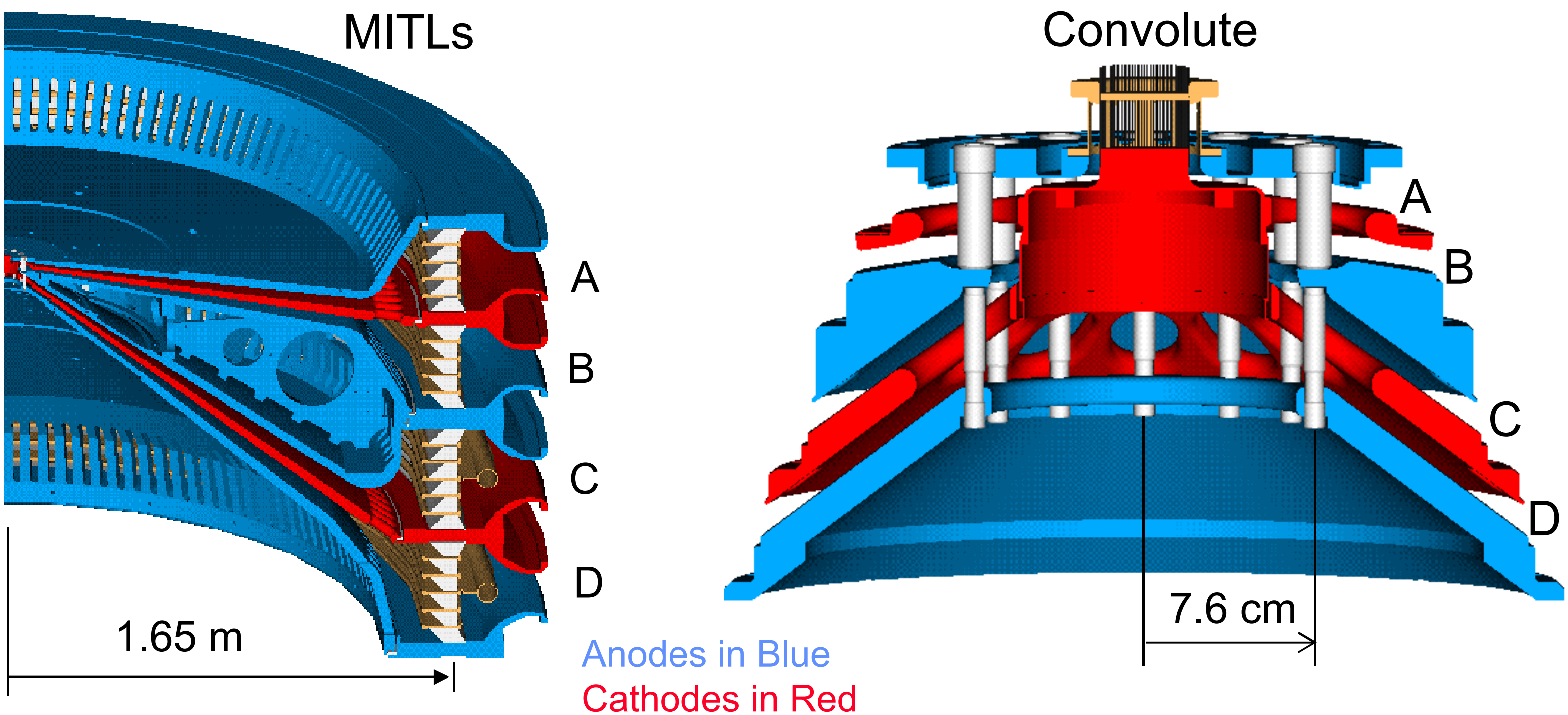
# The vacuum section conducts power from the insulator stack to the load




- The four MITLs are coupled in parallel at the post-hole convolute
- Electron emission in the MITLs, out to the vacuum flares
  - Electrons **E x B** drift radially inwards into the convolute



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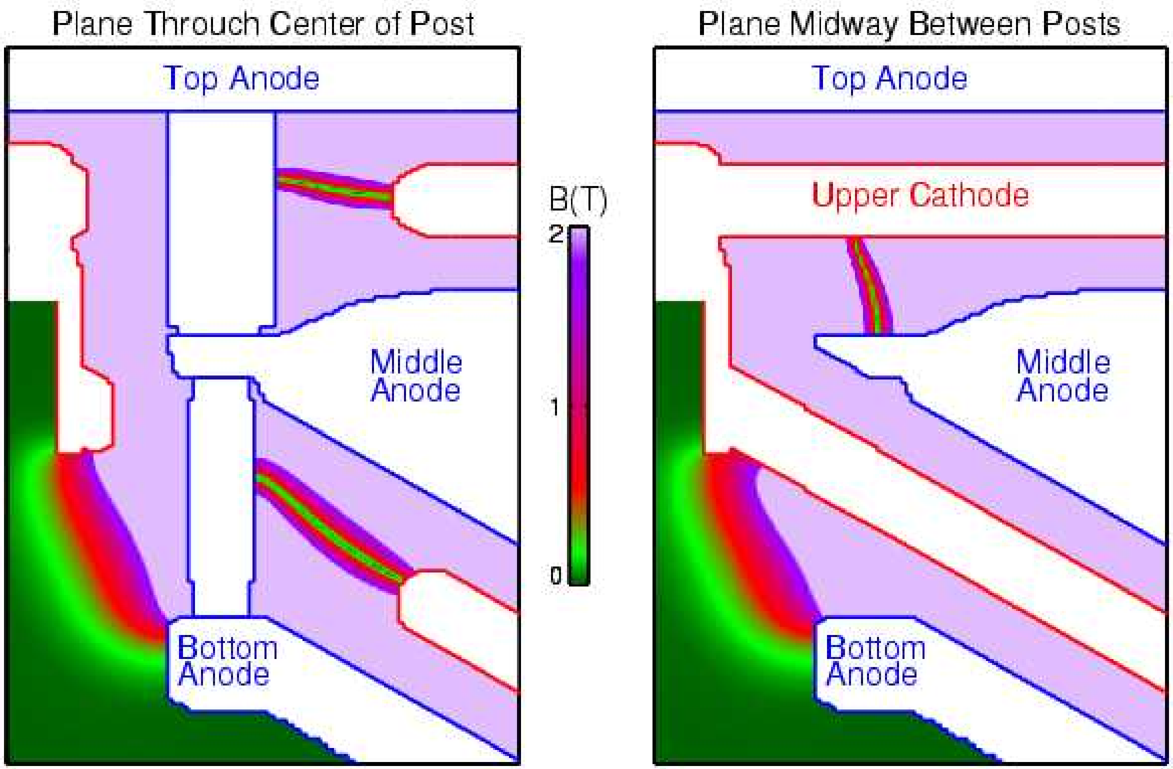
# Magnetic nulls in the convolute




- There will be electron losses at the nulls: “loss of magnetic insulation”
  - How much? How fast does the anode surface heat?



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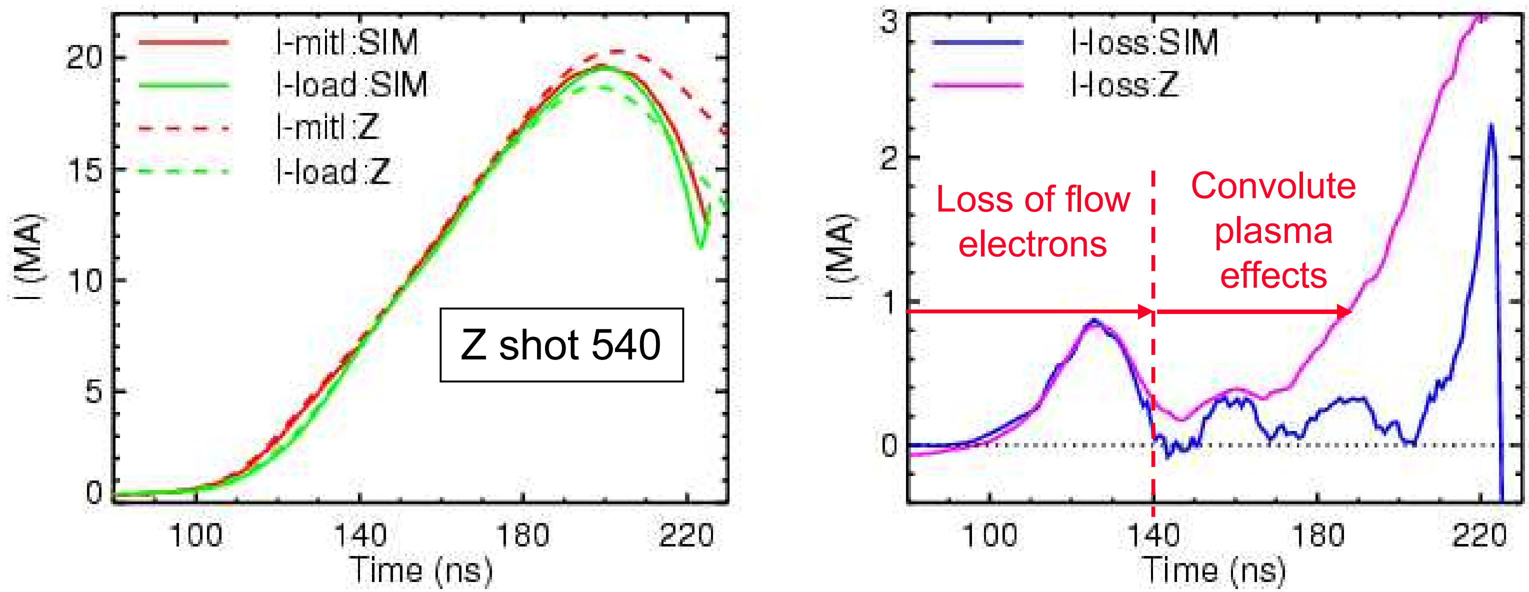
# There are two phases to the current loss in the convolute for low impedance loads




- Early-time loss: MITL electrons lost to the anode in the convolute
- Additional late-time loss is due to electrode plasmas in the convolute
  - Natural to assume that anode plasmas at magnetic null regions play a role
  - Simulations with cathode plasmas have also been done with LSP [D.V. Rose, *et al*., Phys Rev ST-AB **11**, 060401 (2008)].
  - No detailed diagnostics to give guidance from experiment



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# We simulate the vacuum section with Sandia's QUICKSILVER EM-PIC code

- QUICKSILVER is a structured, finite-difference EM-PIC (3-D, 2-D) with a long history of Pulsed Power applications
- Very good pre-processing tools for complex simulation setup
  - Mercury, it's native pre-processor: error checking, array sizes, *etc*.
  - Use IDL as a front-end, with scripts automatically building geometry from a set of input parameters
- Detailed diagnostics, post-processed with IDL
- Many features developed for Z simulations
- Recently enhanced to model electrode plasmas
  - 2$^{nd}$-order, energy-conserving particle pusher algorithm
  - Electrode plasma layer model



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# We use two complementary setups to analyze the electron flow in the vacuum section

- 2-D, high-resolution MITL simulations: ~9 < r < ~60 cm (up to 130 cm)
  - Typical A-K gap resolution: $\Delta x$ ~ 0.1 mm (also done 30 $\mu$m, 10 $\mu$m)
  - Transmission line model for the convolute and load
  - Provide our best estimate for the electron flow into convolute
- Full 3-D convolute simulations: ~3 < r < ~35 cm
  - Typical A-K gap resolution: $0.25 < \Delta x < 0.5$ mm
  - Transmission line model for the inner MITL and load
  - Location of electron losses in the convolute, and anode heating
- Both models use common transmission lines for the MITLs beyond the outer radial boundary; the stack, water section, and load
- A third option is to model everything with transmission lines
  - "circuit code", but using same TLs as the 2-D/3-D simulations



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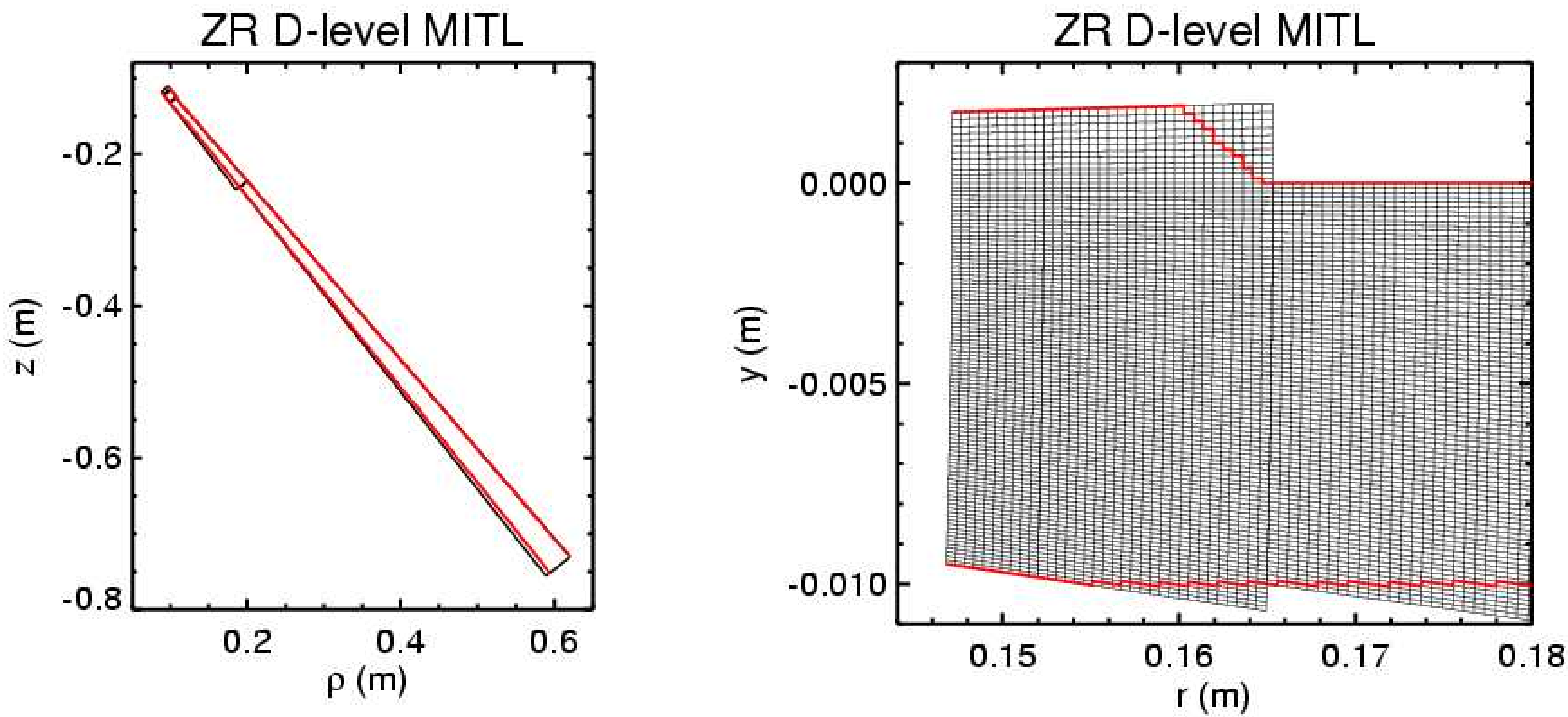
# The 2-D MITL simulations are done in spherical coordinates




- Model MITL cathode cone exactly, without any stair-stepping
- Resolution as high as $\Delta\theta = 10^{-4}$ radian (10 microns at r = 10 cm)
- Full, time-accurate simulations model all four MITLs in 2-D, coupled at their inner ends with transmission lines modeling the convolute



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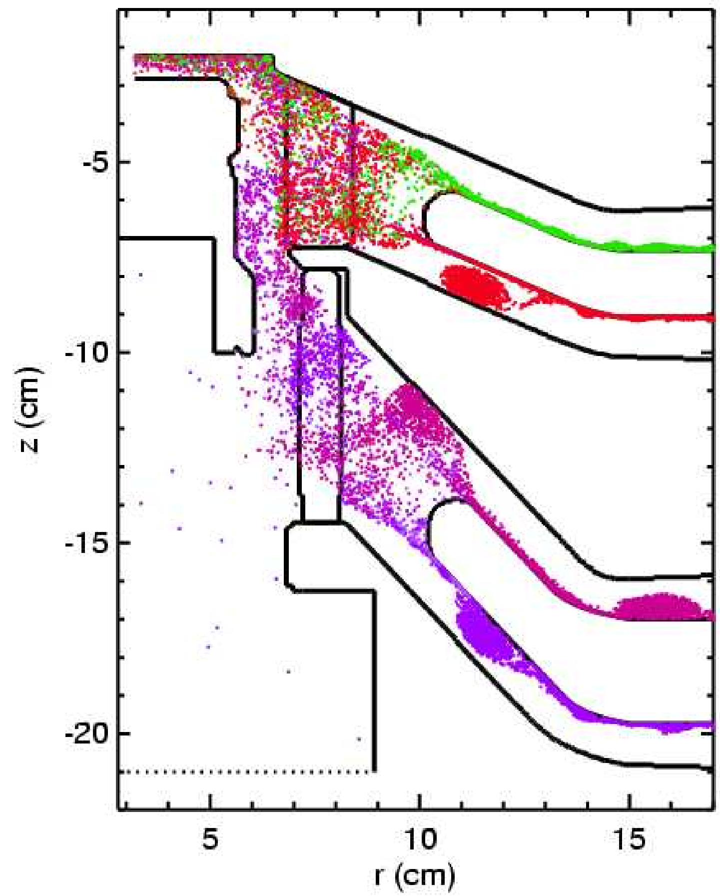
# The 3-D convolute simulations are done in cylindrical coordinates

- Azimuthal range, $0 < \phi < \pi/N_{post}$
  - 35 cells in $15^o$ sector
- MITLs bend to horizontal a few cm outside the convolute
  - Emission out to r ~ 30 cm
  - Tuned to deliver the same electron flow into the convolute as the much higher-resolution 2-D setup
- Slanted surface model used to avoid stair-steps wherever possible
- Subcycling model for electrons in large magnetic fields: Push electron n times per field step; $n = 1 + int(\omega_c(\mathbf{x}_p)\Delta t_f/\theta_{max})$
  - $\theta_{max} = \pi/3$ (6 steps per orbit)
- Compute electron deposition heating of the anode on all surfaces



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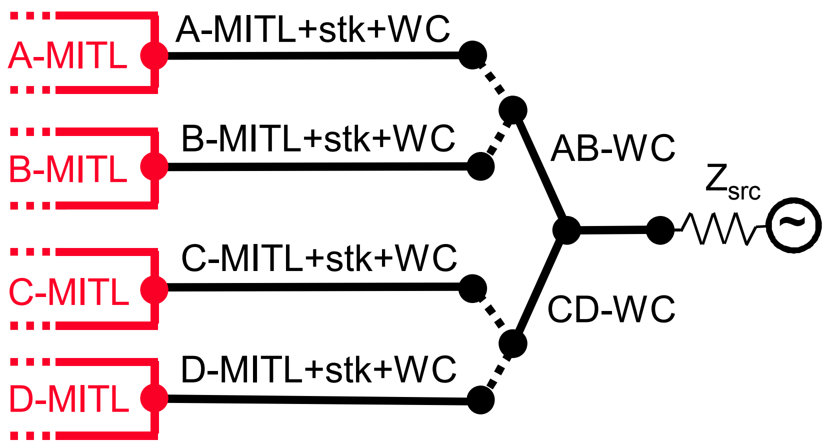
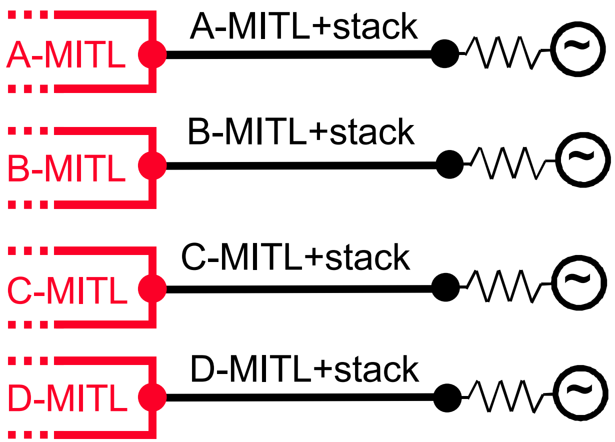
# We have used three different options to drive the simulations




Three transmission line setup and drive options outside PIC domain (in red):

1. Model the water convolute with TLs, and drive with one $V_{oc}$ in water section
2. Extend the four long TLs slightly beyond $r_{stk}$, and drive each one with its own $V_{oc}$ unfolded from $V_{stk}$ and $I_{stk}$ on each level
3. Drive the four long TLs at $r_{stk}$ with a current source: $V_{oc} = Z_{src}*I_{stk}$, where $Z_{src}$ is a very high impedance

- First option has best predictive capability, but a reliable model is still a research area; third option is used for results shown here



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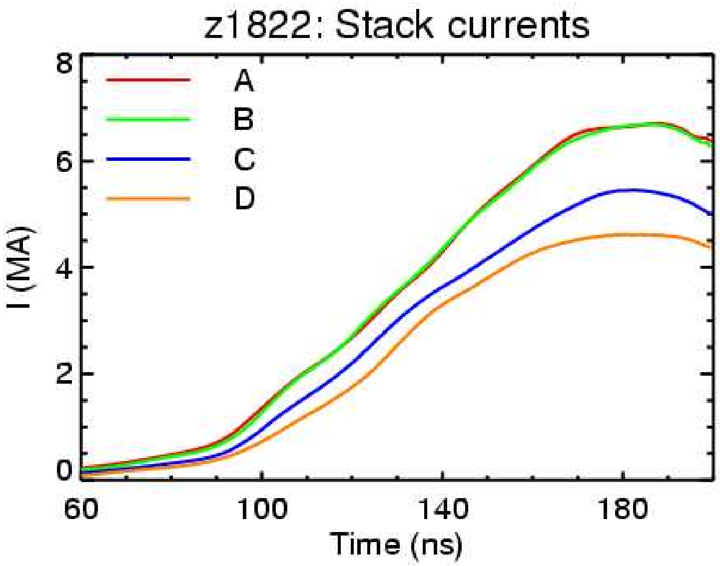
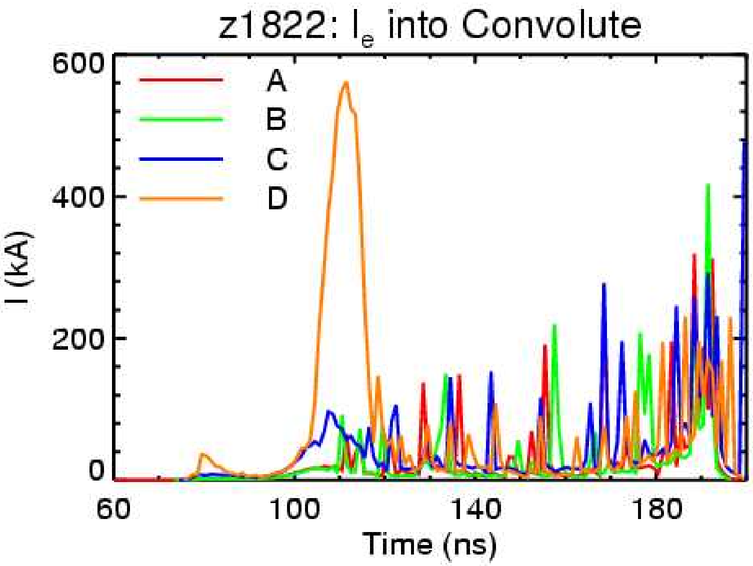
# We have simulated several Z shots

| Shot # | h (cm) | $r_0$ (cm) | $m_{tot}$ (mg) | $L_{IM}$ (nH) | $\tau_{imp}$ (ns) |
|---|---|---|---|---|---|
| 1820 | 1.0 | 2.0, 1.0 | 4.49 | 2.54 | 119 |
| 1822 | 1.0 | 2.0, 1.0 | 3.24 | 2.54 | 110 |
| 1862 | 2.0 | 3.25, 1.625 | 2.52 | 1.50 | 109 |
| 1894 | 1.2 | 2.0, 1.0 | 6.80 | 2.66 | 124 |
| 1906 | 2.0 | 3.25, 1.625 | 1.94 | 1.50 | 110 |
| 1920 | 2.0 | 3.25, 1.625 | 2.41 | 1.50 | 111 |

- All shots are nested wire arrays
  - We use a simple double thin-shell model with 100% momentum transfer when the outer array hits the inner
- Shots 1820, 1822, 1894 part of a series that has the lowest current loss on Z
- Shots 1862, 1906, 1920 have high velocity implosions, giving big dL/dt leading up to stagnation, and larger current loss (esp. 1906)

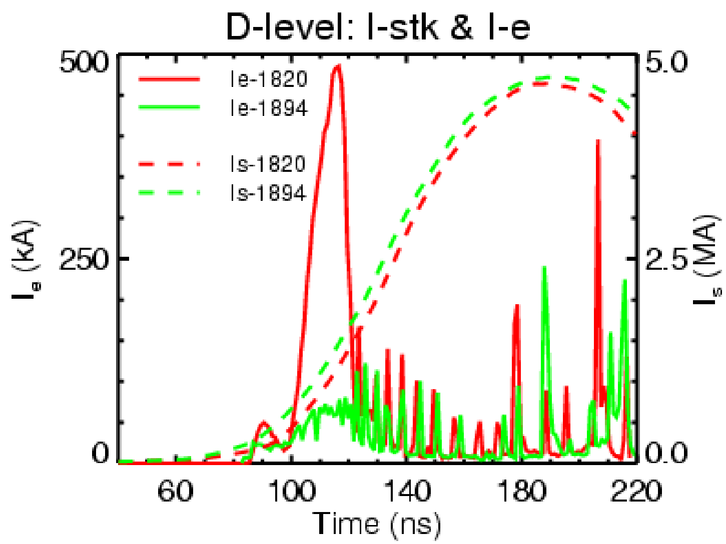
# The simulations give the electron current flowing into the convolute

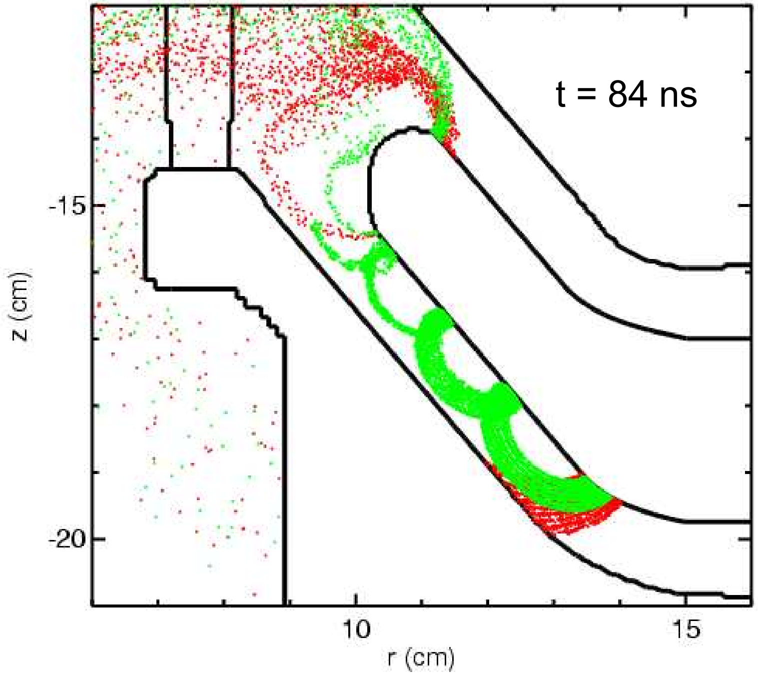



- History of the flow current has three phases:
  - Big surge early in the pulse, before the MITL is insulated
  - Intermediate lower-flow phase: spikes are due to electron vortices
  - Late time rise as dL/dt of imploding load increases voltage
- Typically, the early D-level flow is much higher than the others
  - Higher voltage, lower current

# The flow current is a sensitive function of the MITL voltage and boundary current




- In the 1894 simulation, the slightly higher current insulates the earliest emitted electrons on D-level, radically changing the flow history
- We are still trying to determine how to best evaluate electron losses (and anode heating) with this sensitivity



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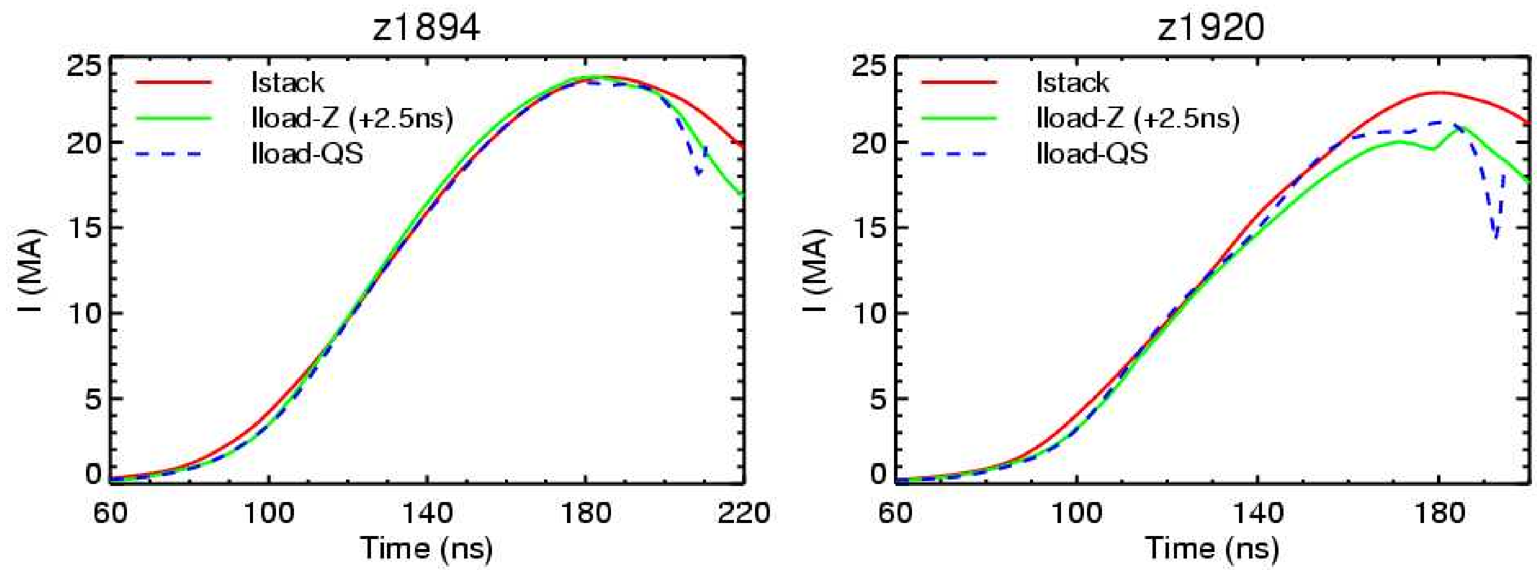
# The simulations predict the early current loss reasonably well




- The other simulations have similar agreement early in time, provided that we use a +2.5 ns timeshift for the Z load current
- Shot 1894 had very low current loss throughout the pulse (<2%).
- In the simulation of shot 1920, there is >2 MA of vacuum electron loss late in the pulse



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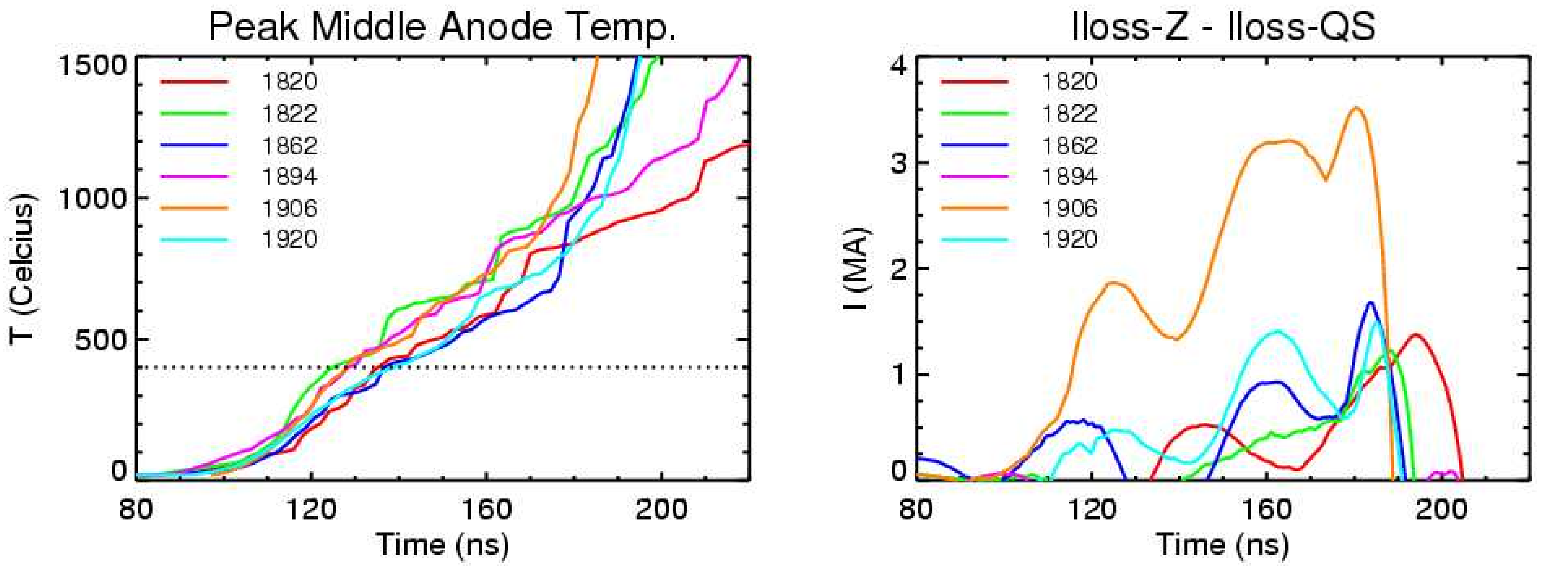
# The simulations monitor electron deposition heating of all anode surfaces



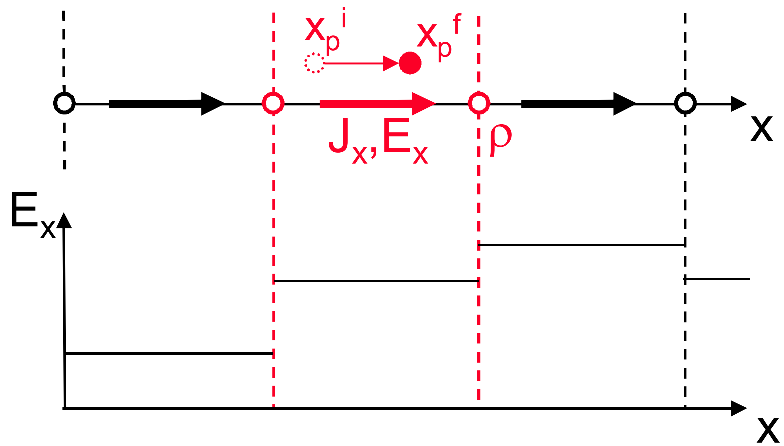

- The magnetic null region of the middle anode always heats the fastest
  - Experimental evidence: anode plasma forms when T > ~400 $^{o}$C
- Preliminary results show little correlation between when the middle anode reaches 400 $^{o}$C and the onset of extra current loss on Z
  - Still many issues to be resolved

# To simulate the extra current loss late in time, we must model electrode plasmas

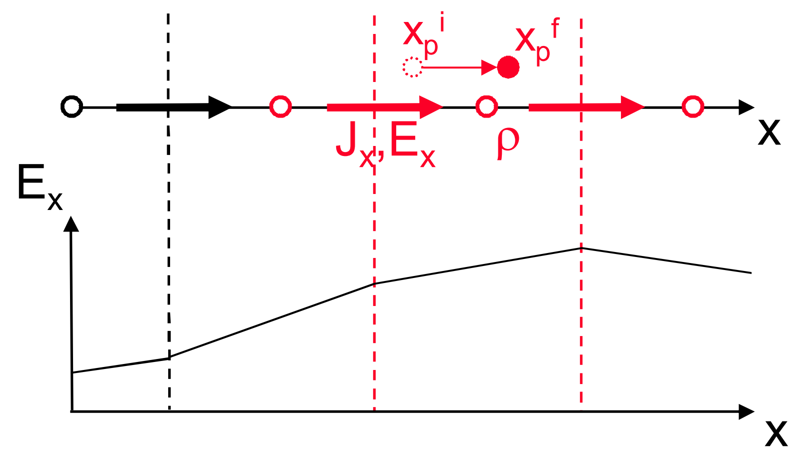
- The major challenge is handling very small Debye lengths
  - For $n = 10^{16}$ cm$^{-3}$, T = 1 eV, have $1/\omega_{pe} = 0.18$ ps, $\lambda_{De} = 74$ nm
  - Timescale comparable to existing constraints
  - Clearly, must operate at $\Delta x/\lambda_{De} >> 1$
- Energy-conserving PIC methods are essential to avoid the numerical heating of the standard algorithm when $\Delta x/\lambda_{De} >> 1$
  - First-order version used in LSP for many years [D.R. Welch, *et al*., Phys. Plasmas **13**, 063105 (2006)]
  - Second-order version recently implemented in QUICKSILVER
- Energy-conserving PIC has its own numerical issues:
  - For n'th order charge weighting, **E**-field interpolation in longitudinal direction (*e.g.* $E_x$ in x-direction) <u>must</u> be done with order n – 1
  - Self-forces

# Higher-order weighting ameliorates issues with energy-conserving PIC

First-order weighting:nodes at cell corners




Second-order weighting: nodes at cell centers

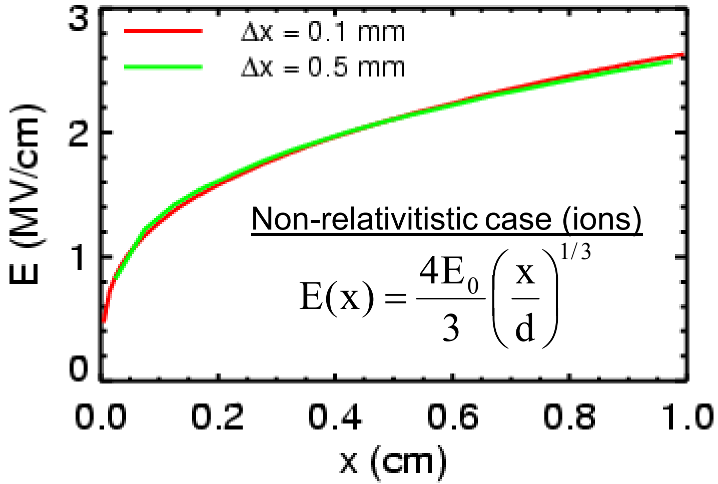


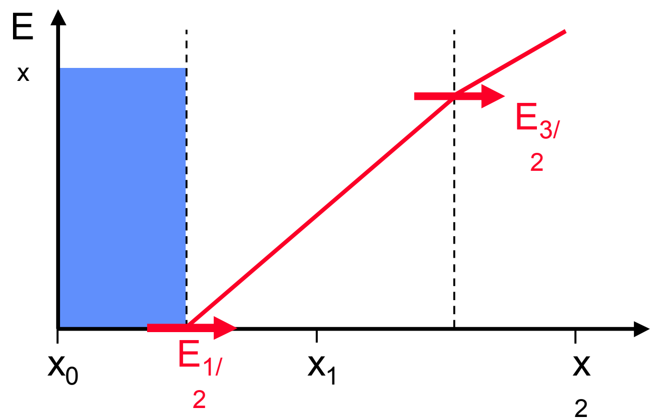

- First-order weighting: discontinous, piecewise-constant E-field profile
  - Potentially an issue for steep E-field gradients
- Second-order weighting: continuous, piecewise-linear E-field profile
  - Handling boundaries in 3-D is complicated, but manageable [T.D. Pointon, Comput. Phys. Commun. **179**, 535 (2008)]

# Electrode plasma layer model

- Must handle large pre-existing E-fields, up to 10 MV/cm
- Simply injecting plasma from the boundary does not work
  - Must create plasma throughout the first cell above the surface
- In our algorithm [T.D. Pointon, SAND2008-6291], emission cells go through four stages:
  1. Breakdown: either $\mathbf{E}_{normal}$ or $T_{surf}$ exceeds threshold
  2. Initial space-charge-limited emission phase: reduce $\mathbf{E}_n$
  3. Preload phase: Abruptly introduce many electron/ion pairs, $\mathbf{E}_n \rightarrow 0$
  4. Maintenance phase: maintain surface density at target value
- LSP uses a different approach: inject neutrals and ionize them in the first cell [D.R. Welch, *et. al, Proc. 2007 IEEE Pulsed Power and Plasma Science Conf*., p. 966]

# Modeling electrode plasma expansion must deal with intense E-fields at the plasma front

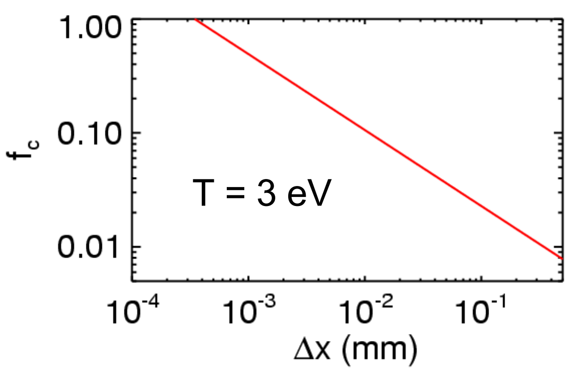


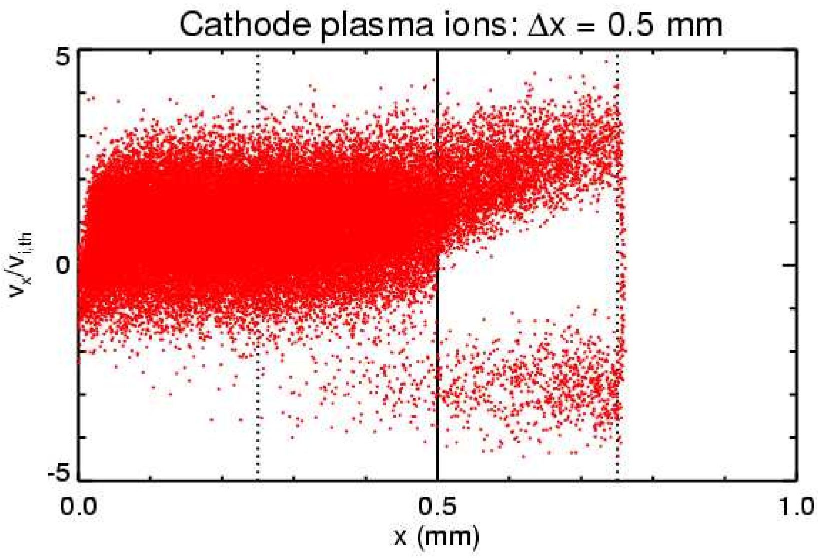




- Planar diode: d = 1 cm, V = 2 MV, $E_0$ = V/d = 2 MV/cm
- Electrode plasma layer model populates first half-cell above the surface, and essentially zeroes out $E_{1/2}$
- First vacuum E-field above layer: $E_v = E_{3/2} \approx (4E_0/3)(\Delta x/d)^{1/3}$
  - $\Delta x$ = 0.5 mm: $qE_v\Delta x$ = 49 keV
  - $\Delta x$ = 0.1 mm: $qE_v\Delta x$ = 6 keV

# With coarse resolution, low energy particles cannot get very far into the first vacuum cell

- Electrons in an anode plasma (ions in a cathode plasma) are turned back to the electrode by $E_v$
  - Mean fraction of cell they traverse: $f_c = \left(\frac{T}{qE_v\Delta x}\right)^{1/2} \approx \left(\frac{3T}{4qV}\right)^{1/2}\left(\frac{\Delta x}{d}\right)^{-2/3}$




- Coulomb collisions enhance the expansion, but may not be able to get particles across a cell when $f_c << 1$



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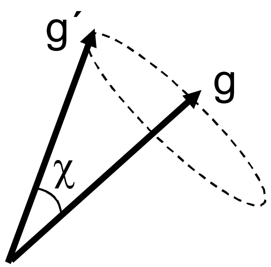
# Coulomb collision model

- We use a particle-pairing method [T. Takizuka, H. Abe, J. Comput. Phys. 25, 205 (1977)]: no assumptions about velocity distribution
  - Gather all colliding particles in a cell
  - Randomly pair up each particle with one other
  - For each pair, compute relative momentum $\mathbf{g} = \mathbf{u}_1 - \mathbf{u}_2$
  - Rotate $\mathbf{g} \rightarrow \mathbf{g}'$ using
    - Polar angle $\chi$, where $\delta = \tan(\chi/2)$ is sampled from a normal distribution; $\langle\delta^2\rangle \propto n\Delta t/g^3$
    - Random azimuthal angle
  - Compute new momenta
    - $\mathbf{u}_1' = \mathbf{u}_1 + m_{12}(\mathbf{g}' - \mathbf{g})/m_1$
    - $\mathbf{u}_2' = \mathbf{u}_2 - m_{12}(\mathbf{g}' - \mathbf{g})/m_2$



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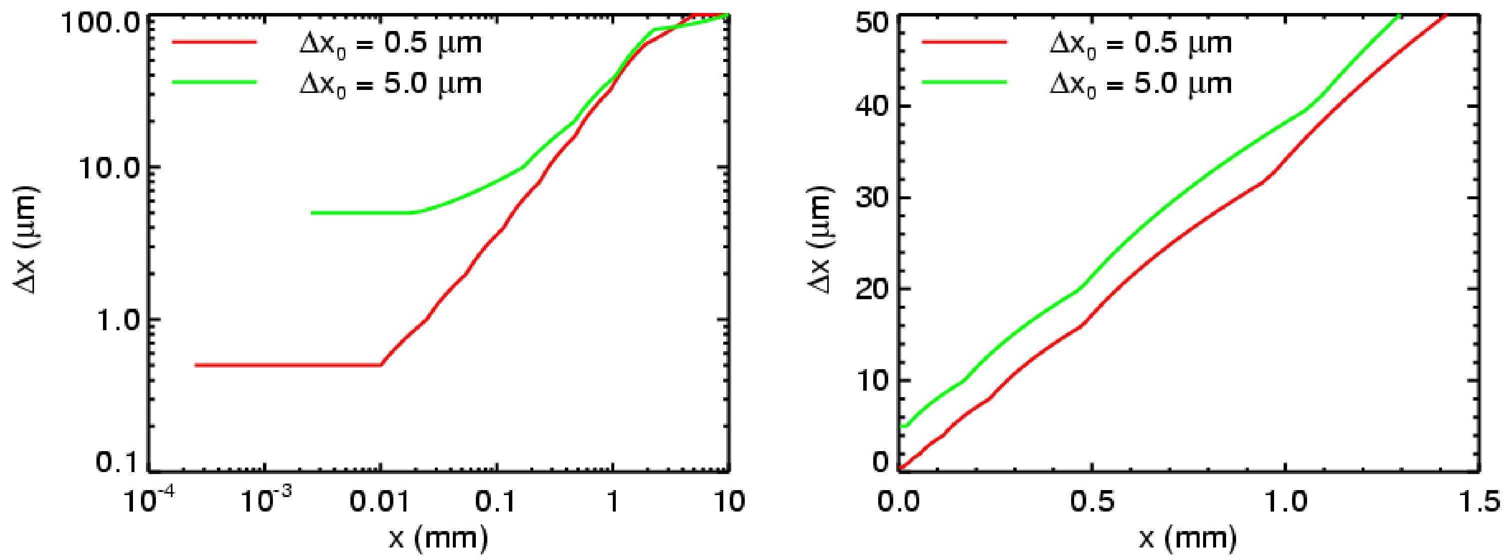
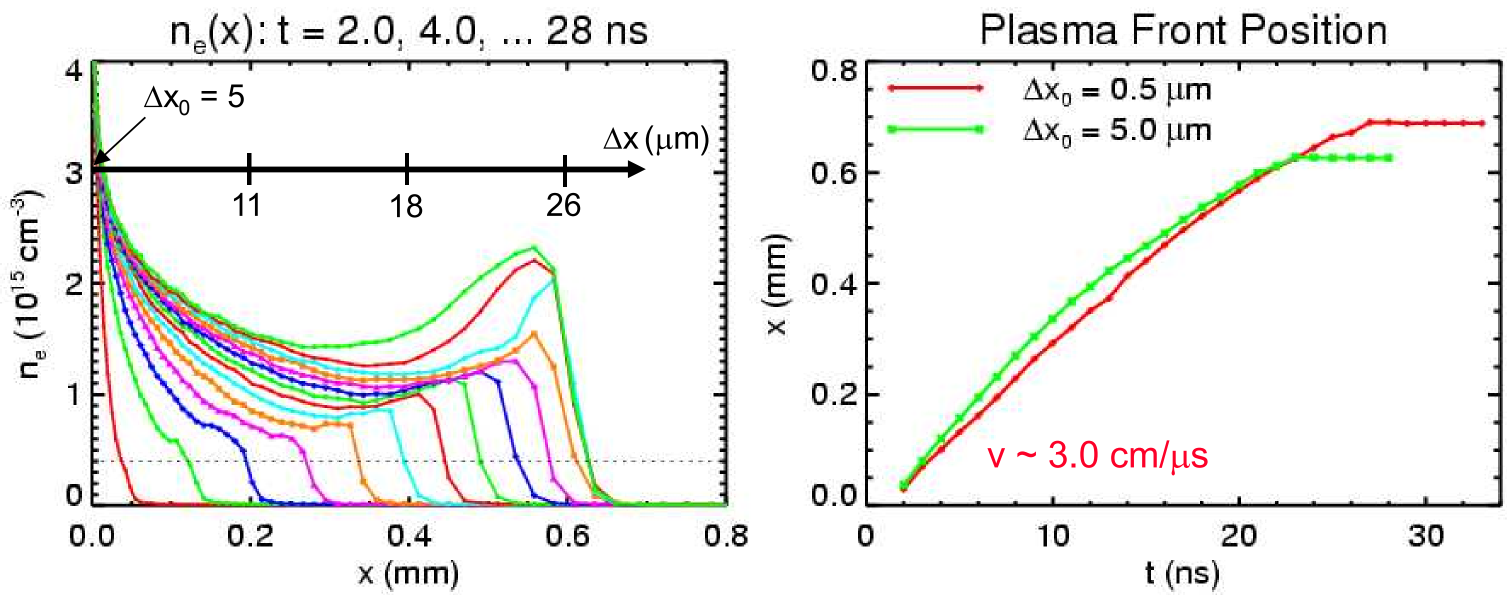
# We use 1-D electrostatic simulations to study plasma expansion over a range of cell sizes




- Three setups for a planar diode with a 1 cm gap and V = 2 MV
  - Non-uniform grid with $\Delta x_0$ = 5 μm or 0.5 μm at emitting boundary
  - Uniform grid with 20 cells, Δx = 0.5 mm (characteristic of large 3-D convolute simulations)
- Can use much larger Δt than an EM simulation -- no Courant limit

# Accurate modeling of cathode plasma expansion requires very small cell sizes




- n = 5•$10^{15}$ cm$^{-3}$, T = 3 eV; $\lambda_{De}$ ~ 0.18 $\mu$m
- The non-uniform grid enables a range of cell sizes to be sampled in a single simulation as the plasma front expands
  - Non-physical profile develops for $\Delta x > 15$ $\mu$m
  - Plasma expansion stops when $\Delta x \sim 25$ $\mu$m



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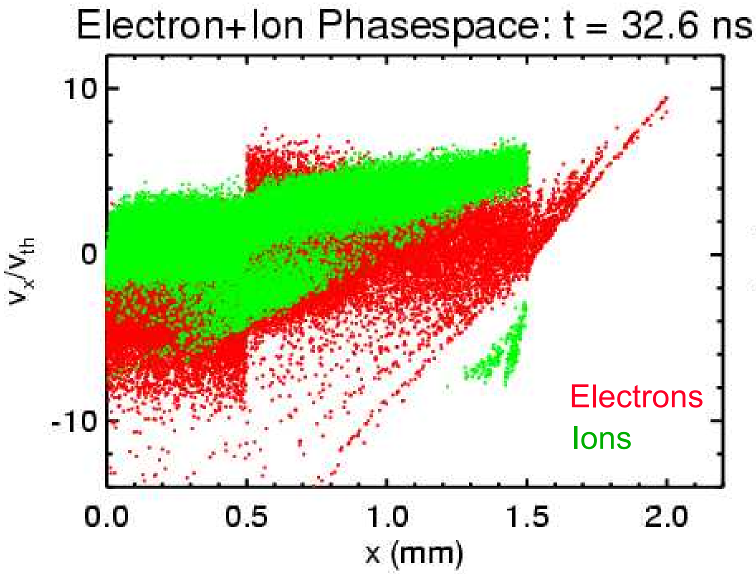
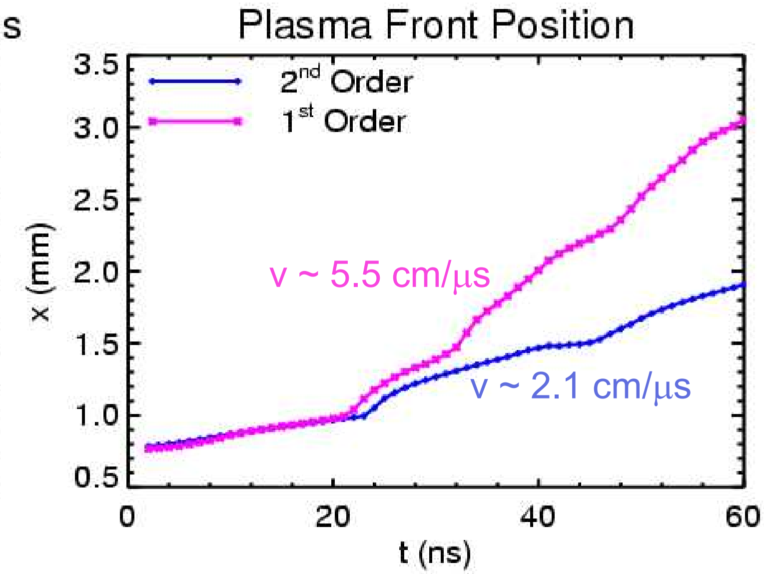
# With coarse resolution, cathode plasma "expands" only via numerical instability




- Particle x-$v_x$ phasespace movies show the "expansion" mechanism
  - Density builds at the front; almost all particles turned around by $E_v$
  - A longitudinal instability develops; then suddenly high-density jets of electrons abruptly cross the vacuum cell (left figure), reducing $E_v$
  - Electrons and then ions stream into vacuum cell, and instability disappears
  - Process is repeated in the next cell
- Instability is more violent with the $1^{st}$-order scheme, giving faster expansion



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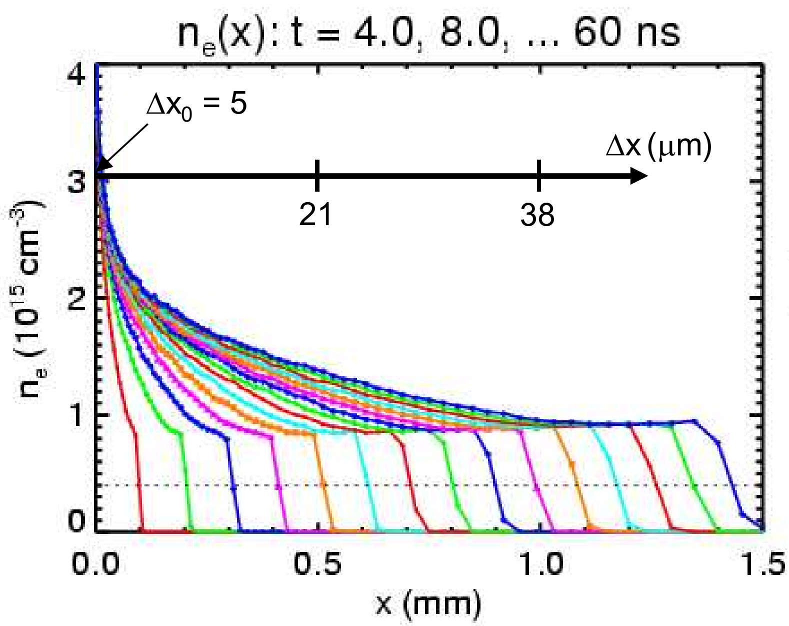
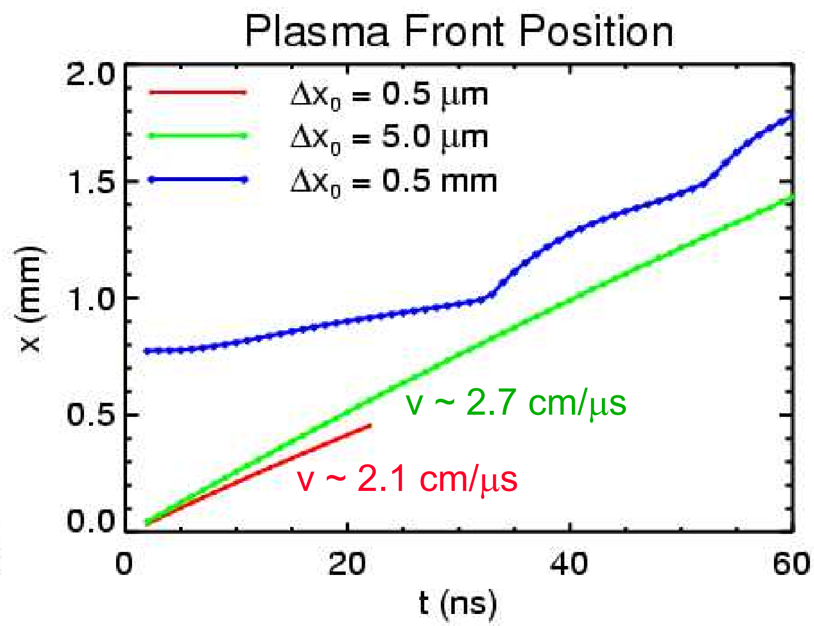
# Anode plasma expansion is less sensitive to the cell size




- At Δx = 0.5 mm, same non-physical "expansion" as cathode plasmas
- At $\Delta x_0$ = 5 μm, continue to get expansion at Δx = 60 μm
  - Not clear that we have converged on the expansion at $\Delta x_0$ =0.5 μm, but cannot go any lower without major code modifications



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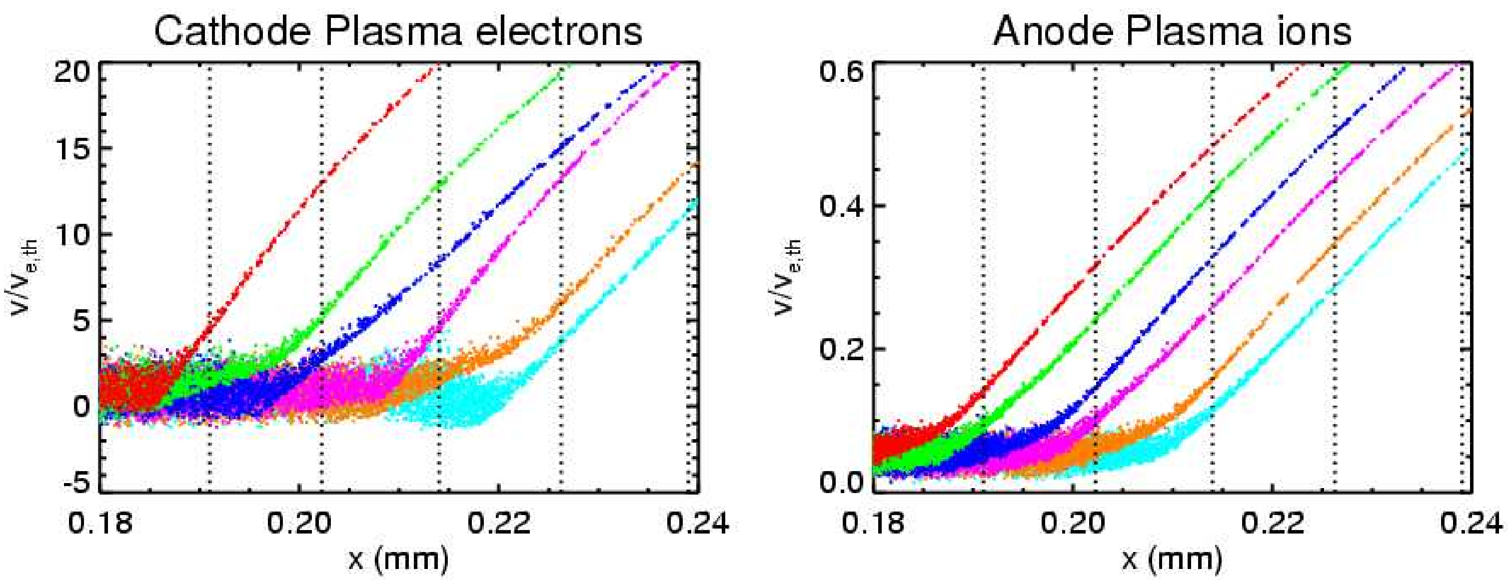
# The asymmetry between anode and cathode plasmas is a consequence of the collisions




- For electron-ion Coulomb collisions, scattering angle $\chi \sim |\mathbf{u}_e - \mathbf{u}_i|^{-3/2} \sim u_e^{-3/2}$
  - Cathode plasma: plasma ions and beam electrons weakly interact
  - Anode plasma: plasma electrons and beam ions interact more strongly
- Operating at $\Delta x/\lambda_{De} >> 1$, the simulations violate an assumption of the collision model: little variation of the particle drift velocity within a cell

# Summary

- We have a detailed PIC simulation model of the Z vacuum section
  - High-resolution 4-level 2-D MITL setup, providing our best estimate of the electron flow into the convolute
  - 3-D convolute setup, showing where the electrons are lost, and the electron deposition heating of the anode
  - The model can accurately simulate current losses in the convolute, until electrode plasma effects dominate
  - There are still issues with how best to drive the simulations
- We have enhanced QUICKSILVER to simulate electrode plasmas
- Fine spatial resolution is required to accurately model electrode plasma expansion from first principles, $\Delta x \ll 100\ \mu m$
  - Can probably do 2-D MITL simulations with cathode plasmas
  - No chance of using this approach for the convolute simulations

# Future plans

- Confirm that the slight differences between stack currents that cause such different behavior in the electron flow current are genuine
- Research options for an external circuit model out into the water section to provide better predictive capability for the 3-D simulations
- Perform series of high-resolution 1-D simulations to characterize plasma expansion as a function of n, T, **E**, and **B**
- Research new ways to simulate electrode plasma expansion in large-scale 3-D convolute simulations
  - Track the plasma front with velocity based on the 1-D results
  - Handle particles and/or fields with special models at the front



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