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An Optimization Study of Stripline Loads for Isentropic Compression Experiments

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Abstract

The Z accelerator at Sandia is a unique platform to study matter under extreme conditions [1]. In its shaped pulse mode, it can deliver up to 20 mega-amperes of current to an inductive load over ~600 nanoseconds. The high current and corresponding multi-megagauss magnetic field enable quasi-isentropic compression experiments to stresses of several megabars. A recent innovation in this area has been the use of a stripline, rather than coaxial, load configuration. This configuration allows higher magnetic fields at sample surfaces than a coaxial configuration for the same driver current. Also, the magnetic fields on the anode and cathode surfaces are inherently balanced. However, there are new issues that arise with the introduction of such loads. The coaxial configuration is a closed system in the sense that all the magnetic flux is contained between the electrodes. In contrast, the flux in the stripline configuration is not contained between the electrodes, but in fact loops around the outside of each electrode. This, combined with constraints associated with the stripline's termination and connection to the driver, necessarily introduces an axial variation (in the direction of the current flow) in the magnetic field of the stripline. In addition, the transverse cross-section of the stripline has a significant effect upon the amplitude of the magnetic field between the stripline's electrodes for a fixed drive current, as well as the transverse uniformity of the magnetic field within the stripline. In this paper, we will describe the electromagnetic modeling of various stripline configurations, as well as our efforts to optimize the stripline's geometric configuration to maximize both the magnetic field strength available for compression (for a fixed current) and the uniformity of that field. This will include a discussion of the effects of constraints dictated by other aspects of the experiment, and the tradeoffs that must be considered in the optimization process.

1. Marcus D. Knudson, Use of the Z Accelerator for Isentropic and Shock Compression Studies, in Shockwave Science and Technology Reference Library, Vol. 2, Y. Horie, Ed., Ch. 1, Springer Berlin Heidelberg , 2007.

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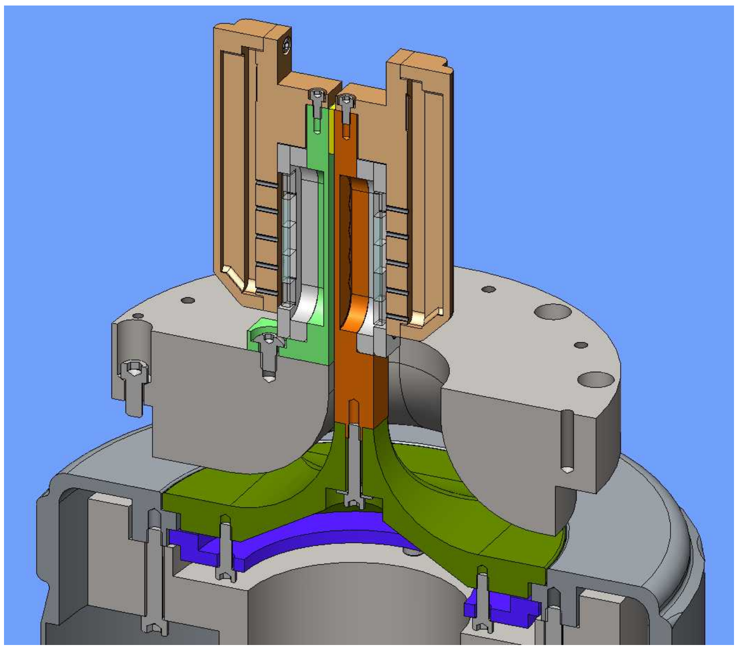
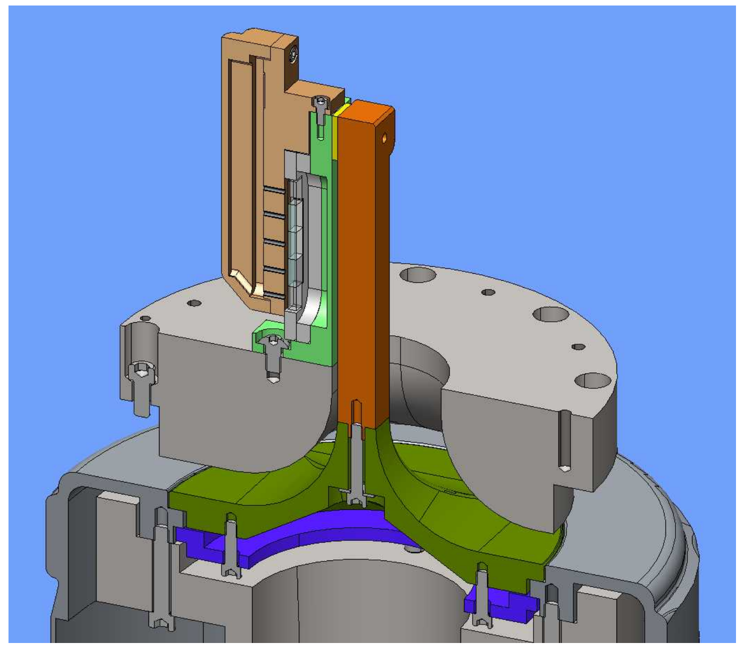
Stripline ICE loads on Z

- Stripline load configurations have significant advantages over coaxial configurations:
  - Magnetic pressure equal on opposite electrode surfaces
  - Higher pressure for the same drive current
  - Significantly reduced curvature of driven flyer plates
- But they are more complex
  - Open system
  - Termination and driver connection introduce increased axial variation in current distribution
  - Transverse cross-section can strongly affect amplitude and distribution of magnetic field
  - Increased transverse variation of magnetic field due to edge effects



Double-sided Sample Array



Single-sided Sample Array

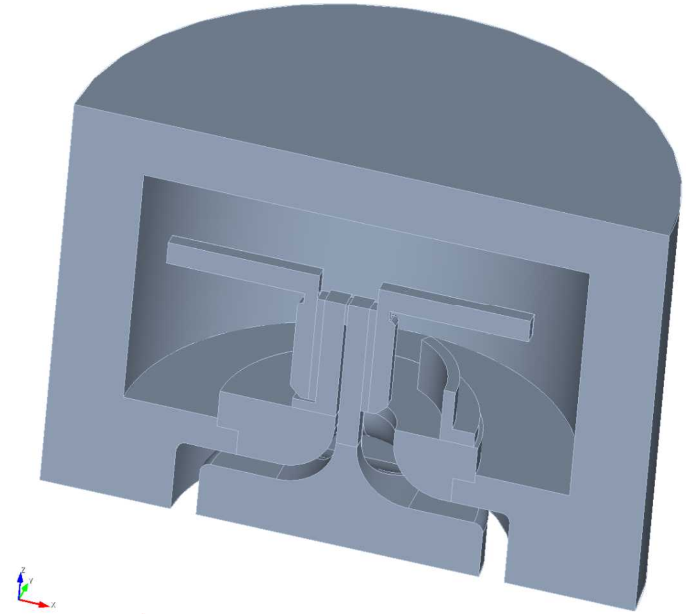
2D Analysis of Stripline Design Constraints

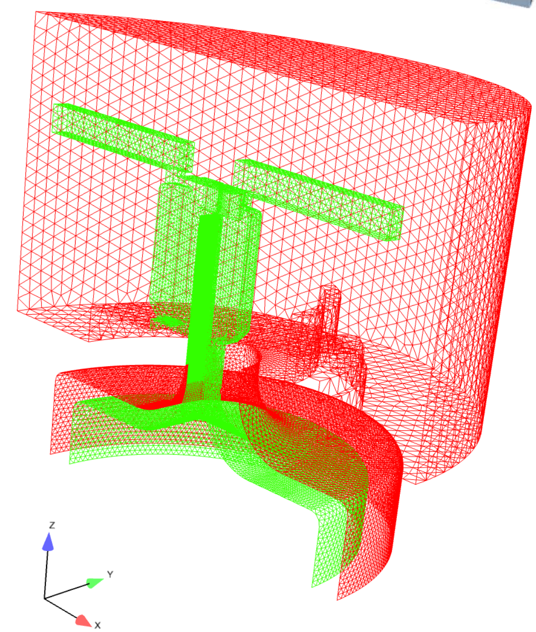
- Use Green's theorem and 2D Green's function to obtain integral equation for ρ_s on electrode surfaces
  - $\Phi(\vec{x}) = \int_S \left[\frac{\rho_s(\vec{x}')}{\varepsilon_0} g(\vec{x},\vec{x}') + \Phi(\vec{x}') \frac{\partial g(\vec{x},\vec{x}')}{\partial n'} \right] dS' \; on \; S, \; g(\vec{x},\vec{x}') = \frac{\ln}{}$
  - Discrete approximation for ρ_s reduces integral equation to a matrix equation
  - Use fixed potential difference (e.g., $\Delta\Phi$ = 1 volt)
  - $Q_a + Q_c = 0$ constrains potentials of electrodes
  - $J_s = \rho_s c$, $B_s = \mu_0 J_s$
- Design Goals
  - Maximize ***B*** field on inner surfaces of stripline electrodes for a fixed current
  - Maximize ***B*** field uniformity over inner surfaces of stripline electrodes
- Normalize stripline geometry to width *w* – parameters are thickness (t_a/w & t_c/w) and gap (g/w)
- Fraction of current carried inside stripline depends most strongly on the stripline gap

Improving Axial Uniformity of the Magnetic Field

Unstructured meshes provide better resolution of tapered striplines

- Use Emphasis/UTDEM code
  - Unstructured tetrahedral mesh
  - Meshes generated directly from solid models
- Advantages over structured grid codes:
  - More accurate representation of complex surfaces
  - Better spatial resolution where it is needed with significantly fewer cells (~1M tetrahedral elements vs. ~10M rectilinear cells for Quicksilver simulations)
  - Unconditionally stable field-solver allows relaxation of Courant constraints on Δt
  - Total solution time is smaller (2-3 hours vs. 4-5 hours on 3 GHz quad-core Linux system)
  - Quicker turnaround for geometry variations – structured reblocking and regridding can be tedious and error prone
- Allows accurate modeling of small variations in the stripline geometry
  - A strategy of multiple iterations to improve axial field uniformity is credible





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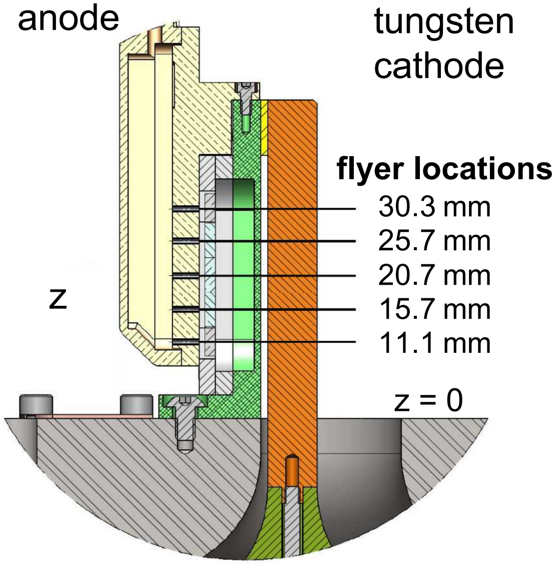
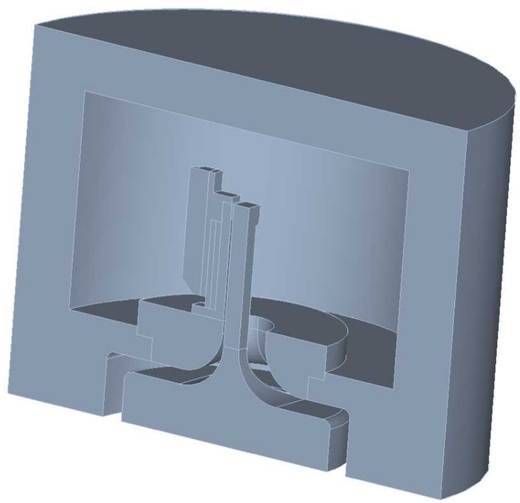
Comparison of Measured B in stripline to Emphasis simulation

- Z Shot 1934 collected flyer plate velocity data for 5 flyers using VISAR
- The time-dependent magnetic field pressure in the stripline at each of the 5 flyer locations was unfolded from the VISAR data using a series of 1D MHD simulations.
- Compare early in pulse before electrodes have deformed
  - Agreement is within 2%
  - Unambiguous quantitative experimental error bars difficult to obtain
  - Best estimate is that error bars are not less than 2%
- This shot achieved:
  - 45.7 km/s (>100,000 mph) flyer velocities
  - ~6 Mbar drive pressure
  - Driver current pulse shaping provided shock-free acceleration of flyers



Shot 1934 stripline detail

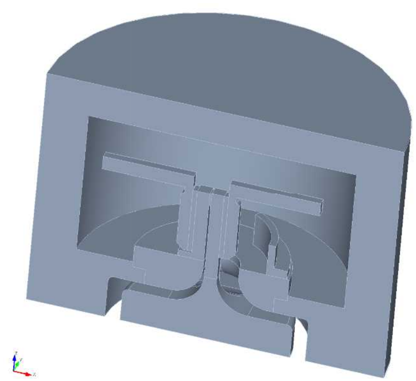


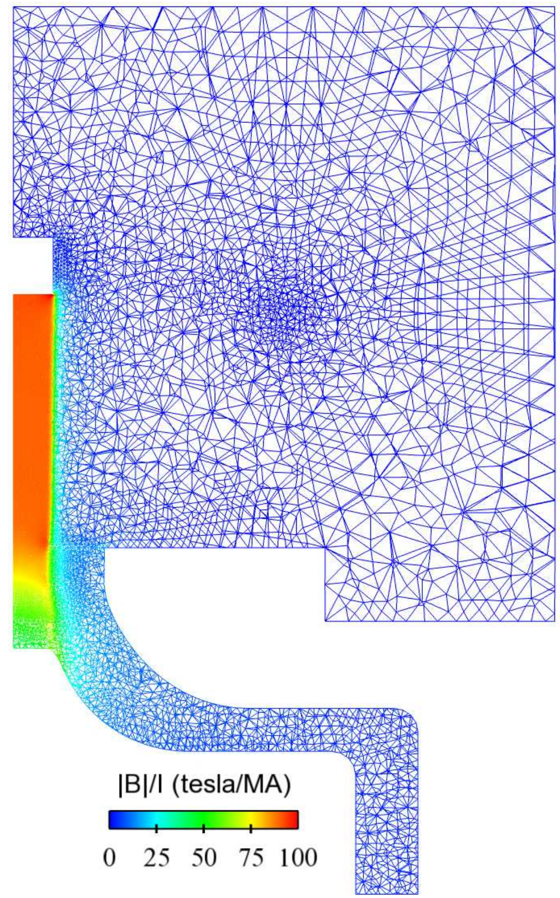
Solid model for simulation

Drive Pressure Variation with Height

Iterative Optimization of B axial uniformity

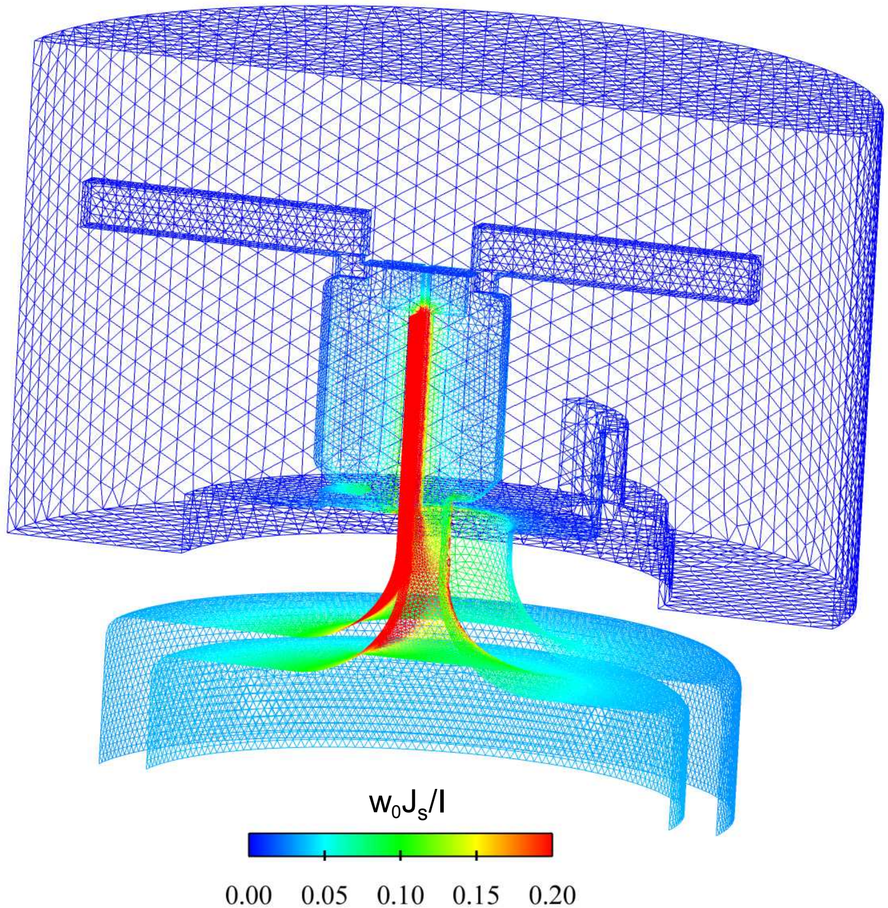
- Optimization of a particular hardware configuration with:
  - 1 mm gap
  - 11 mm width
  - curved feed
  - double-sided diagnostic package
- Optimization criteria:
  - B_1 chosen to equal $B_0(z\text{=}33\text{mm})$
  - $w_1(z)$ less than or equal to w_0
- For first iteration, use $w_1(z) = w_0 B_0(z)/B_1$
- Further iterations used weighted averages of previous iterations:
  - $w_n(z) = f\, w_i(z) + (1 - \text{f})\, w_j(z)$
  - $f = \alpha\, [B_{targ} - B_j(\text{z})]/[B_i(\text{z}) - B_j(\text{z})]$
- Unstructured mesh allows accurate resolution of minor geometric variations



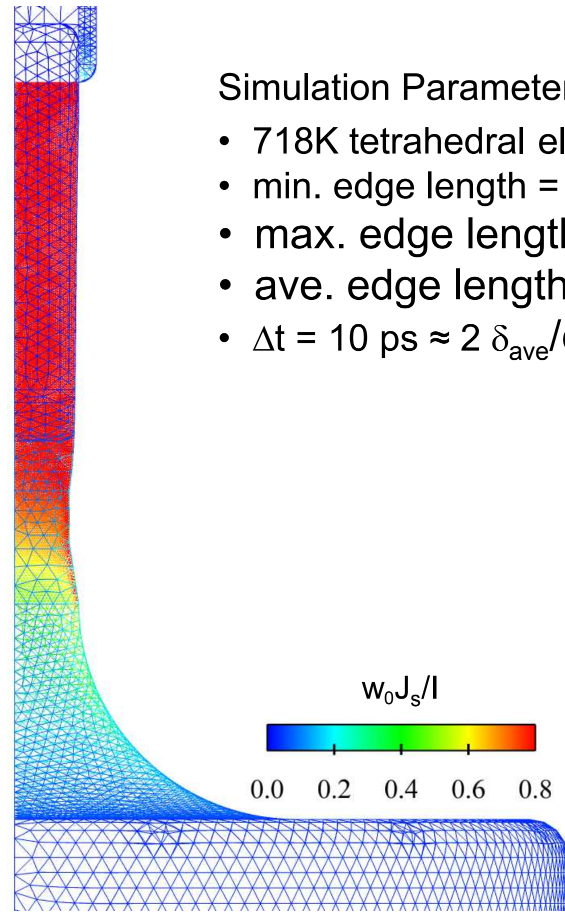


Mod 4 – Midgap plane

Surface Current Density of 4th Iteration (Mod 4)



All electrode surfaces



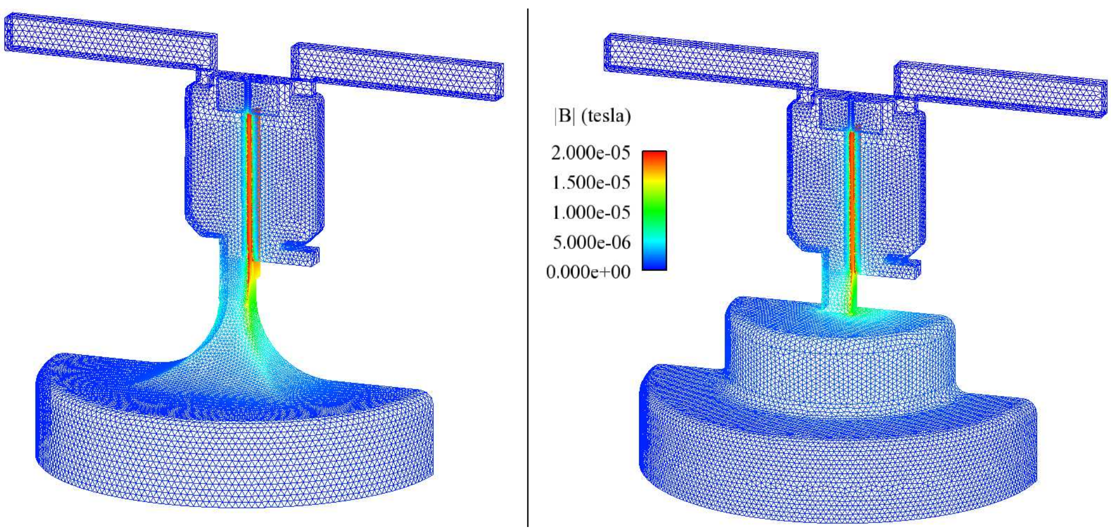
Stripline's cathode surface

Simulation Parameters

- 718K tetrahedral elements
- min. edge length = 0.079 mm
- max. edge length = 8.9 mm
- ave. edge length (δ_{ave}) = 1.4 mm
- Δt = 10 ps ≈ 2 δ_{ave}/c

Feed geometry affects field uniformity in the stripline

- We examined replacing the curved feed with a stepped feed for the Mod 4 optimized tapered stripline
- Details of the feed configuration of the stripline can have a significant effect on axial dependence of magnetic field
- Results show that if the feed is changed, the stripline must be re-optimized for uniform axial B



Curved feed geometry   Stepped feed geometry

Optimization for a stepped feed geometry

- For first iteration, use $w_1(z) = w_0 B_0(z)/B_{target}$
- Tradeoff – Higher B_{target} requires narrower stripline
- We optimized for two values of B_{target} :
  - $B_{target} = B_0(z_0\text{=7mm})$
  - $B_{target} = B_0(z_0\text{=18mm})$
- 1st iteration very different from 1st iteration for curved feed
- Used a different strategy for further iteration:
  - pick new B_{target} from uniform B section of last iteration (α_k)
  - for $z < z_k$, $w_{k+1}(z) = w_k(z)$
  - $z < z_k$, $w_{k+1}(z) = w_k(z)B_k(z)/\alpha_k$
- July experiment on Z will use Mod-2a tapered stripline

z_0 = 7 mm

z_0 = 18 mm

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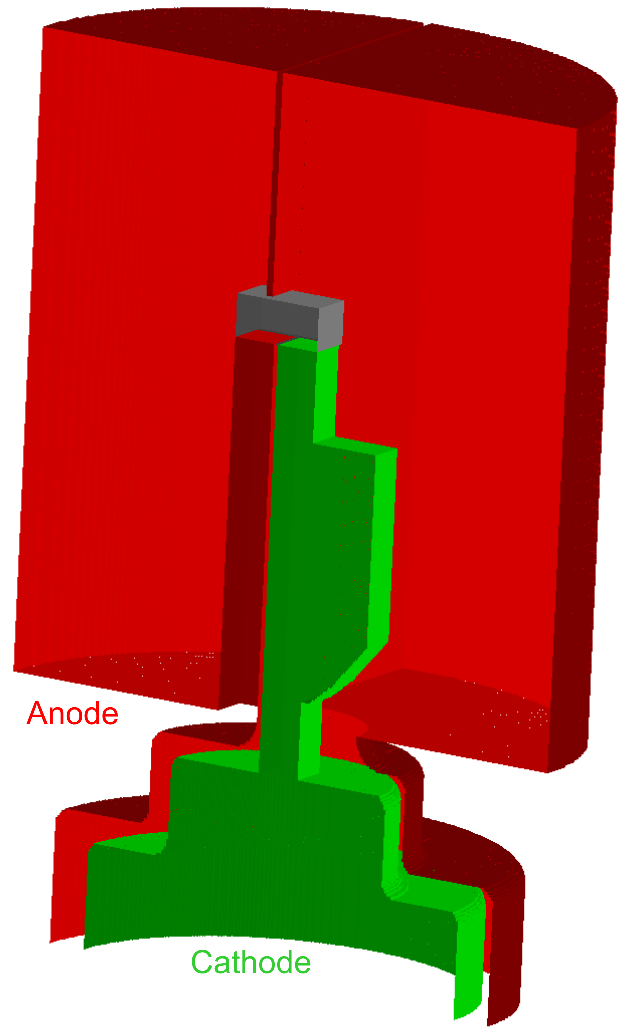
Modeling electron flow in stripline loads

- Stripline load configuration
  - 1 mm gap
  - 20 mm width
  - 69 mm length
- Quicksilver code used
  - Cartesian coordinates, 21 blocks, ~14.3M cells
  - 256K timesteps with Δt = 0.078 ps, particle push used 4 subcyles to resolve ω_c to ~450 Tesla
  - ~12M particles ave.
  - ~13 hours on 64-processor Linux cluster (~170 hours w/o dynamic particle load-balancing)



Simulation Geometry

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Electron losses in stripline are not an issue due to high magnetic fields

Drive current

Magnetic Field

Electron charge density

- Simulated 20 ns window of typical current pulse chosen for high (dI/dt)/I.
  - 5 ns risetime
  - particles turned on at 10 ns
- Not a single one of the ~87M electrons killed hit the anode
  - Because of Z's convolute feed, there will probably be some heating due to electrons injected into the feed near the anode
- Joule heating will clearly dominate electrode plasma formation in this region

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Summary

- Electromagnetic simulation of stripline loads is a valuable tool for stripline loads for Isentropic Compression Experiments (ICE)
  - provide understanding of their behavior
  - can be used as a design tool
- This is an ideal application for unstructured-grid EM tools, such as Emphasis/UTDEM, because of their ability to accurately resolve complex, non-conformal structures
- Our methods have been validated using experimental data from Z
- We have designed configurations that minimize the axial variation of the magnetic pressure of the stripline – these will be tested in upcoming experiments
- Simulations including electron flow indicate that electrode heating due to electron deposition will be small, particularly when compared to Joule heating.

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