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EM-PIC Simulation of Pulsed Power Systems at Sandia National Laboratories

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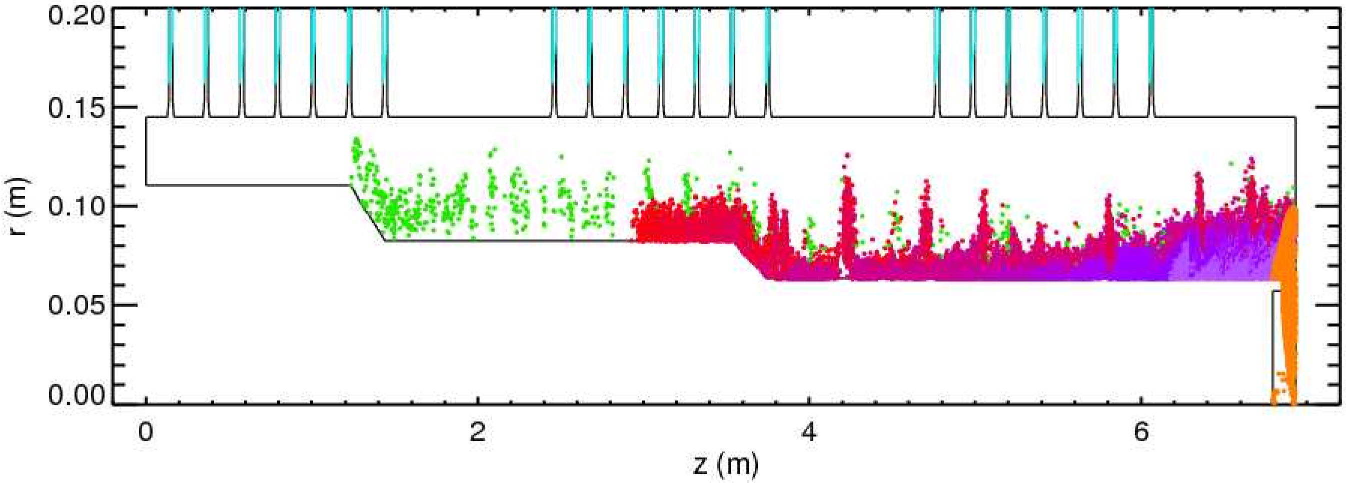

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Boulder CO, June 29, 2012

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Outline

- Applications driving analysis and code development:
  - Magnetically insulated transmission lines (MITLs) (ongoing)
  - Light ion beams for fusion: applied-B ion diodes (1987 – 1997)
  - Power flow in the vacuum section of the “Z” accelerator (1997 –)
  - The 21-cavity “Ursa Minor” linear transformer driver (LTD) for radiography (2009 –)
  - Electron beam transport in gas (“gas chemistry”)
- The Quicksilver 2D/3D EM-PIC code
  - Geometry, 1D transmission lines
  - Other features - physics models
- Other PIC work (not discussed here)
  - Implicit ES hybrid fluid-PIC codes: DYNAID (1D), MUFPHI (2D)
  - Unstructured EM-PIC: tetrahedral meshes

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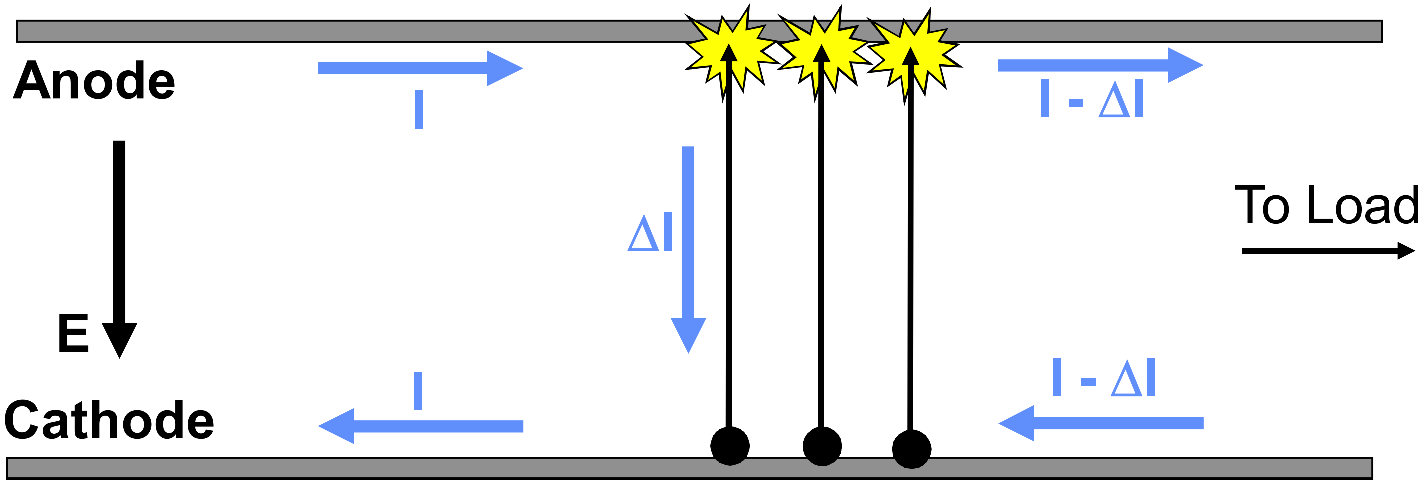
Cathode electron emission is unavoidable for a multi-MV EM pulse in a transmission line



- ***Without special treatment***, a cathode surface emits electrons when the normal electric field E_n exceeds ~50 – 200 kV/cm
- Electrons flowing to the anode is undesirable
  - Reduces current delivered to the load
  - Heats the anode -- can create an anode plasma

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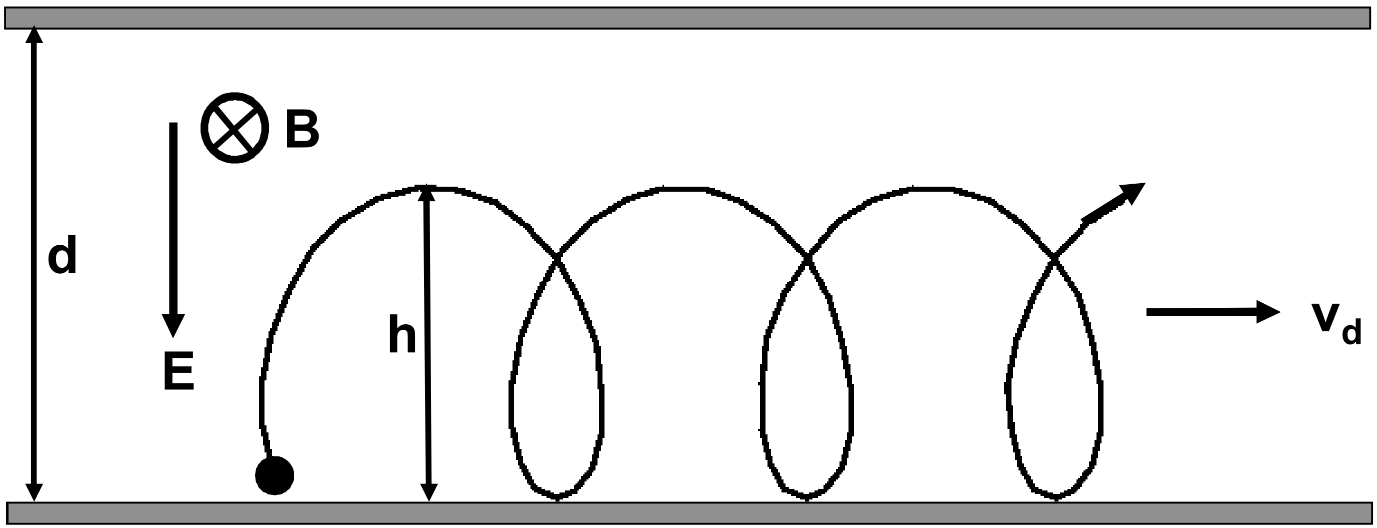
A transverse magnetic field can inhibit electrons from crossing the A-K gap



- For cB > E, the electrons "drift" with velocity $\mathbf{v_d} = (\mathbf{E}\times\mathbf{B})/B^2$
- For uniform **E** and **B** fields: $h = \dfrac{\frac{2m}{e}E}{B^2 - E^2/c^2}$
    - For sufficiently large B, h < d

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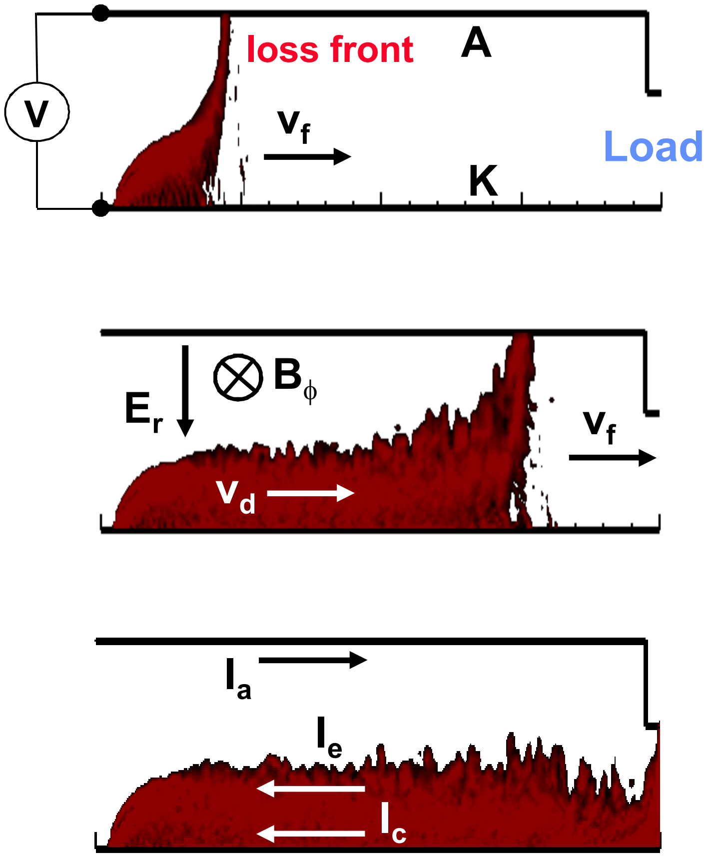
Efficient power transfer is possible with "magnetically insulated transmission lines"

- Schematic illustration of a coaxial "MITL" driving a load
- Behind the "loss front", B-field of the current flowing in the conductors insulates electrons: they "**E**x**B** drift" towards the load
- In equilibrium, current flow in the "electron sheath" is related to the anode and cathode conduction currents by: $\mathbf{I_e = I_a - I_c}$
- Technical issues for real systems
  - Current loss if load impedance is too high
  - Adding lines in serial or parallel



Courtesy of Steve Rosenthal

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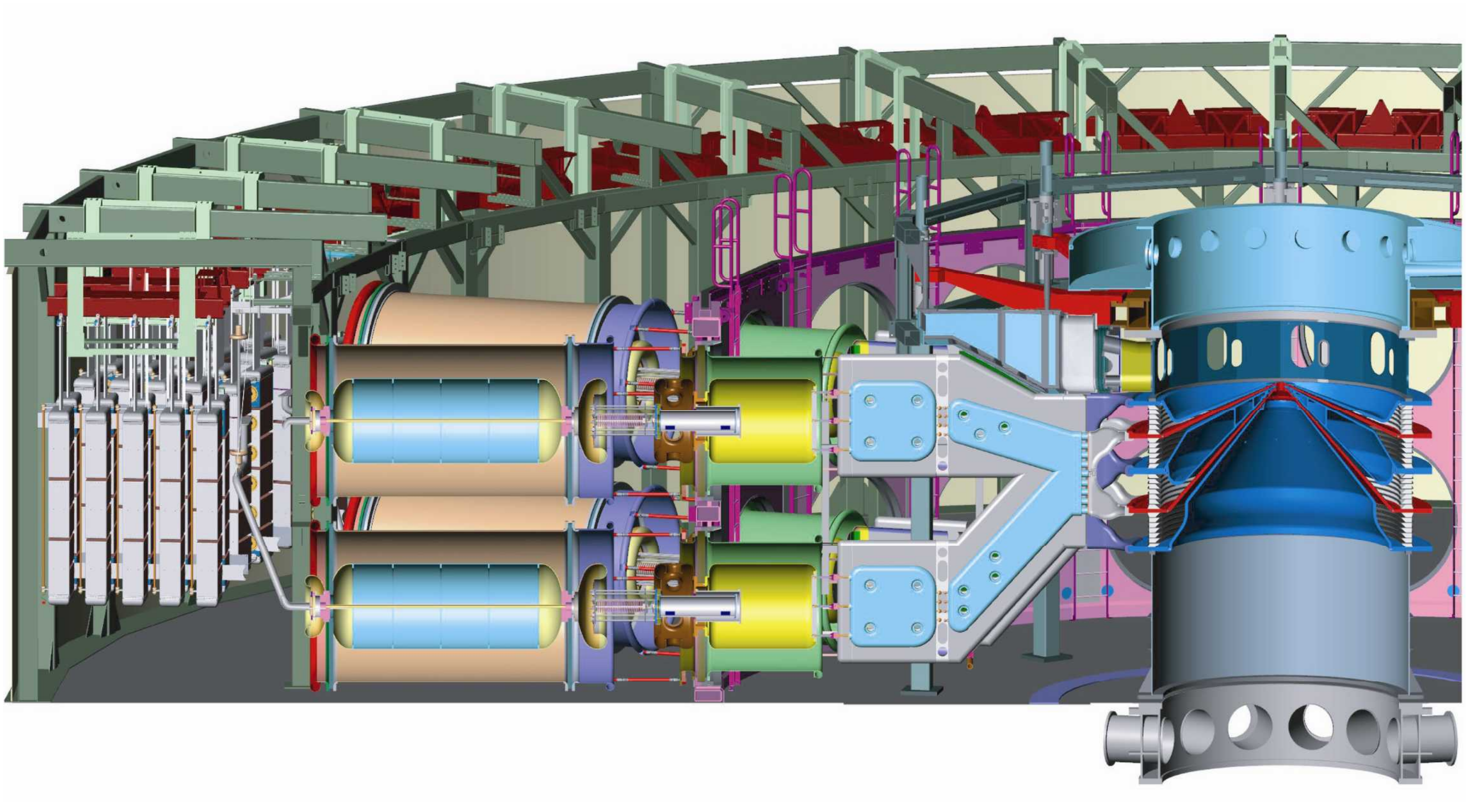
Sandia's Z accelerator is the world's most powerful high-current driver



- 33 m in diameter, 6 m high, 36 pulse-forming lines
- Drives variety of loads, *e.g.* 26 MA, 100 ns pulse to a Z-pinch

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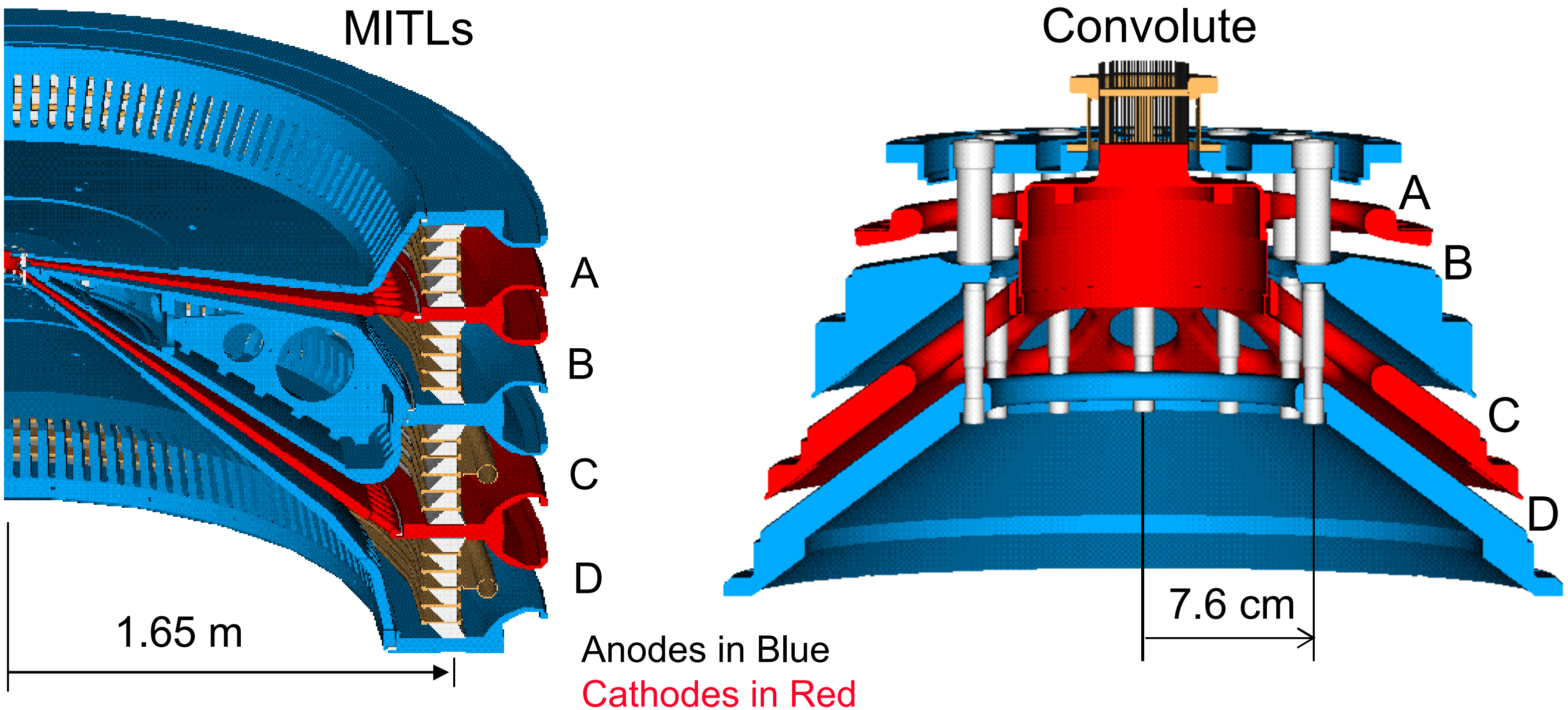
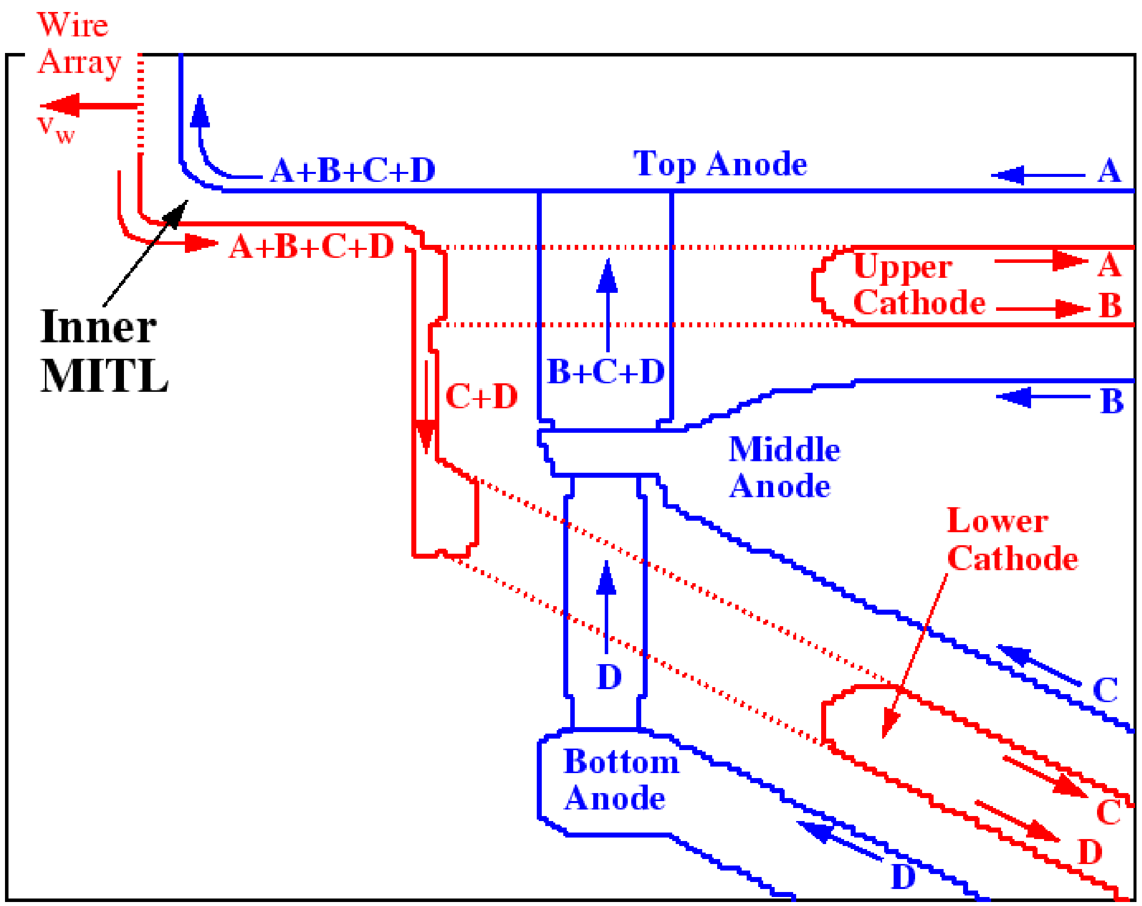
The vacuum section conducts power from the insulator stack to the load



- The four MITLs are coupled <u>in parallel</u> at the post-hole convolute
- Electron emission in the MITLs, out to the vacuum flares at r ~ 1.5 m
  - Electrons **E x B** drift radially inwards into the convolute

The convolute adds the currents from the four feed lines into the inner MITL



- Surface current distribution in the convolute is highly nonuniform.

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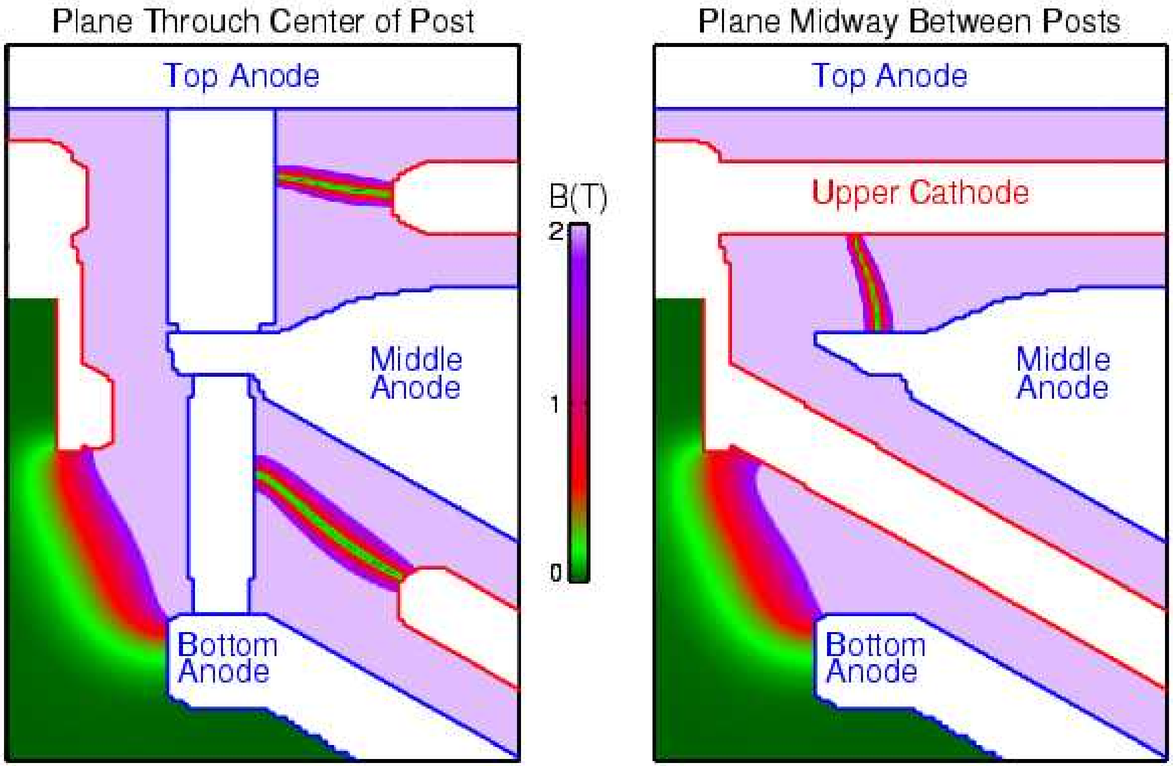
Magnetic nulls in the convolute



- 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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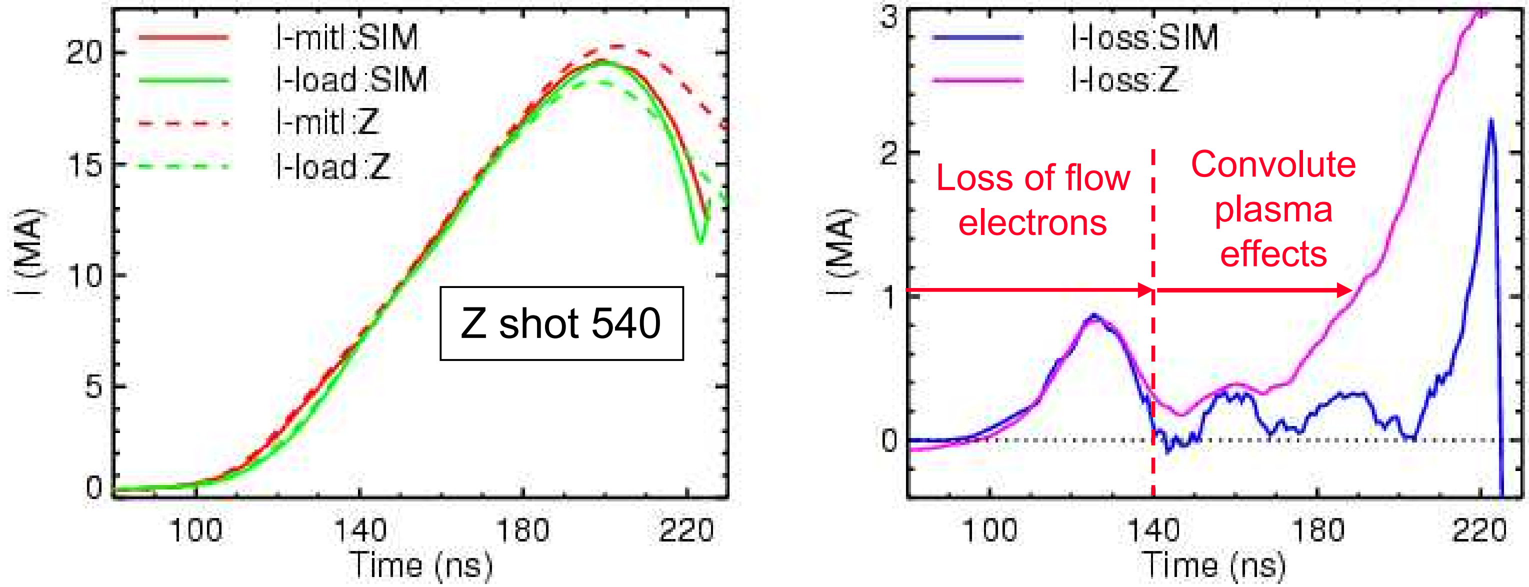
Quicksilver accurately computes the early current loss … but not late in time



- Simulation has only vacuum flow electrons
- Early-time loss: MITL electrons lost to the anode in the convolute
- Additional late-time loss is due to electrode plasmas in the convolute
  - No detailed data: anode? cathode? both?

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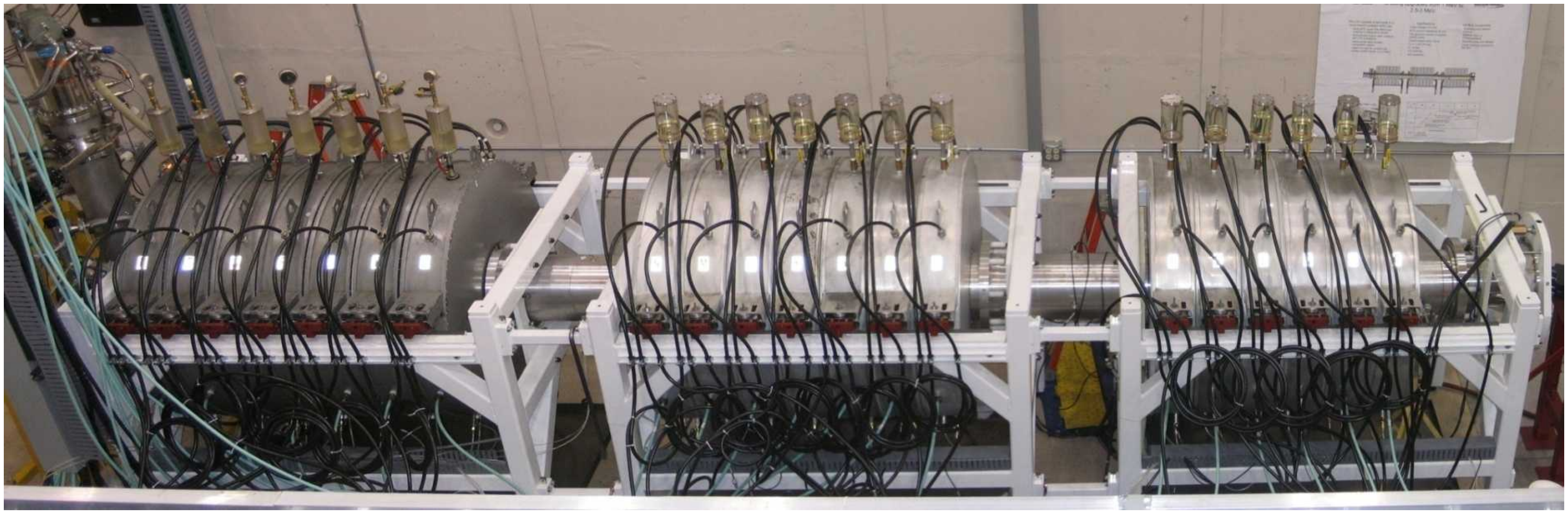
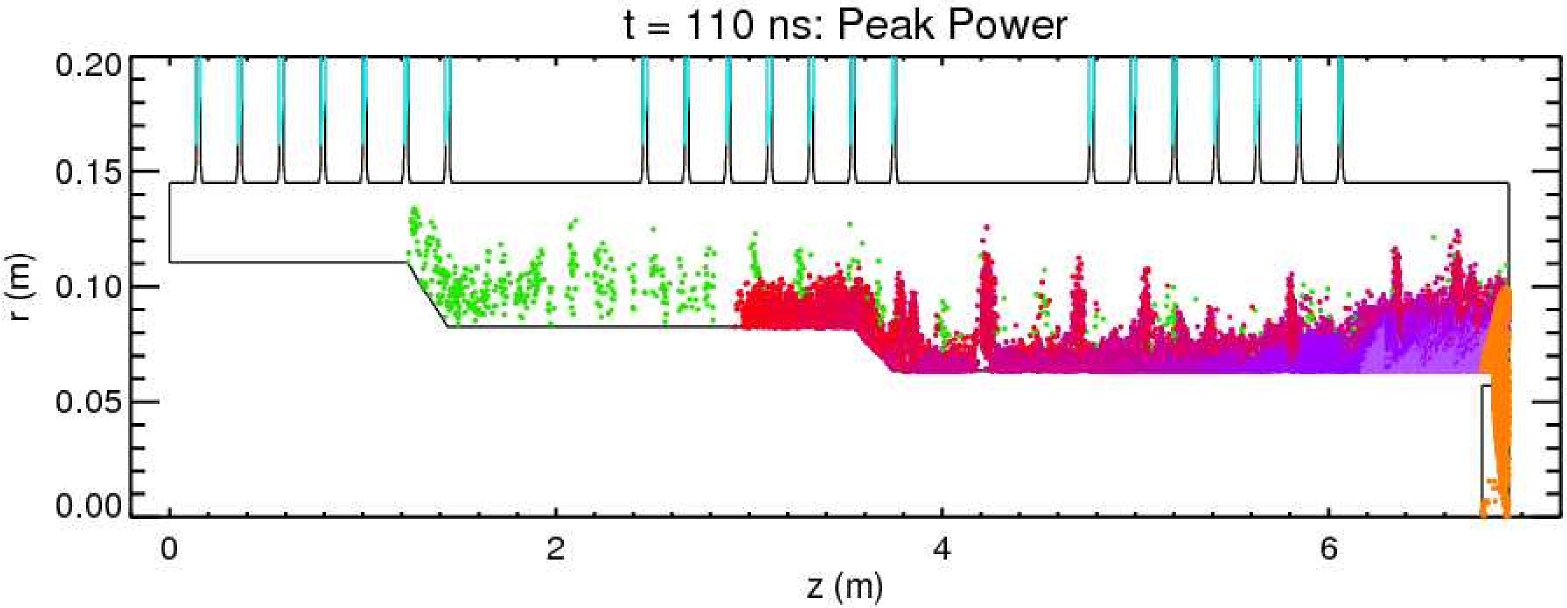
Ursa Minor is a testbed for adding many LTD cavities in series for voltage addition



- Ultra-compact pulsed power: each cavity has 10 “bricks” in parallel, composed of two capacitors and a low-inductance switch in oil
  - No need for pulse-forming water section
- 21-cavity voltage adder, 7.5 m long, 1.5 m diameter
  - 180 kV/cavity → ~2.5 MV delivered to the load … with unavoidable internal losses, but minimal electron flow loss

We have set up a 2-D r-z Quicksilver model of the full 21 cavity geometry



- 1 mm cell size across the 2.2 cm A-K gap of the 21 feeds
- Electrons "color-coded" by creation location
- Key questions:
  - What are electron losses to insulators (shown in cyan)?
  - What factors contribute to the loss?

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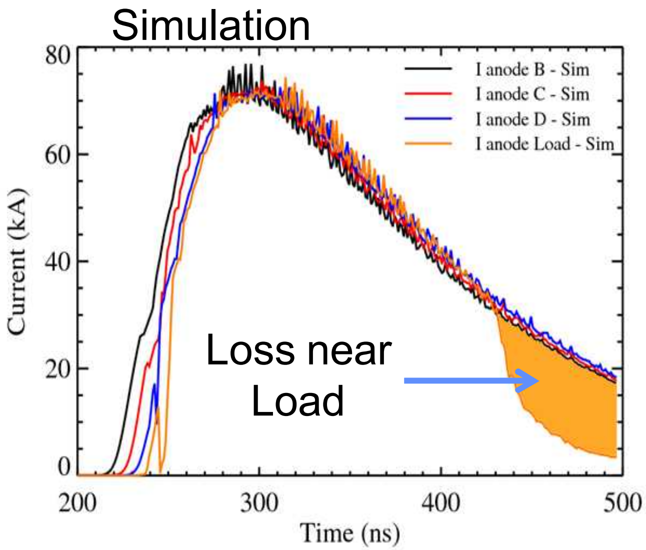
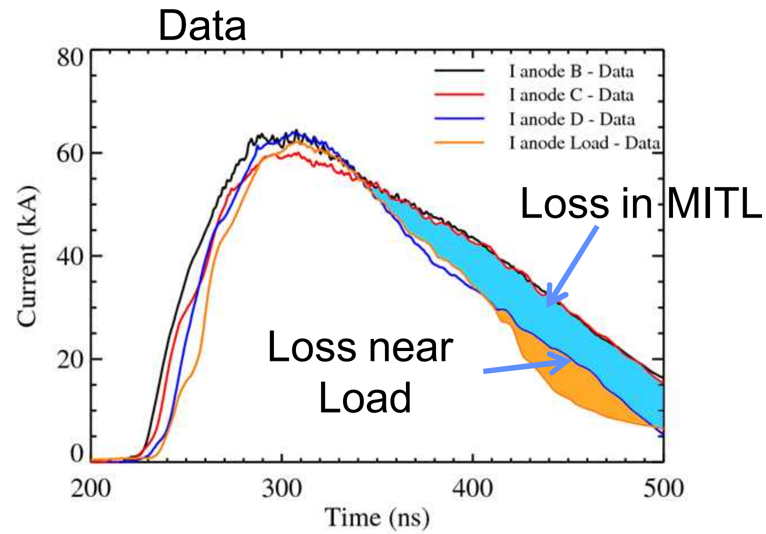
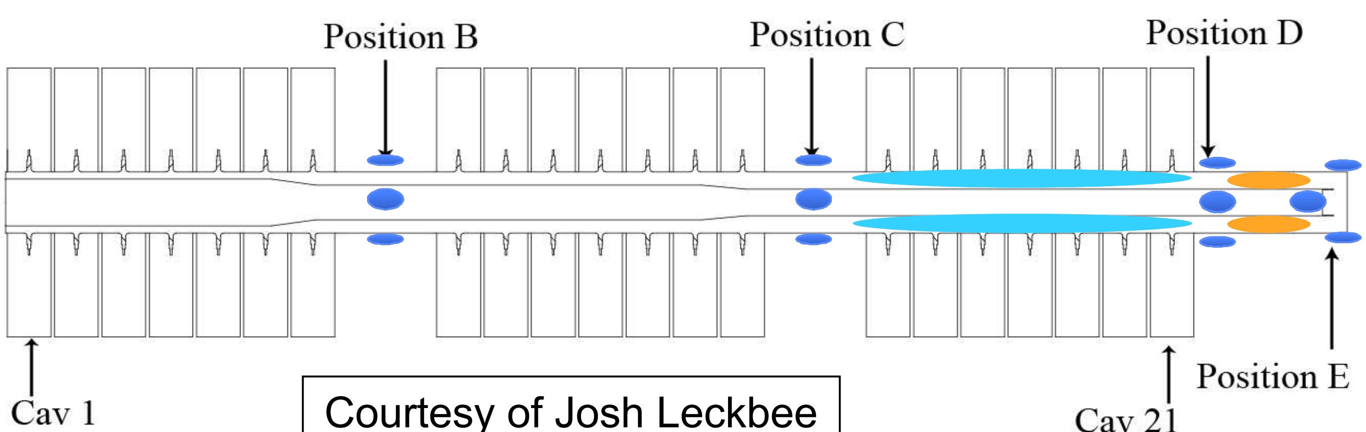
Experiment has lower peak MITL current and higher loss current than simulations







Courtesy of Josh Leckbee

The Quicksilver code has been under development since the mid-1980's

- Originally ANSI-standard F77 for portability; now has F90, C, C++
- Mercury preprocessor
  - Process input text file(s) with symbolic variables, arrays, loops, if-tests, and include files
  - Error checking and computing array sizes
- 2D/3D multi-block geometry
  - Cartesian, cylindrical or spherical coordinates
  - 1D transmission lines for external circuits
- Parallelized with MPI
  - Static decomposition for field solver
  - Dynamic load-balancing for the particle handler
- IDL for all post-processing
  - Also use IDL extensively as a preprocessing tool

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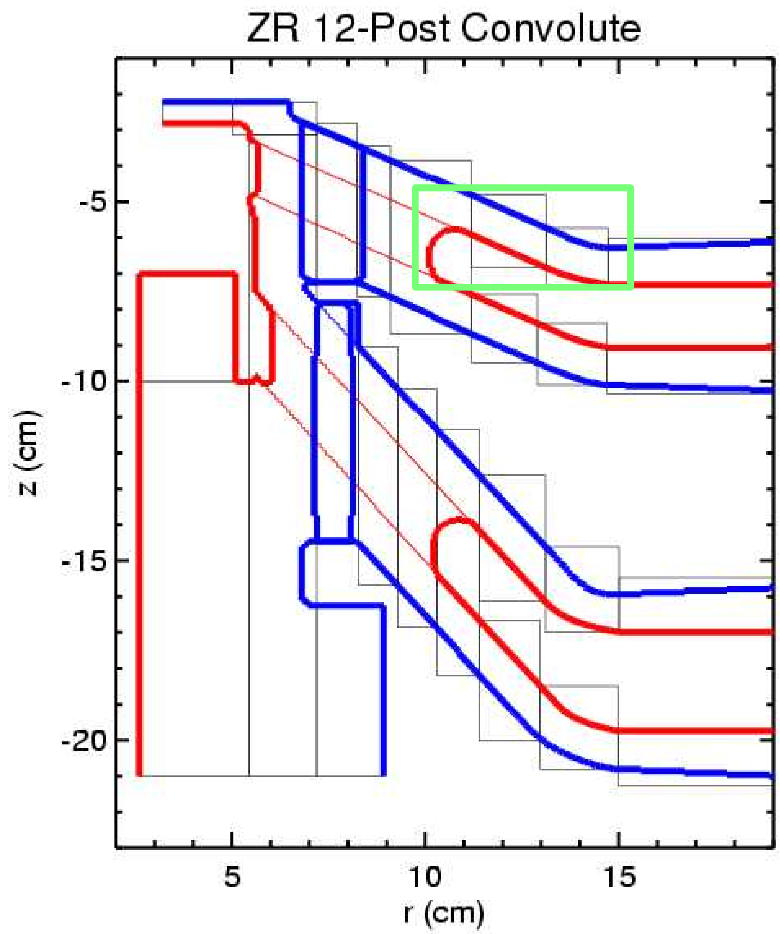
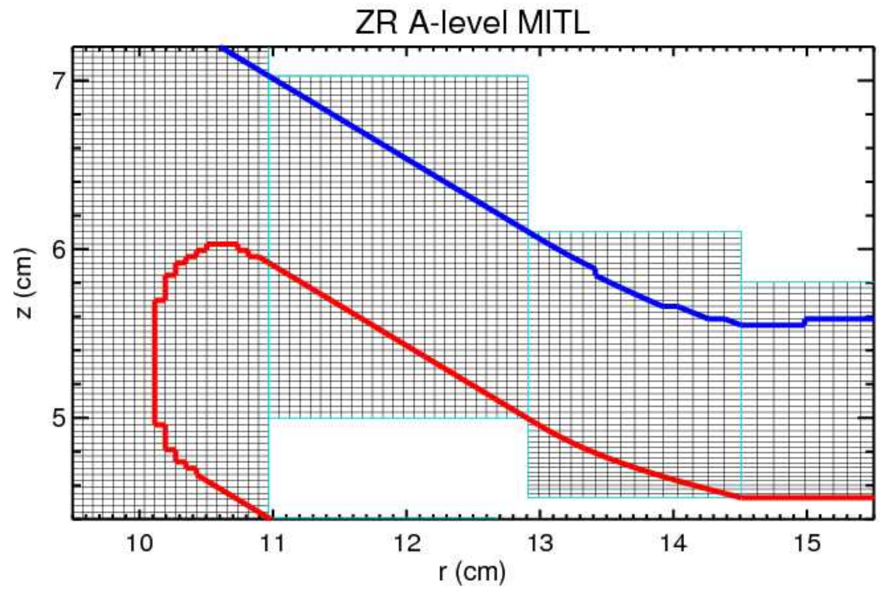
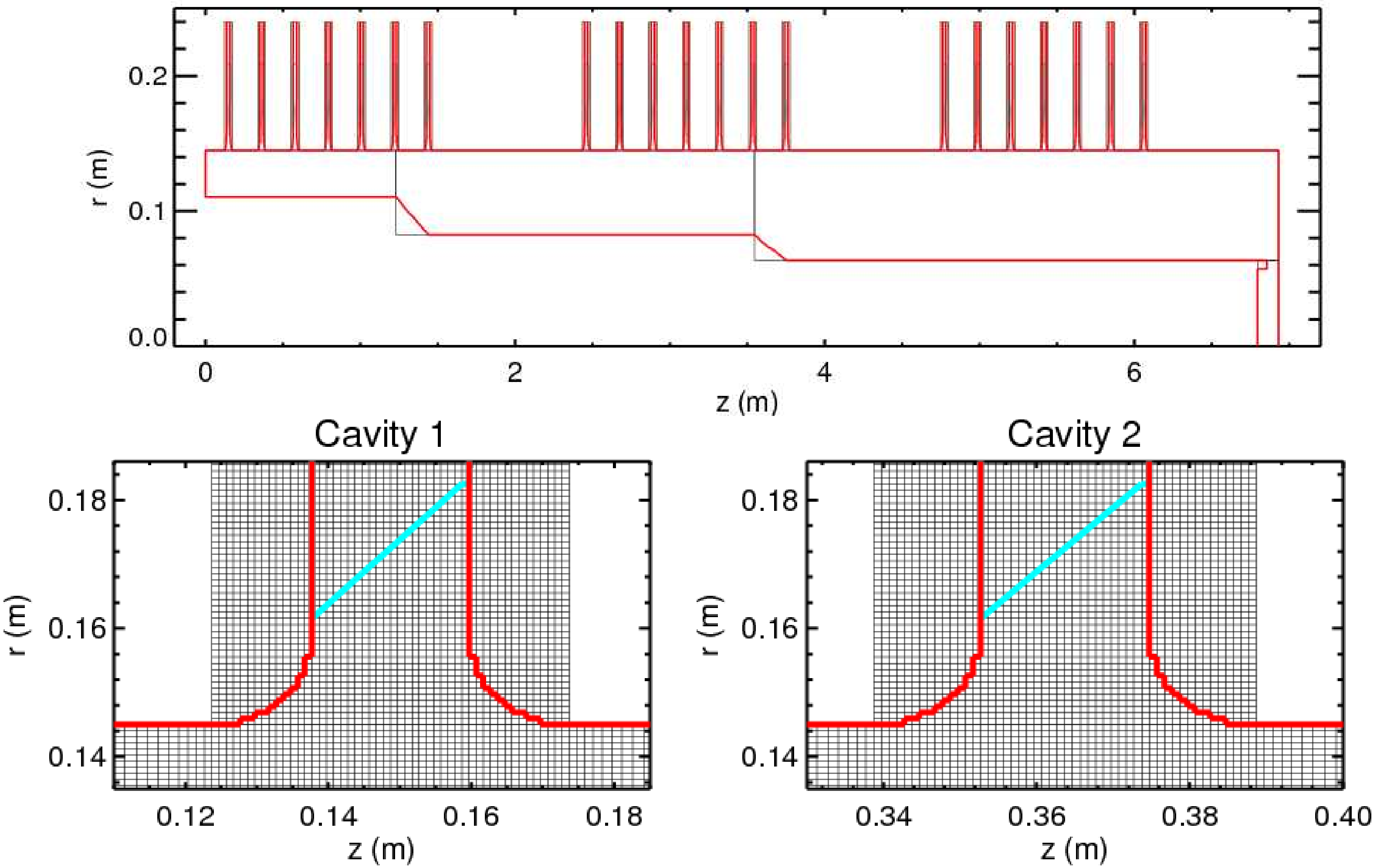
QS uses multi-block geometry to efficiently grid complex systems





This geometry is built with IDL scripts and post-hole convolute geometry is imported from an acis file

Multi-block geometry is an essential capability for the Ursa Minor simulations



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Augmenting PIC with 1D transmission lines is essential for modeling large systems

- TL's connect to a boundary plane of the 2D/3D domain at a "port" – two conductors (anode,cathode) with arbitrary "x-y" cross-section
- TEM mode E-field determined by:

  $\nabla_T^2 \phi = 0; \phi_{cat} = 0; \phi_{ano} = V_0$; V_0 = 1 Volt

  $\boldsymbol{E}_p = -\nabla \phi$; "Poisson Field"

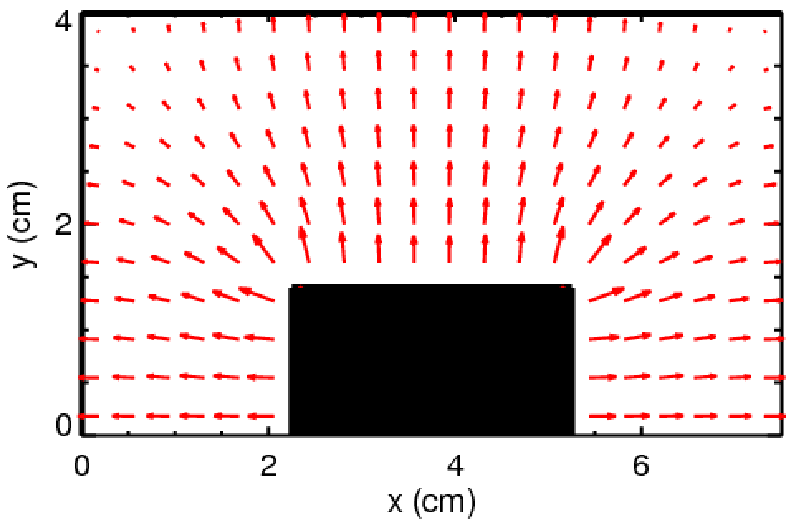
  $\boldsymbol{E}_{TEM}(V) = (V/V_0)\, \boldsymbol{E}_P$

- Per-unit-length capacitance

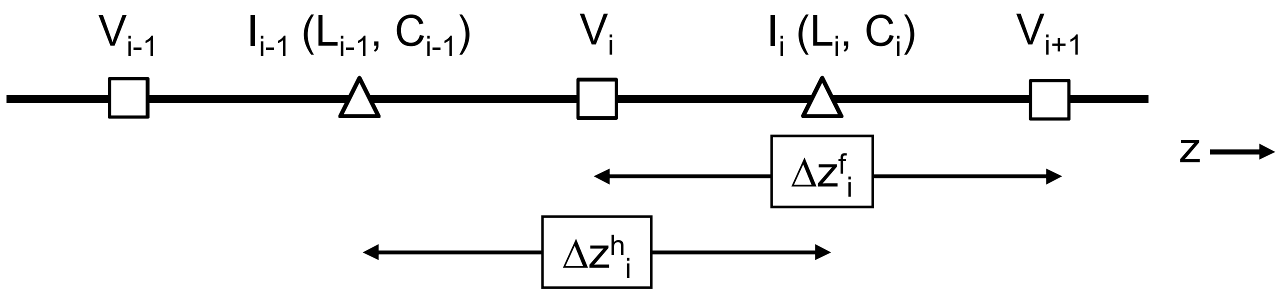
  $C = \frac{\varepsilon}{V_0^2} \int E_p^2 dA$

- Per-unit-length inductance

  $L = 1/(v_{ph}^2 C)$; $v_{ph} = (\varepsilon\mu)^{-1/2}$



Voltage and current in the T-line are updated with the telegrapher's equations



- Telegrapher's equations for a lossless line:

$$\frac{\partial I}{\partial t} = -\frac{1}{L}\frac{\partial V}{\partial z} \quad ; \quad \frac{\partial V}{\partial t} = -\frac{1}{C}\frac{\partial I}{\partial z}$$

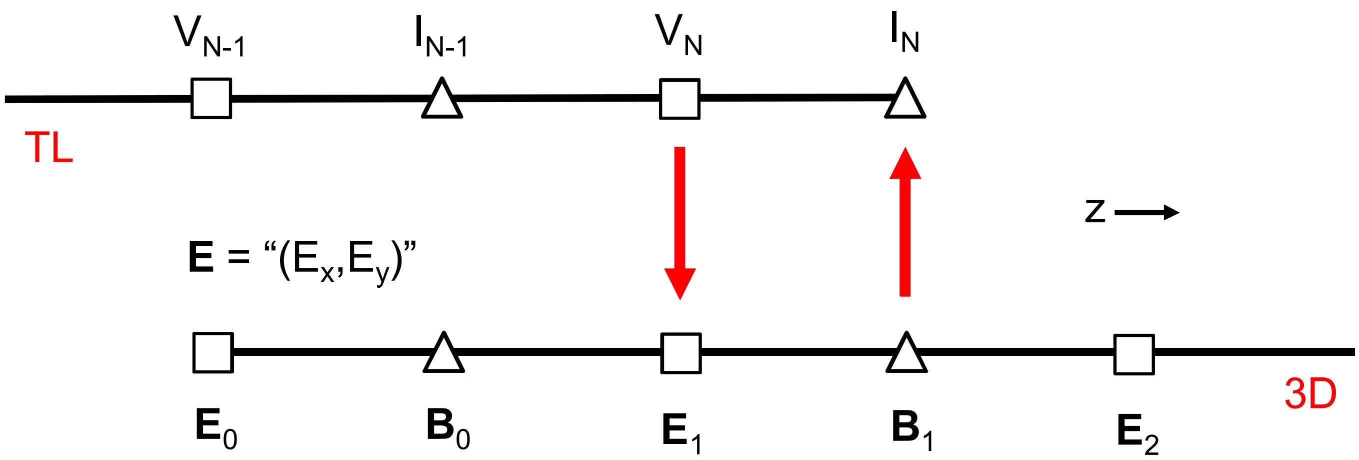
- Leapfrog finite difference, $\{V^{n-1}, I^{n-1/2}\} \rightarrow \{V^n, I^{n+1/2}\}$:

$$V_i^n = V_i^{n-1} - \gamma_i (I_i^{n-1/2} - I_{i-1}^{n-1/2}) \quad ; \quad \gamma_i = 2\Delta t / (\Delta z_i^h [C_{i-1} + C_i])$$

$$I_i^{n+1/2} = I_i^{n-1/2} - \lambda_i (V_{i+1}^n - V_i^n) \quad ; \quad \lambda_i = \Delta t / (\Delta z_i^f L_i)$$

- Blazingly fast compared to 2D/3D field solver update
- Easy to add BC's at the end of a TL: generators, Z-pinch loads, etc.

The transmission line couples naturally to the TEM mode in the 2D/3D system



- TL voltage V_N^n determines $\mathbf{E}_T^n$ on boundary plane of the 3D system
  - $\mathbf{E}_1^n = \mathbf{E}_{TEM}(V_N^n) + \mathbf{E}_{non\text{-}TEM}^n$
  - Hard part is specifying $\mathbf{E}_{non\text{-}TEM}^n$
- 3D magnetic field $\mathbf{B}_1^{n+1/2}$ determines boundary current $I_N^{n+1/2}$
  - $I_N = \frac{1}{\mu V_0}\int \boldsymbol{e}_z \times \boldsymbol{E}_p \bullet \boldsymbol{B}_1 dA$ (filters out non-TEM part of $\mathbf{B}_1$)
  - This defines V_N^{n+1} on next timestep

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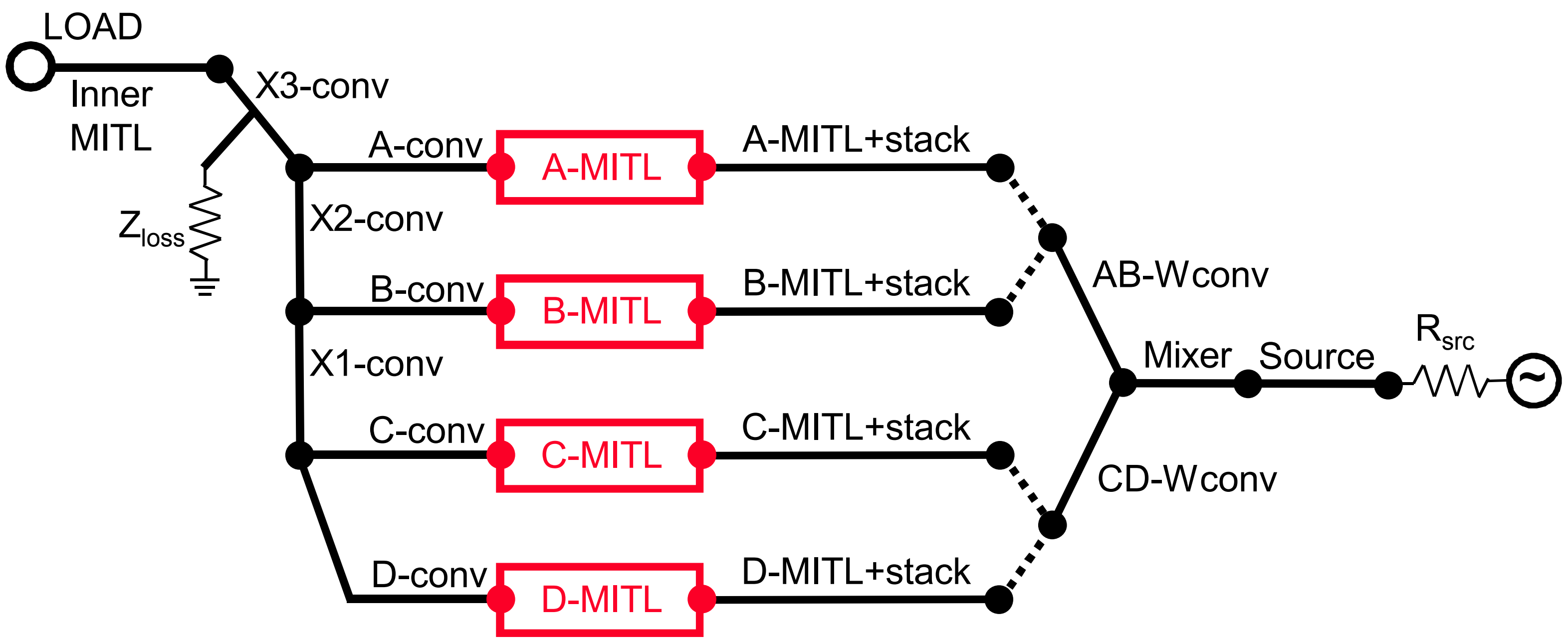
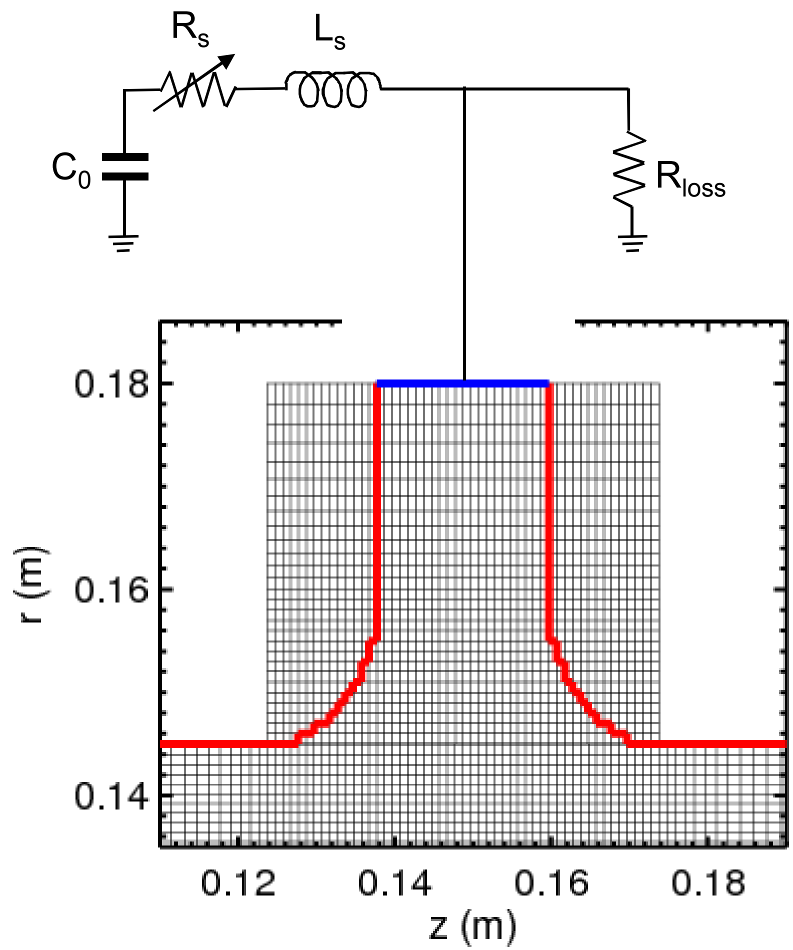
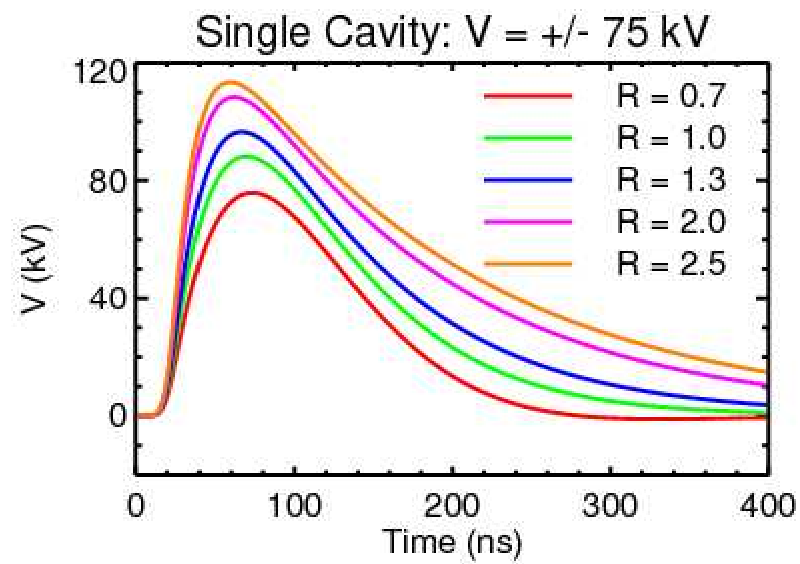
High-resolution simulations of the Z MITLs use four 2D PIC regions coupled with TL's



- 2-D PIC region for each MITL, spherical coords., 0.1 < r < 0.6 m, shown in red
- 1-D transmission lines in black
  - Outer lines extend out to r ~ 3 m
  - Inner convolute line parameters obtained from 3-D simulations
  - Optional, time-varying convolute Z_{loss} element
  - Either a Z-pinch or ICE load

Ursa Minor simulations use an external RLC circuit with core loss for each cavity





- C_0 = 100 nF, L_s = 25 nH, R_{loss} = 4 Ω
- R_s: $10^5 \rightarrow 0.2\ \Omega$ with 2 ns exponential decay
- Single cavity into resistive load R agrees to ~5% with more detailed circuit model

Other features in Quicksilver

- Friedman's explicit EM field solver with adjustable damping, $0 \le \theta \le 1$
  - Also use this scheme to add damping to the explicit particle pusher
- Exact, second-order **J** and ρ accumulation, handling boundaries
  - At conductors, morph 2nd $\rightarrow$ 1st order within half a cell of boundary
- Energy-conserving particle pusher: interpolate **E** directly from the Yee mesh using exactly the same weighting that **J** is laid down on the mesh
  - Enables stability at $\Delta x/\lambda_D >> 1$, $\omega_p \Delta t \sim 1$ (little numerical heating)
  - Accuracy? *Caveat emptor!*
- Floating-point precision issues:
  - Particle push in local coord. system relative to lower corner of cell
  - Build executables with 4- or 8-byte reals
    - ~1.6 slowdown for r8 – memory access

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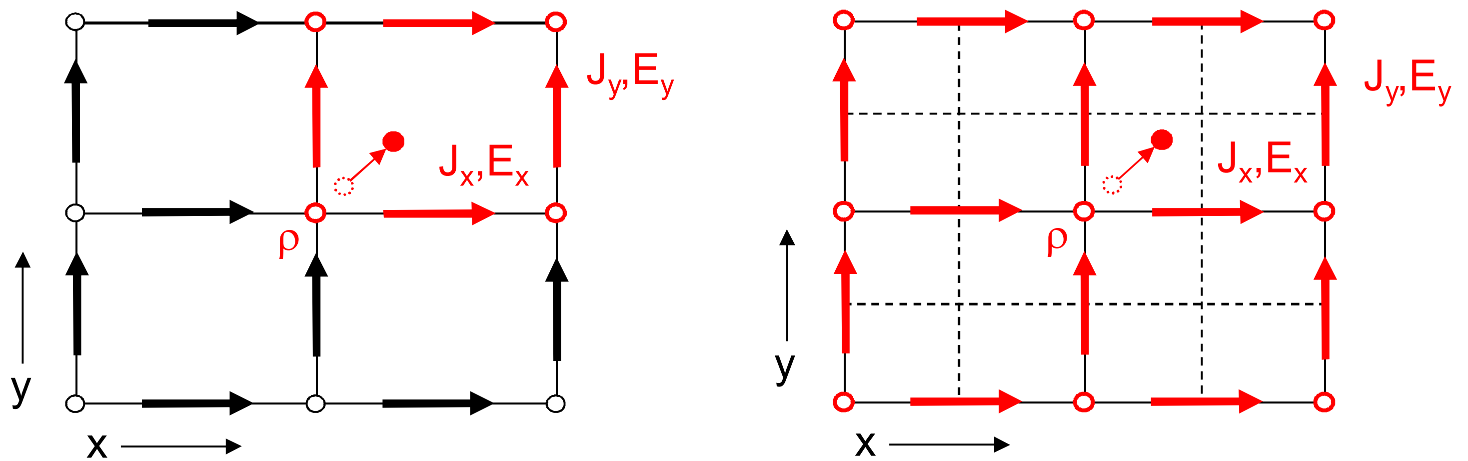
Other features in Quicksilver, contd.

- Sort particles by cell and species:
  - Required for Coulomb collisions and particle merger
  - Improved performance by limiting cache-thrashing
- Particle-particle Coulomb collisions for cold, dense plasmas
- Electron-surface interactions
  - Heating
  - Reflection and secondary emission
- Kinetic gas-chemistry model
  - Gas breakdown plasma modeled with electron-ion pairs
  - Robust particle merger to deal with exponentially-growing particle count

Energy-conserving PIC: Specific scheme for E-field interpolation to the particles

First-order Weighting   Second-order Weighting



- For EM codes: interpolate **E** directly from the Yee mesh to the particles, using exactly the same weighting scheme as **J** from the particles to the grid
- First-order weighting: Interpolation of E_x is nearest-grid-point in x, linear in y
  - Although it appears crude, we have found it very useful
- Second-order weighting: Interpolation of E_x is linear in x, quadratic in y
  - Handle boundaries: T. Pointon, Comput. Phys. Commun. **179** (2008) 535.

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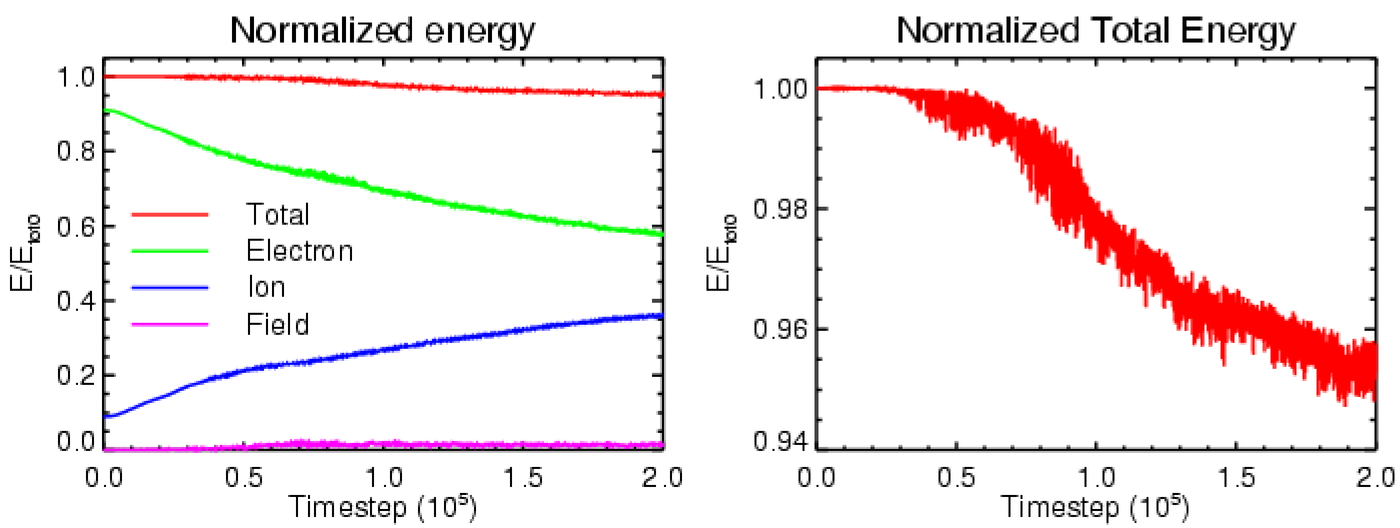
Energy-conserving PIC removes the restriction of having to run at $\Delta x/\lambda_D$ < ~1

- Explicit, energy-conserving PIC runs are stable for $\Delta x/\lambda_D \gg 1$
  – Minimal numerical heating
- Stability does not imply accuracy!
  – 1st-order algorithm cannot handle extremely large E-field gradients
  – Neither algorithm can accurately model a plasma at temperature T in presence of a large external E-field satisfying $qE\Delta x \gg T$
- For well-chosen parameters, neither of these factors is an issue, and we can run at $\Delta x/\lambda_D \gg 1$ with reasonable accuracy, limited only by $\omega_p \Delta t$ < ~1
  – For Δt = 1 ps, $\omega_p \Delta t = 1 \rightarrow n < 3.1\times10^{14}$ cm^{-3} (~1% ionization at 1 Torr)
- However … 'On two occasions I have been asked "Pray Mr. Babbage, if you put into the machine wrong figures, will the right answer come out?" I am not able rightly to apprehend the kind of confusion of ideas that could provoke such a question', Charles Babbage, 1864

Canonical test for high-density plasma: 1-D expansion of plasma slab into vacuum



- Use $\Delta x = 0.5$ mm, $\Delta t = 0.5$ ps; characteristic of Z-convolute runs
- Plasma density near explicit limit: $n = 10^{15}$ cm^{-3}; $T_e = 1$ eV, $T_i = 0.1$ eV
  - $\omega_{pe}\Delta t = 0.89$, $\Delta x/\lambda_{De} = 2130$
- ~5% numerical cooling after 200,000 timesteps (~4% with no damping in the field solver)

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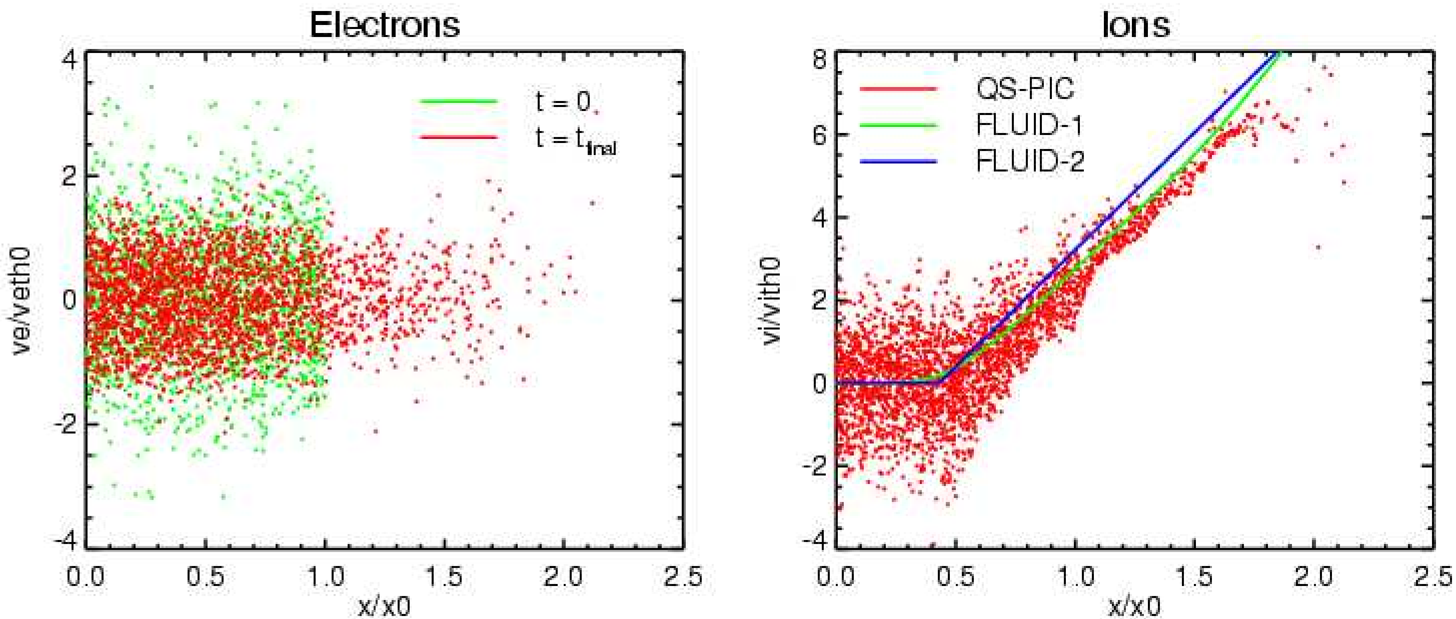
Particle phasespace plots show the plasma expansion is modeled quite well



- Transfer thermal electron energy to directed ion energy at the front
- Results agree well with 1-D multi-fluid (electron/ion) simulations
  - 1^{st} multi-fluid simulation uses same Δx as the QS run
  - 2^{nd} m-fluid simulation uses Δx 2000 times smaller ($\Delta x/\lambda_{De} \sim 1$)

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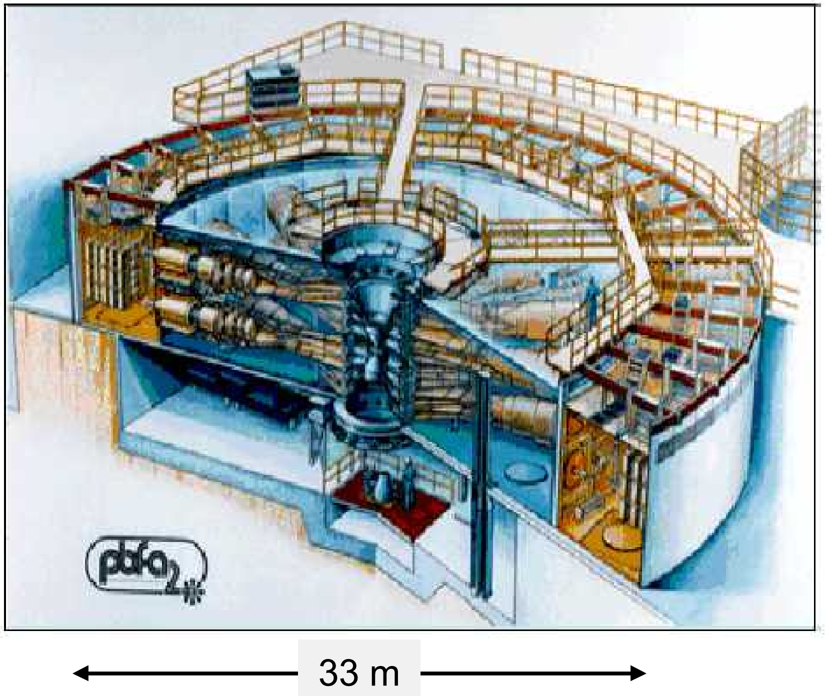
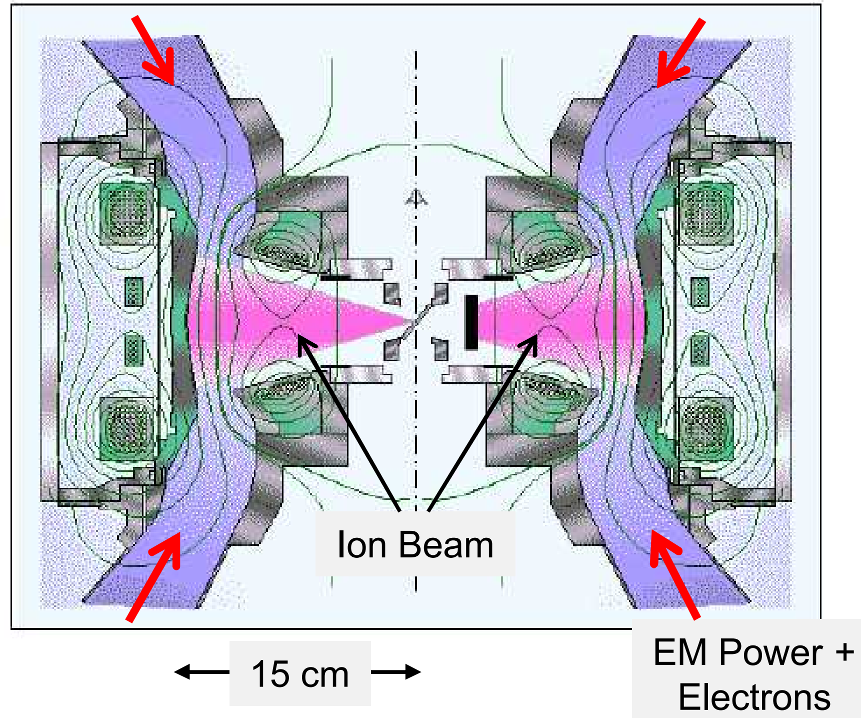
Summary

- Quicksilver is a mature 2D/3D EM-PIC code with a set of features driven by it's application space
  - Pulsed power systems
  - EM response to gas-filled cavities with electron emission from walls
- Quicksilver features
  - Excellent capabilities for handling complex geometry
  - Energy-conserving PIC
    - Stability at $\Delta x/\lambda_D >> 1$, $\omega_p \Delta t \sim 1$ (minimal numerical heating)
- Post-processing with IDL

Backup Slides

The applied-B ion diode on PBFA II produced 10 MV, 1 MA, 40 ns Li^+ ion beams





- 2D PIC simulations: coupling 4 MITLs in series to achieve 10 MV
- 3D PIC simulations: EM instabilities → beam divergence
- 1D DYNAID simulations: anode plasma expansion → gap closure

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Quicksilver and IDL use PFF (portable file format) to handle floating-point data

- PFF was developed by David Seidel in late 1980's for QS
  - Save disk space by encoding floating-point arrays into 16-bit integer arrays using an offset and multiplier
    - Full precision is now available if necessary
  - Pre-defined "dataset types" for data relevant to PIC
- User interface at the dataset level is machine-independent
  - UF1: uniformly spaced 1-D data (time histories)
  - NF3, NV3: Scalars and 3-D vectors on 3-D multi-block domain (field snapshots)
  - VTX: List of vertices on an m-D space with n attributes per vertex (particle snapshots, surface field snapshots)
  - NGD: m-D vectors on a single n-D block
- Public domain: http://sourceforge.net/projects/hermes-util

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Quicksilver uses IDL for post-processing … and for more and more pre-processing

- “PFIDL” layer of IDL routines (Paul Mix)
  - PFF dataset read/write
  - Waveform (1D time history) processing: plot, arithmetic, FFT, *etc.*
  - “Structure” processing: 2D/3D field snapshots, particle snapshots
- My IDL routines for post-processing
  - Time history modification: filtering, etc.
  - Field, lineout, and particle snapshot animation
- My IDL routines for QS pre-processing
  - Generation of simulation geometry
  - Processing rad-transport simulation output for EM simulations: electron reflection, secondary emission and surface heating
  - Processing gas-chemistry cross-section data

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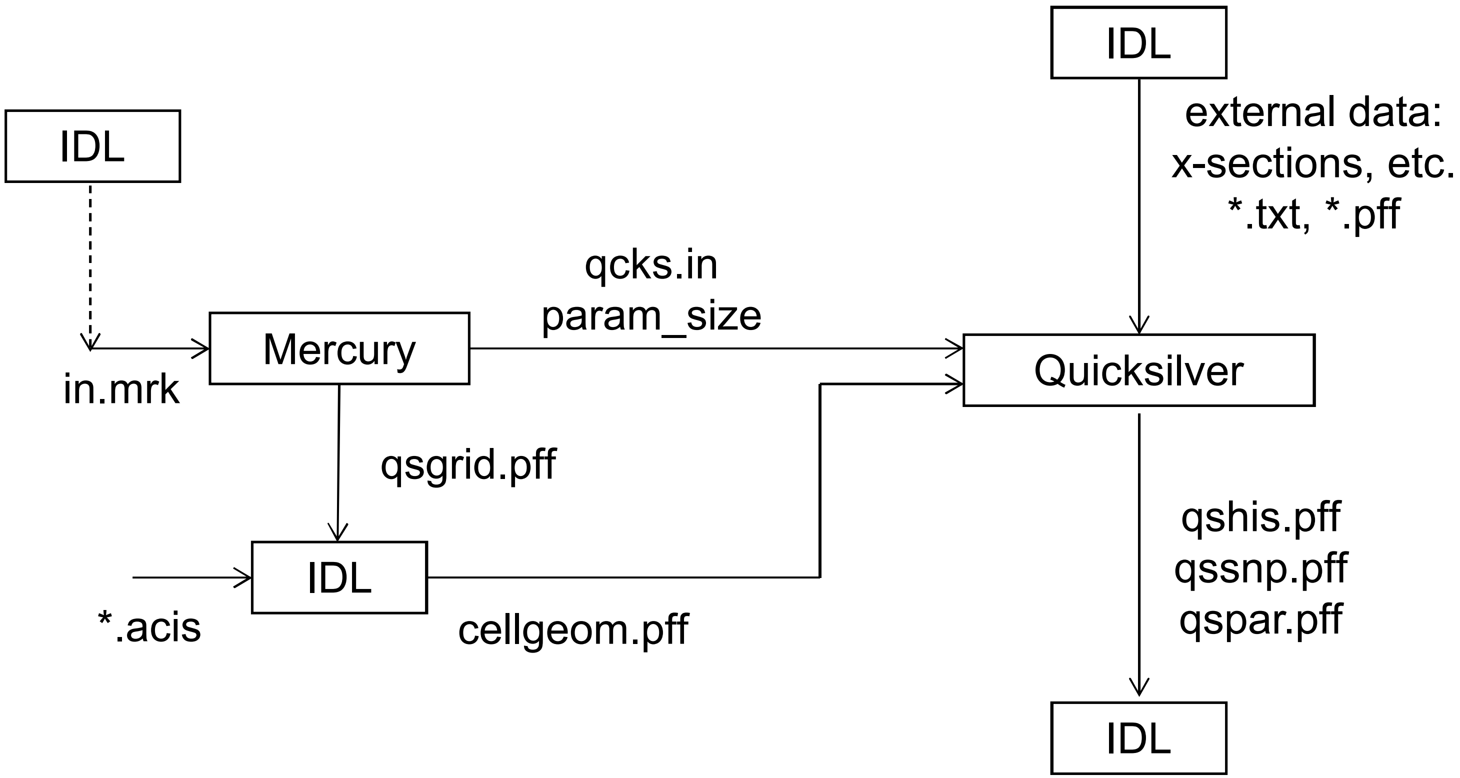
Quicksilver/Mercury/IDL flowchart



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