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Particle-in-Cell Simulations of the Magnetically Insulated Transmission Lines and Post-Hole Convolute of ZR

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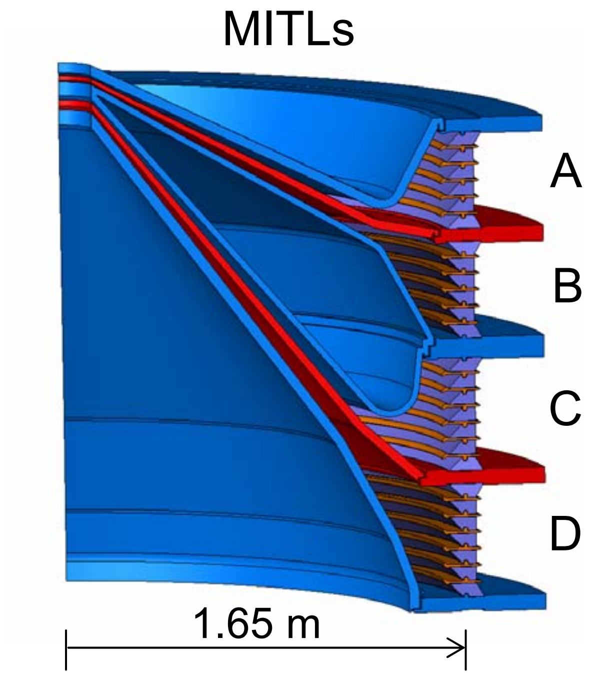
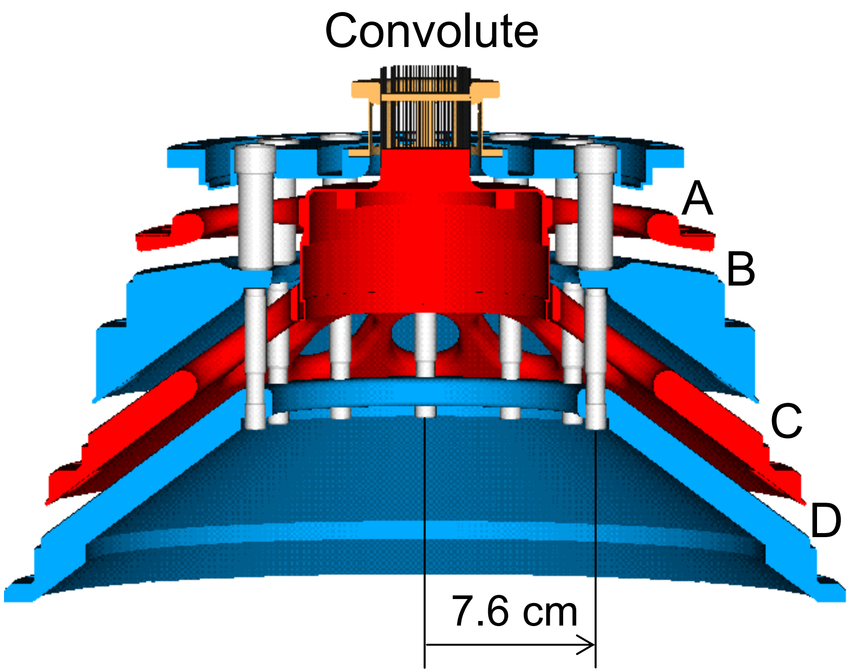
The vacuum section conducts power from the insulator stack to the load

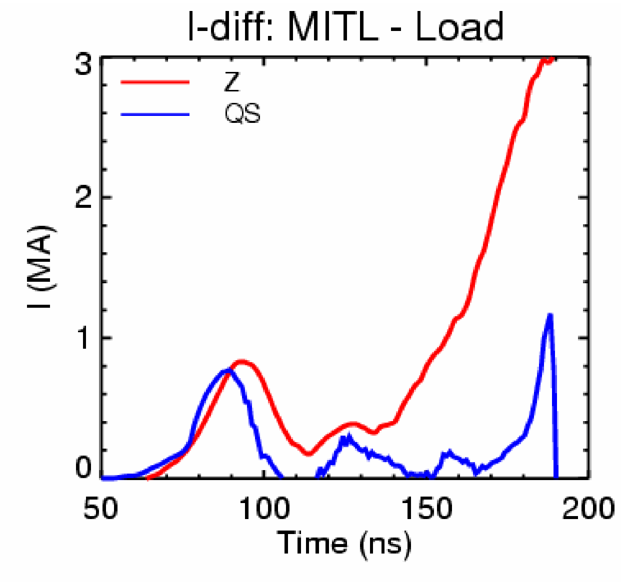




- The four MITLs are coupled in parallel at the post-hole convolute
- The electric field on the MITL cathodes exceeds the threshold for emission of electrons, all the way out to the vacuum flares

Electron flow into the convolute from the MITLs is the seed for late-time current losses

- 3-D PIC simulations of the convolute do not explain the late-time current loss on Z
- Experiments show that the loss is in the convolute — we believe this is due to dense plasmas formed at anode surfaces by electron deposition
- It is very difficult to scale this to ZR



- However, the root cause of the problem is electrons flowing into the convolute from the MITLs – there is no emission in the convolute itself
- Assumption: Losses on ZR will not be excessive, if we modify the MITLs to limit the flow to be some fraction (f ≤ 1) of that on Z today
  - Fraction depends on voltage scaling of surface heating

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The ZR MITL profiles

- Limit the flow into the convolute to be no higher than on Z today, while operating at ~40% higher voltage and ~30% higher current
  - Open up the gap by 20% for r > 20 cm. 1 cm gap for r < 13.6 cm.
- To improve diagnostic access, raise the load by 16 inches
  - Increases the slope and length of the MITLs
- Both changes increase the inductance of the ZR MITLs

Level	Angle (degrees)		L (nH)	
	Z	ZR	Z	ZR
A	8.1	24.9	9.01	11.57
B	9.1	26.0	9.30	12.42
C	35.9	48.9	13.54	19.63
D	36.7	49.7	14.18	21.99

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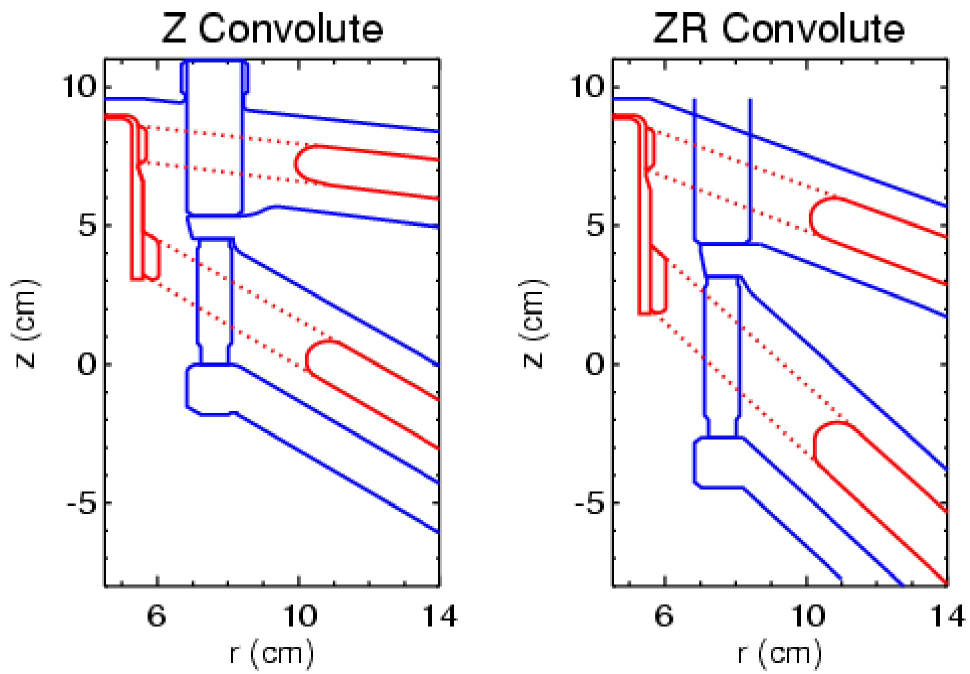
The ZR post-hole convolute closely follows the existing Z design



- Posts at r = 7.62 cm, with same diameters
- Same convolute hole shape
- Vertically stretched to match the steeper MITLs and thicker cathodes

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We can study the MITLs with 2-D simulations

- Full 3-D convolute simulations show that:
  - No electrons flowing back into the MITLs from the convolute (except after stagnation)
  - The electron flow in the MITLs is essentially azimuthally symmetric, even slightly upstream of the convolute
- 2-D geometry allows high-resolution MITL simulations, extending out to very large radius (to the stack if necessary)
  - 1-D transmission lines attached at inner and outer radius
  - Inner boundary is ~2.5 cm inside the MITL/convolute boundary
  - Electron flow through the MITL/convolute boundary closely approximates actual flow into the convolute in the full 3-D system

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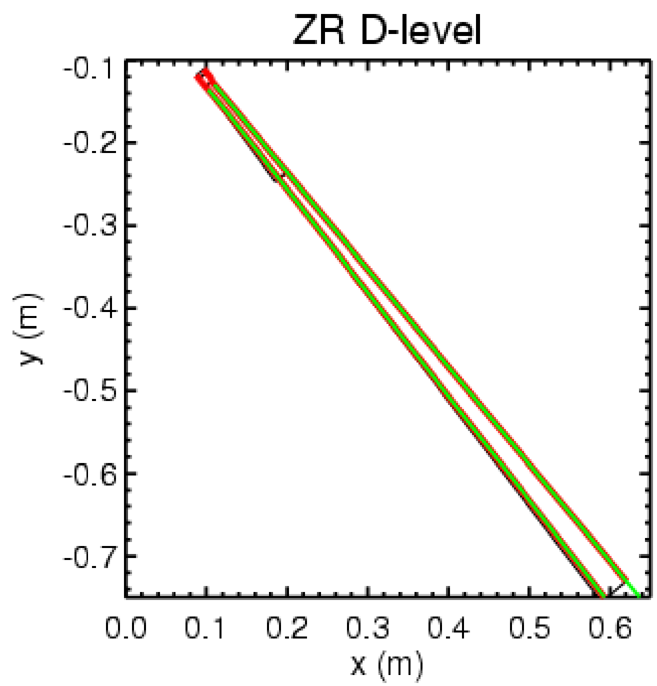
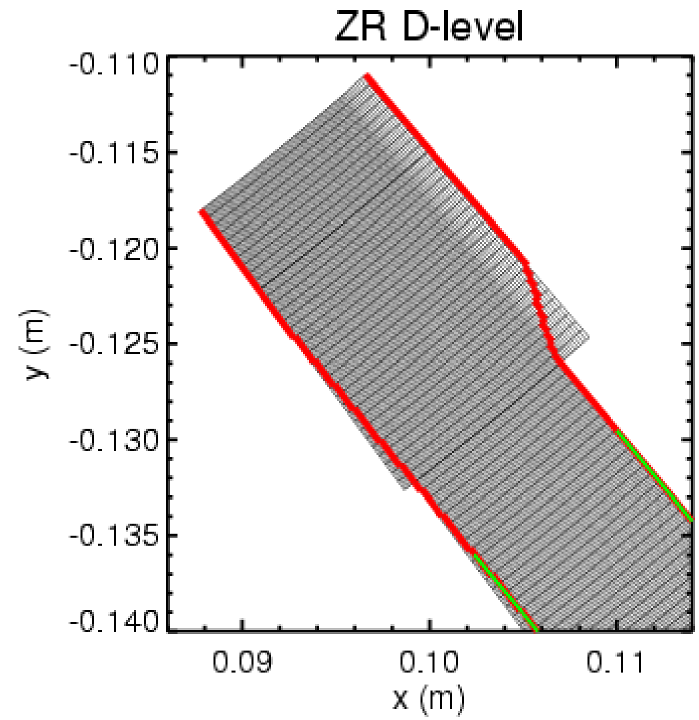
The 2-D MITL simulations are done in spherical coordinates





- Model MITL cathode cone exactly, <u>without any stair-stepping</u>
- Anode <u>is</u> stair-stepped, but this is not critical

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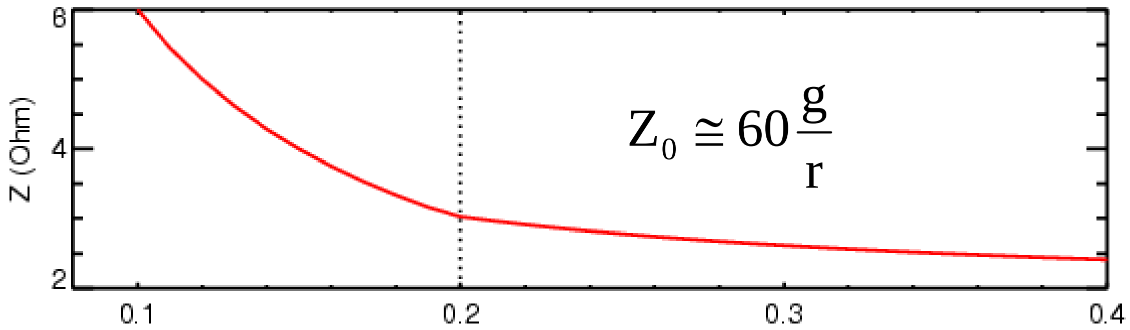
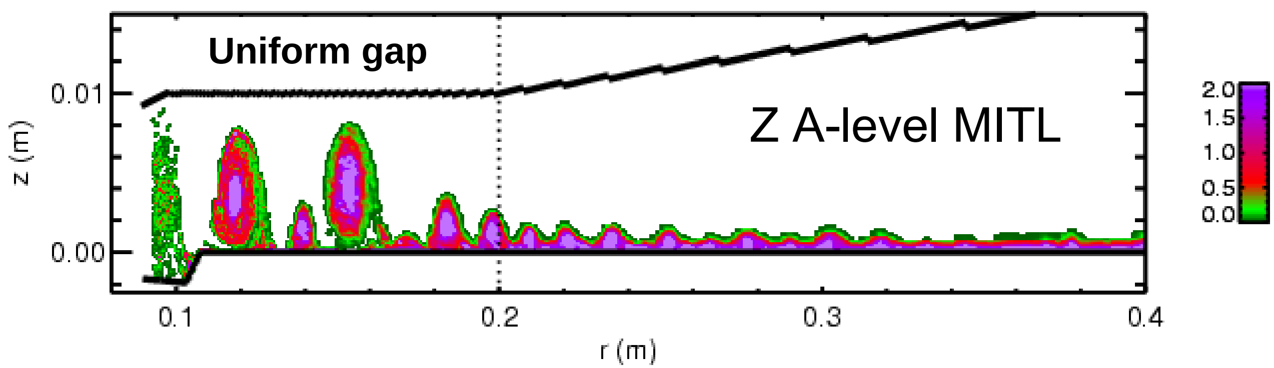
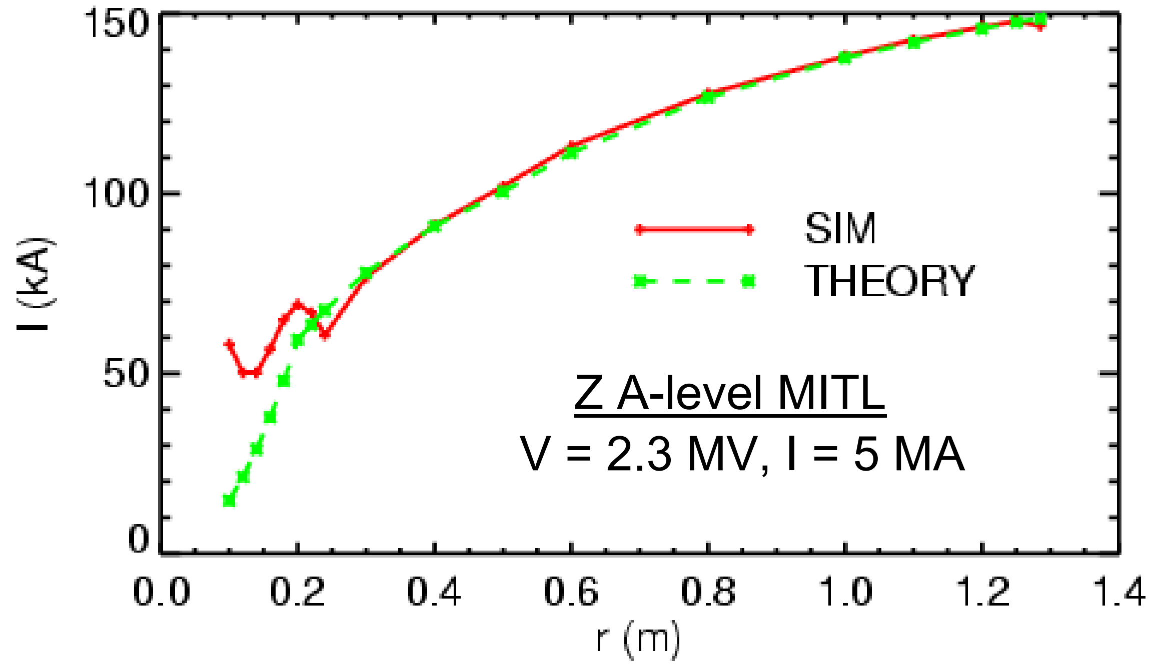
At high current, the strongly insulated electron flow is unstable





- Amplitude is related to $|dZ_0/dr|$:
  - Negligible at large radius, r > ~0.35 m: thin, laminar electron sheath
  - Large-scale vortices in constant d = 1 cm gap section

The electron flow agrees very well with 1-D theory, except at small radius



- For laminar sheath with $I_e << I$, $I_e \approx \frac{V^2}{2I_c Z_0^2} \propto \left(\frac{V^2}{I}\right)\frac{r^2}{d^2}$
- Vortices enhance the flow <u>into the convolute by a factor of ~3 – 4</u>

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Extending out to large radius and resolving the thin electron sheath is challenging

- Sheath thickness (g << d): $g \cong \frac{mE}{eB^2} \propto \left(\frac{V}{I^2}\right)\frac{r^2}{d}$
- Z A-level at peak current, V ~ 2.3 MV, I ~ 5 MA

r (cm)	d (cm)	g (mm)
20	1.0	0.052
130	4.14	0.533

- Because of the electron vortices, do not need to resolve the very thin sheath at the inner radius to get the correct flow <u>into the convolute</u>
- Extend outer radius to well beyond where the vortices form Baseline setup:
  - Outer cylindrical radius ρ_{max} ~ 60 cm ($r_{max} = \rho_{max}/\cos\theta_0$)
  - Cell size at the cathode $r\Delta\theta$ ~ 0.2 mm at ρ = 20 cm
- A few benchmark runs done with smaller $\Delta\theta$ and larger ρ_{max}
  - Baseline setup is adequate

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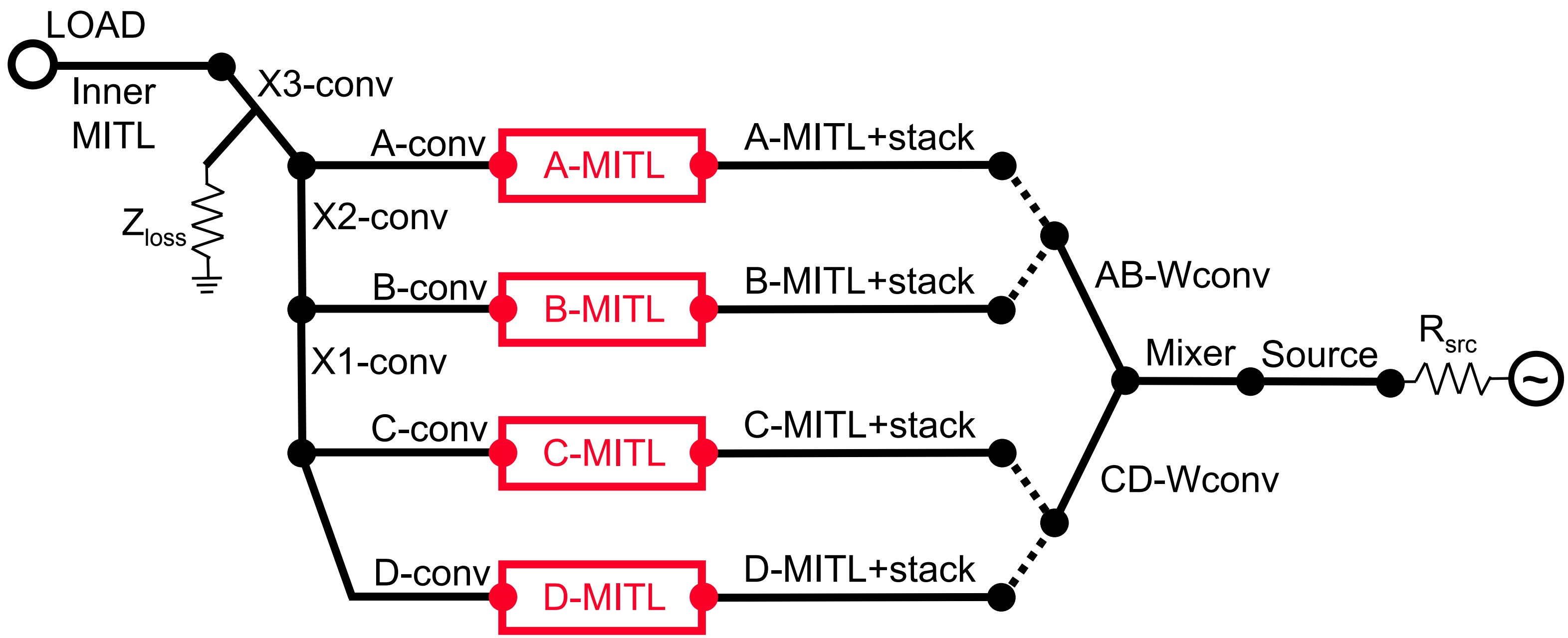
The full ZR MITL simulations use accurate external circuit and load models



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

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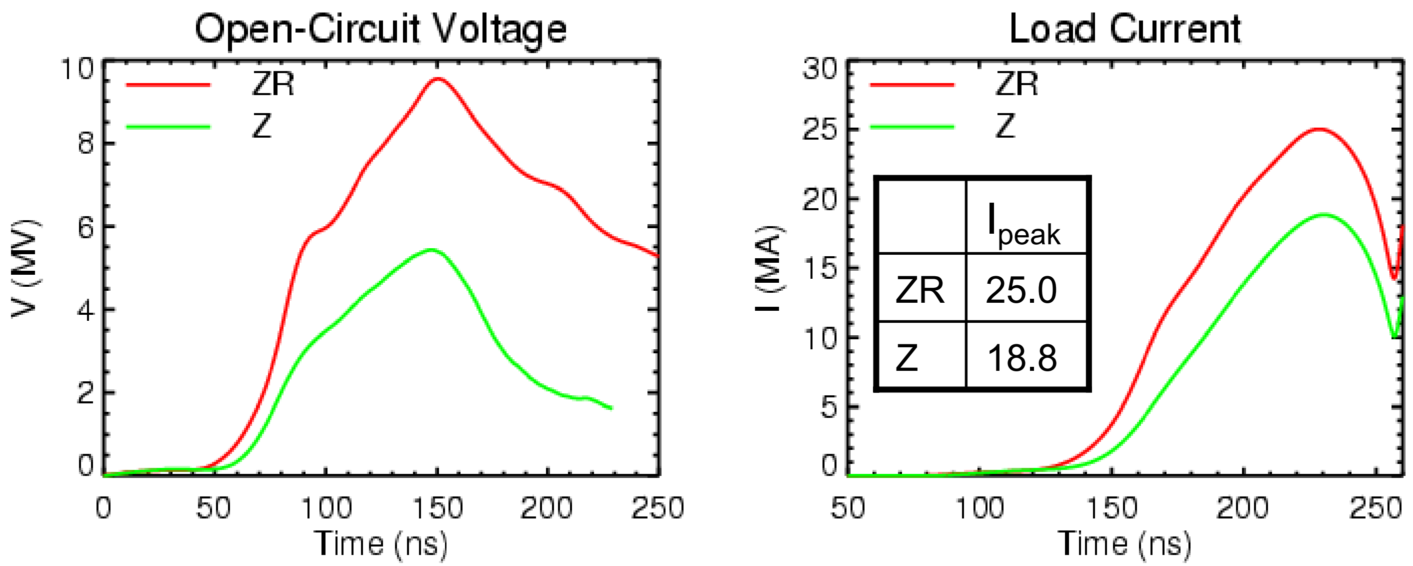
We use Z20 shot data for the open-circuit waveform used to drive the ZR simulations



- Use Z540 V_{oc} and Z-pinch load parameters for Z simulations
- For ZR, use V_{oc} from Z20 shot 1237, and scale up the load mass
- Comparison of load current with fixed $Z_{loss} = 0.25\ \Omega$
  - Z data time shifted to line up implosion time

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We use time-varying Z_{loss} to model additional convolute current losses (1)

- Vacuum electron loss at a simple magnetic null is well described by:

$$V = Z_{loss}(I_{au}^2 - I_{ad}^2)^{1/2}$$

  where I_{au} and I_{ad} are the upstream and downstream anode currents, V is the voltage, and Z_{loss} is a constant, depending only on geometry*
- This functional form of current loss is used in circuit codes
  - Simulations of Z typically use a fixed $Z_{loss} = 0.25\ \Omega$
- The 2-D MITL simulations have vacuum electron loss, which already matches the early loss on Z quite well
- Use additional time-dependent Z_{loss} to fit the late-time current loss:
  - Initially very large, so it has no effect
  - Smoothly ramps down as the MITLs become strongly insulated

* C. W. Mendel, *et al*., Phys. Plasmas **13**, 043105 (2006)

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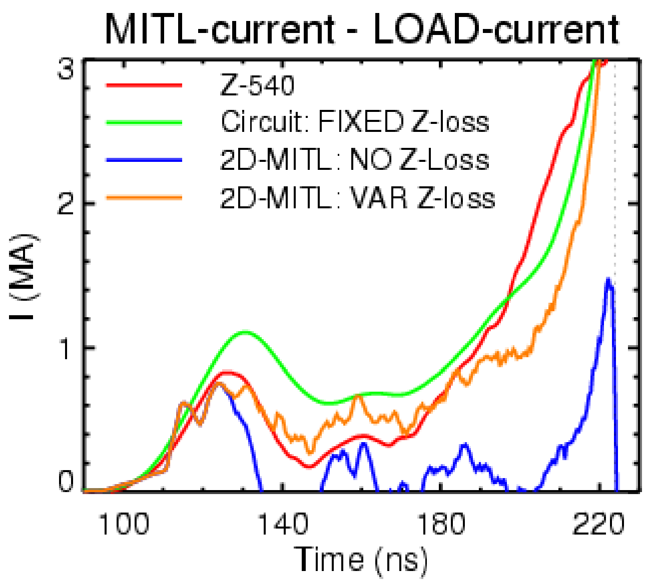
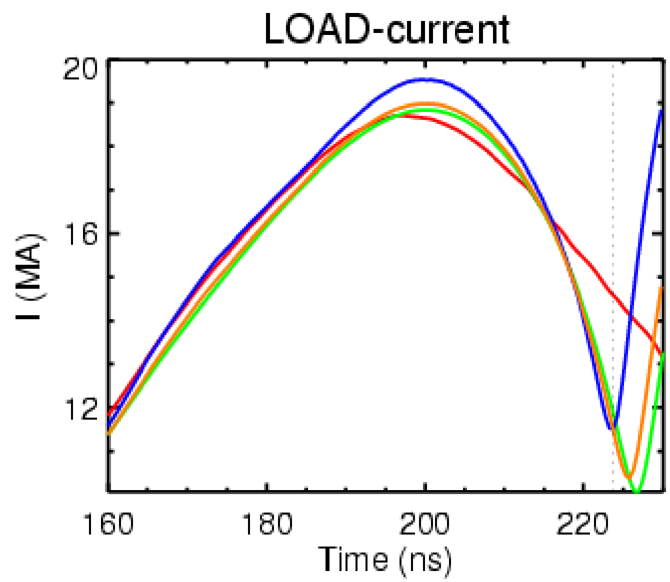
We use time-varying Z_{loss} to model additional convolute current losses (2)





- Additional Z-loss turned on at t ~ 125 ns, when I_{load} ~ 3 MA
  - Better fit to peak load current
  - Reduces convolute voltage, and electron flow into the convolute
- For ZR, we turn on Z_{loss} at the same load current

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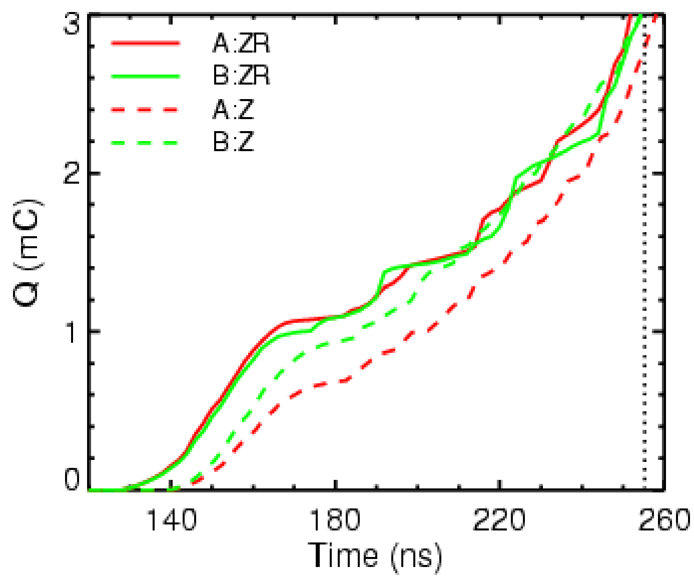
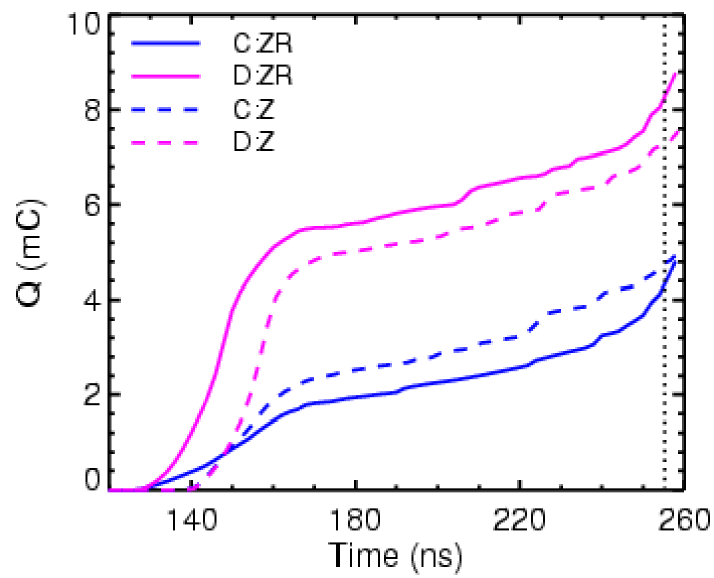
The net electron charge flowing into the convolute is slightly higher on ZR





- Z-data time-shifted to align implosion time (t_{imp} = 253.2 ns)
- Net charge flowing into the convolute is ~4% higher on ZR
  - ~12% higher on D-level
  - Lower on C-level than Z today

The 3-D convolute simulations

- Must be done in cylindrical coordinates
  - Simulate $1/(2N_{post})$ fraction of full azimuth: $N_{post} = 12$, $\phi_{max} = \pi/12$
- Slanted surface model* used wherever possible in the convolute and MITLs to avoid stair-steps, providing "flat" surfaces for:
  - Electron emission and flow dynamics at the cathode
  - Electron energy deposition at the anode
- Slanted surface model does not work well when under-resolving strongly insulated electron flow -- must establish flow upstream:
  - Bend MITLs to radial lines just upstream of the convolute
  - Upstream MITL gaps are adjusted to get the same flow into the convolute as the 2-D spherical-coordinate MITL simulations
- For the Z convolute, A/B MITLs are purely radial

* T. D. Pointon, J. Comput. Phys., **96**, 143 (2006)

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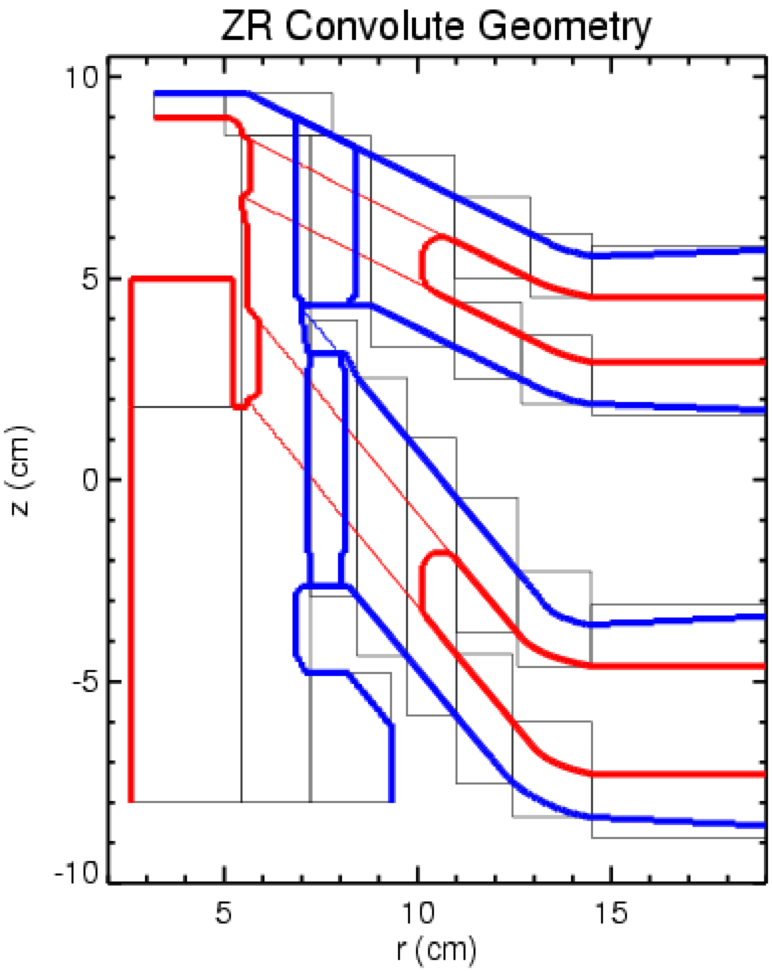
We use IDL to automatically build the convolute geometry from a DXF file

- Principal user input:
  - Geometry of the outer MITLs
  - Δr and Δz at key locations
- IDL procedures automatically build
  - The QS block-covering of the geometry
  - Non-uniform grids matching user $\Delta r, \Delta z$ values
  - The conductor geometry
  - A set of non-overlapping regions for each level (diagnostics, emission tagging)
- Independent zoning of overlapping regions in non-overlapping blocks is essential for this geometry



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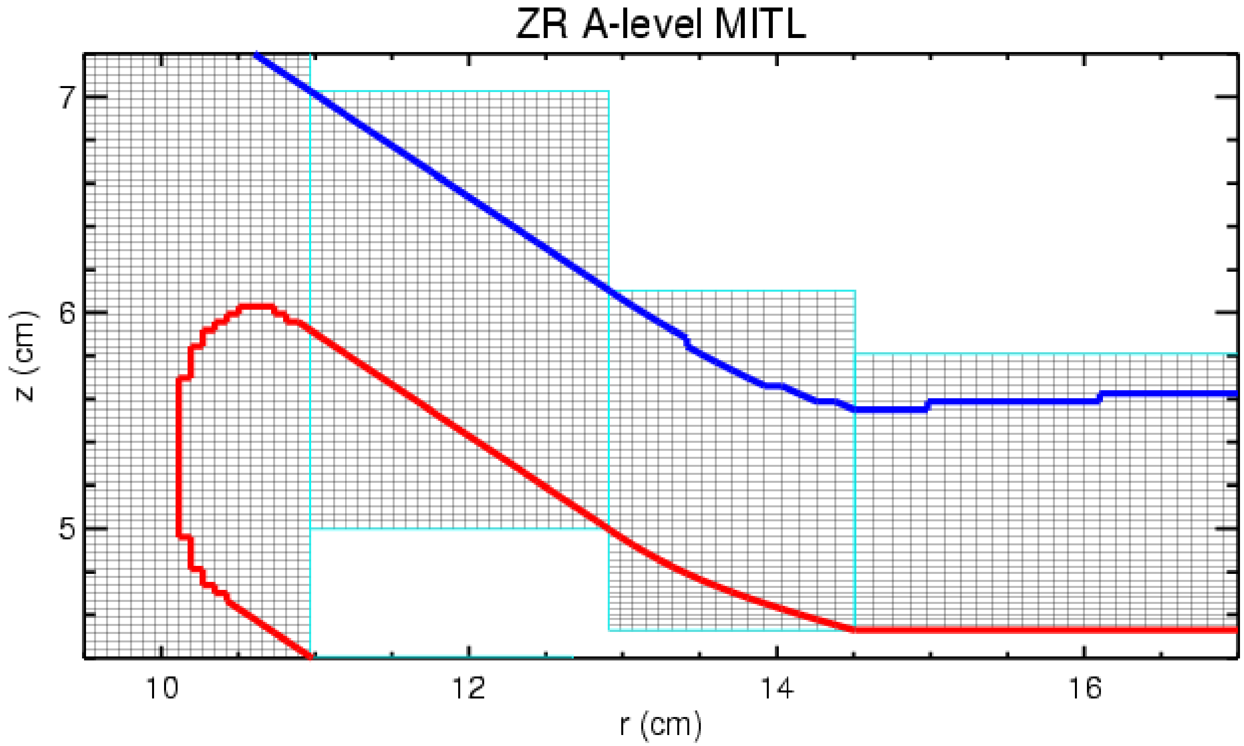
We bend the MITLs to horizontal just upstream of the convolute



- Smooth bend on the cathode by decreasing Δz and increasing Δr
- Have a <u>single</u> corner on the cathode: conformal → very shallow slant
- Smaller Δz at horizontal cathode also improves electron flow

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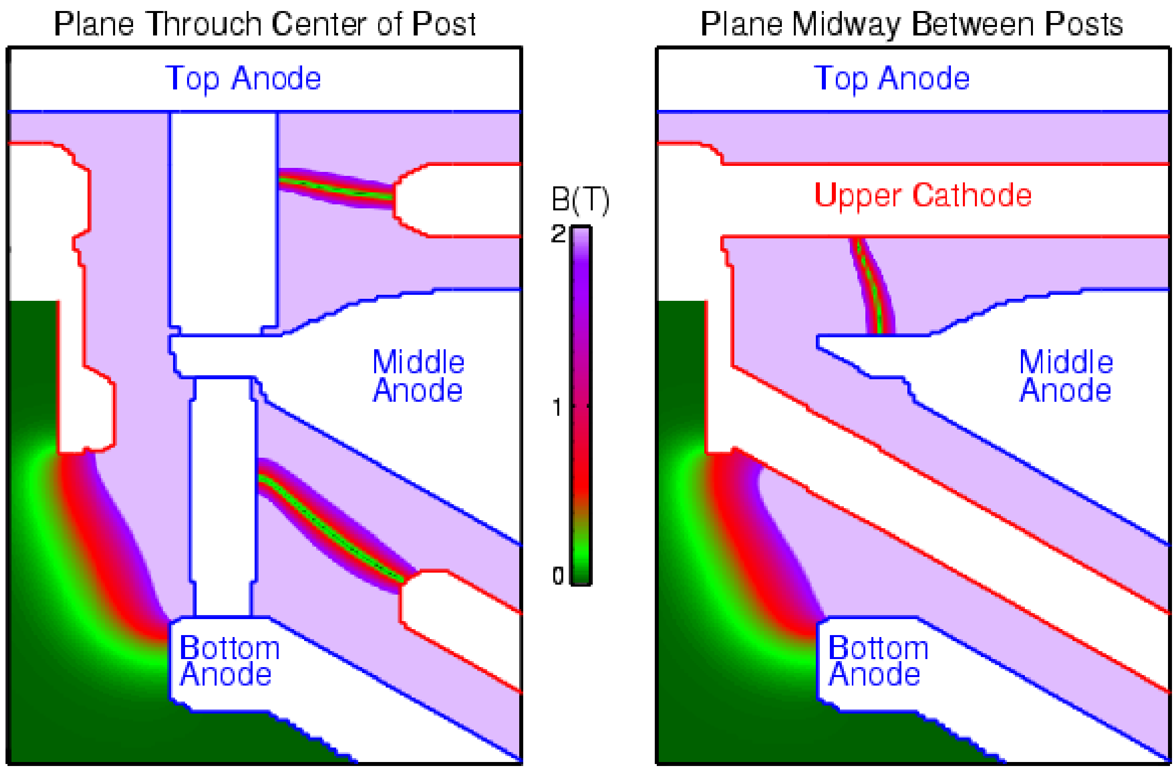
There are numerous magnetic nulls in the convolute



- Nulls in the Z convolute: ZR has similar nulls
- Contours of |B| over the range 0 – 2 T highlight the nulls (B_{max} ~ 50 T)

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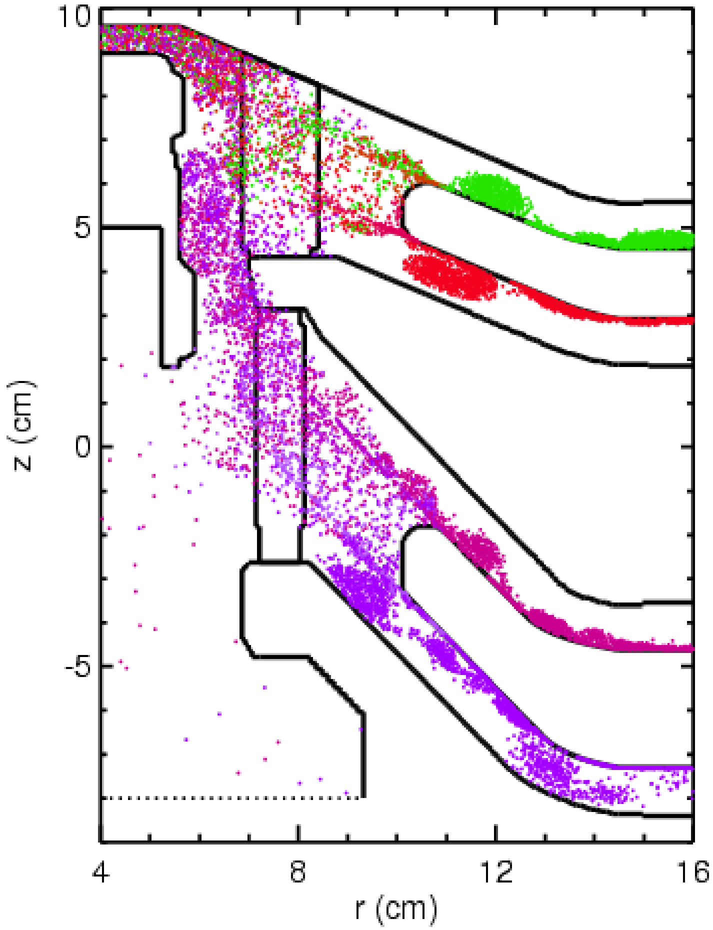
Particle setup for the convolute simulations

- Dynamic electron sub-cycling to handle high magnetic fields:* multiple particle pushes per field timestep where $\omega_c \Delta t > \pi/3$
- Electron energy deposition at the anode and surface heating -- including slanted surfaces
- Electrons tagged with an index of their creation location
  – Particle plots illustrate where electrons come from
  – Particle flux into anode surfaces can be filtered by creation index



* T. D. Pointon, *et al.*, Phys. Plasmas, **8**, 4534 (2001).

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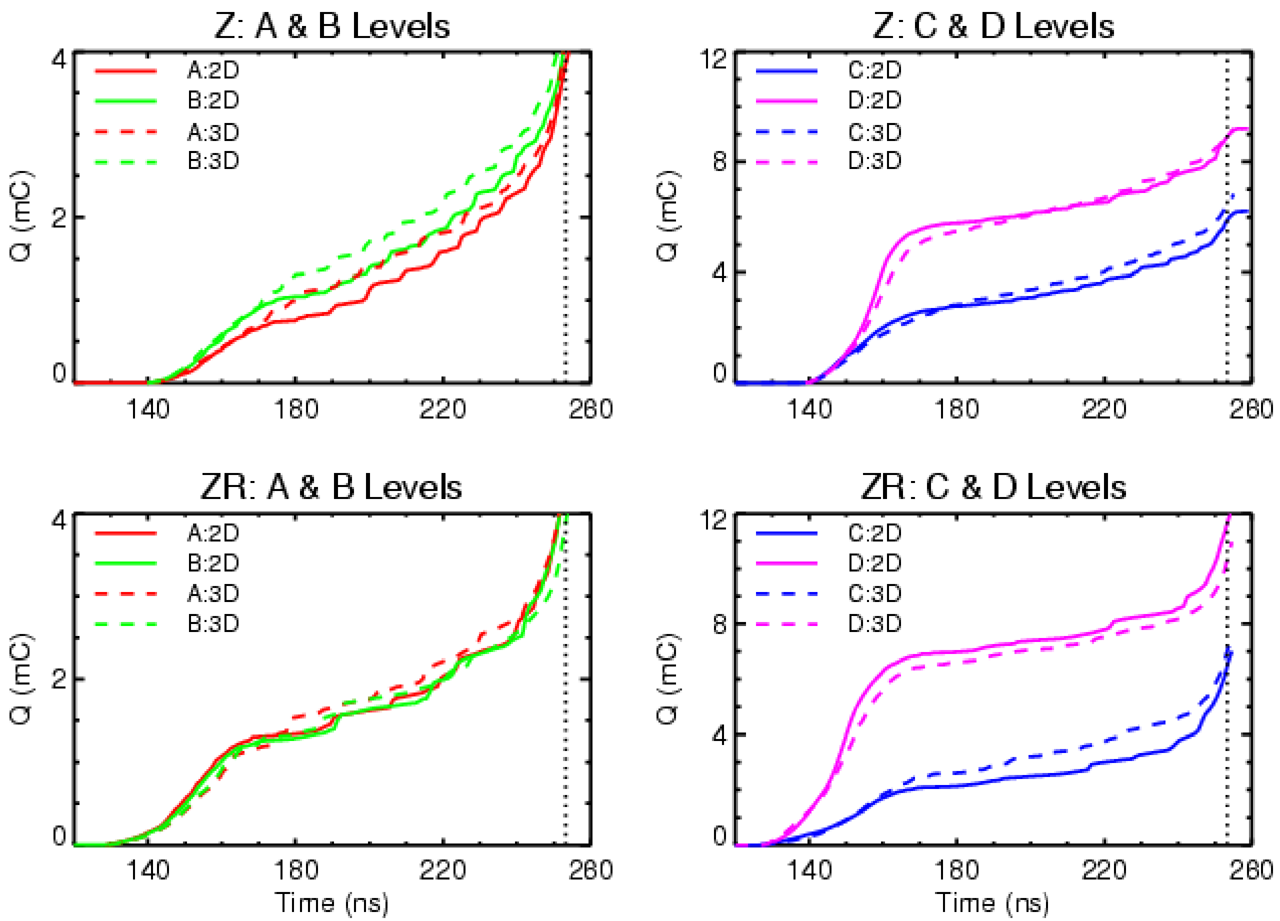
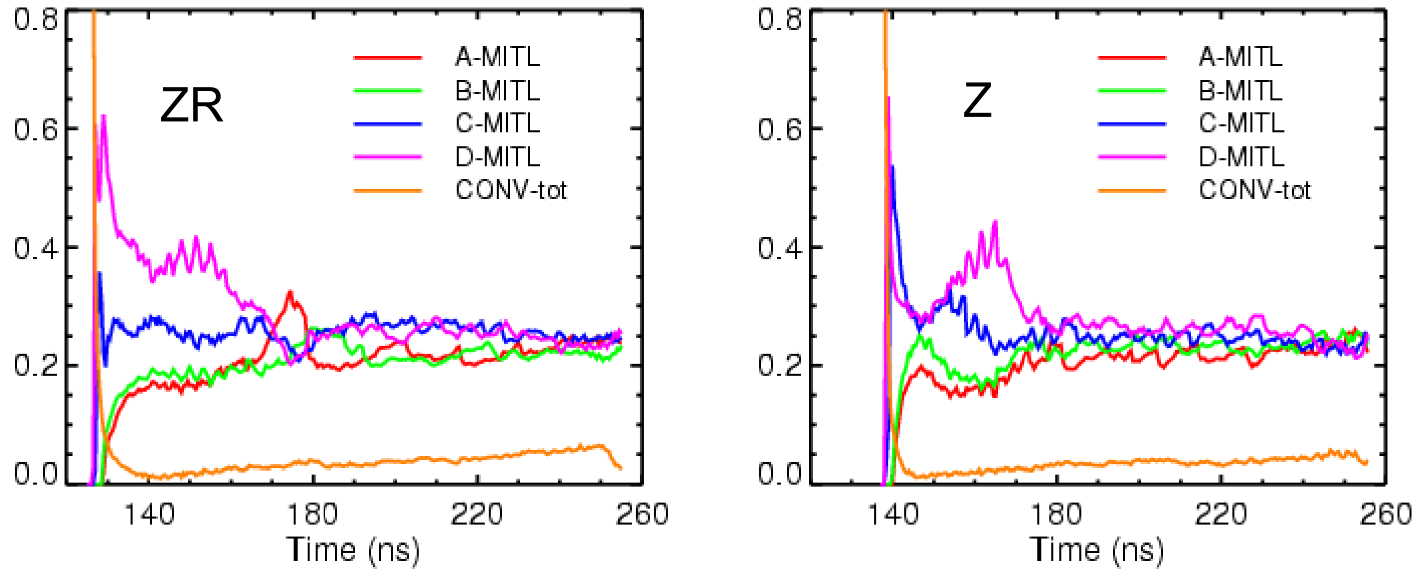
Electron flow into the convolute agrees well with the 2-D MITL simulations



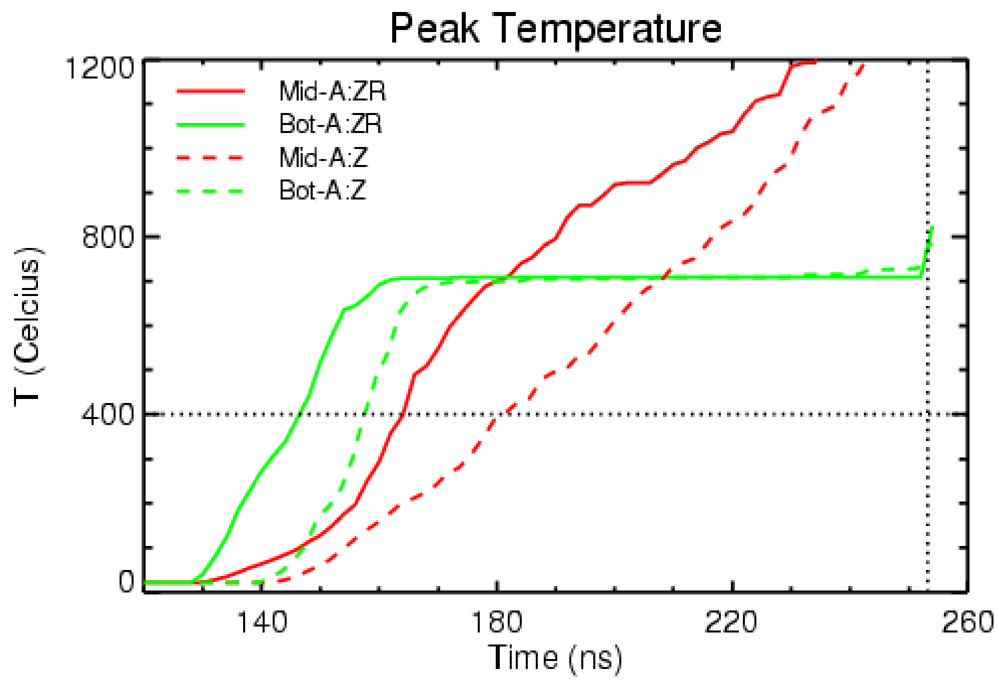
- 2-D simulations run with Z_{loss} model disabled

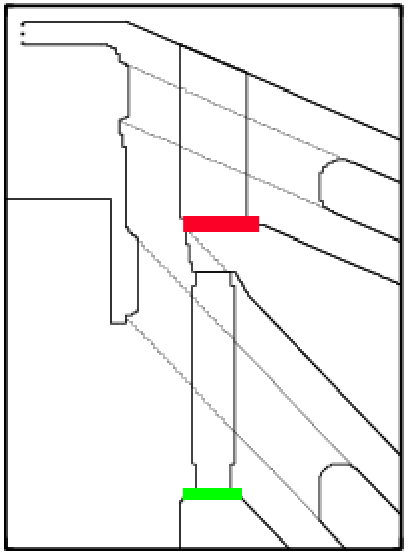
Particle statistics confirm that there is very little emission in the convolute itself



- Figures show the fraction of charge in the system by emission location
- The convolute is the first region to start emitting, but once the MITLs turn on, fraction of charge emitted in the convolute is < 5%
- Anode deposition heating is due almost entirely to MITL electrons

The most rapid electron deposition heating occurs on the bottom and middle anodes





- Bottom anode region is not a magnetic null, just a region of weaker magnetic field: heating cuts off when the D-level MITL insulates
- The middle anode magnetic null region is of greater concern

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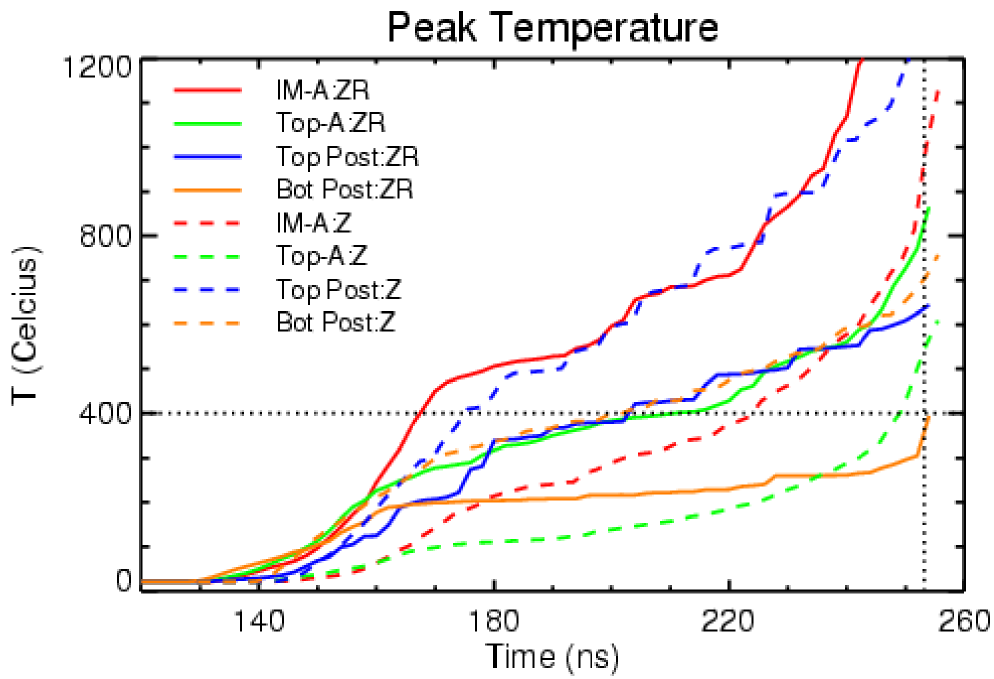
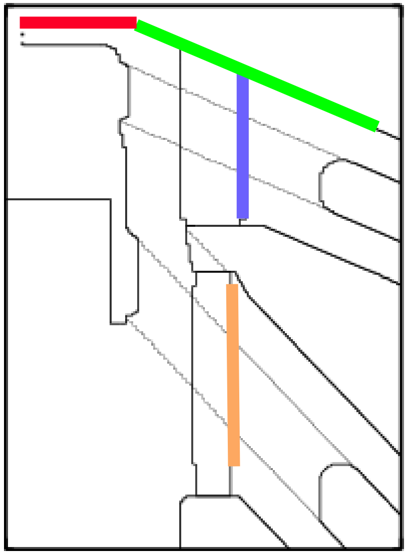
Elsewhere, the deposition heating is higher on ZR in some regions, lower at others





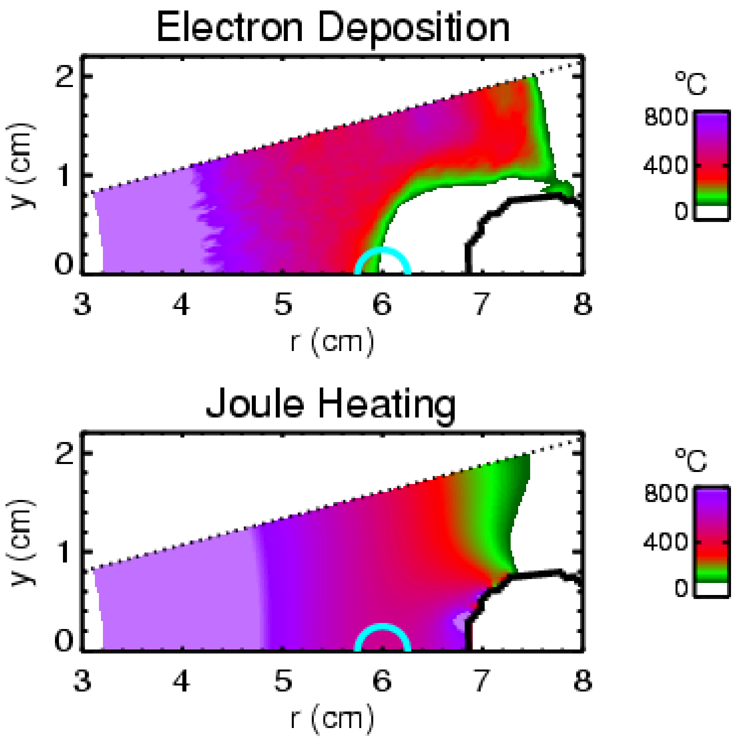
- Heating of the inner MITL is much more intense on ZR
  - This could be an issue, since the A-K gap is only 6 mm
- Heating of the posts is substantially lower on ZR

The conduction current significantly heats the top anode and inner MITL

- Simple model for linearly ramped field: $B(t) = B_0(t/t_0)$:*

$$\Delta T(t) = \frac{2}{\pi \mu_0 c_v}[B(t)]^2$$

- For stainless steel: $\Delta T \sim 0.12B^2$
- Data for Z: Joule heating is dominant for r < ~7 cm
- On ZR this radius increases
- Magnetic field is very high where Joule heating is strong



* H. Knoepfel, “Pulsed High Magnetic Fields”, London UK: North Holland Publishing Co., 1970, p. 81.

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Summary

- High-resolution 2-D MITL simulations provide reliable estimates of the electron flow current into the convolute from the MITLs
  – Net charge is ~4% higher on ZR than Z
  – D-level flow is ~12% higher
- We now have 3-D convolute simulations with electron flow into the convolute in good agreement with the 2-D MITL simulations
- The convolute simulations allow us to compare electron deposition heating of the anode surfaces in the convolute
  – Middle anode ring is the magnetic null region that heats the fastest
  – Significantly greater heating of the inner MITL and top anode on ZR
  – Heating of the posts is lower on ZR

Future plans

- We are still analyzing the wealth of data from the 3-D simulations
  - With the creation location index tag, we can compute the contribution of electrons from each MITL to the heating at any region in the convolute
- Currently, computation of Joule heating is a post-processing step. We will build this into the code so that we have the total temperature rise at each surface cell during the run
- Modify the code to create dense surface plasmas
  - We already have an energy-conserving particle pusher that allows us to go to much higher plasma density
  - We are in the process of adding a plasma emission model driven by the surface temperature exceeding a threshold value