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A Physics-Based Model for Convolute Current Loss on Z

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Abstract

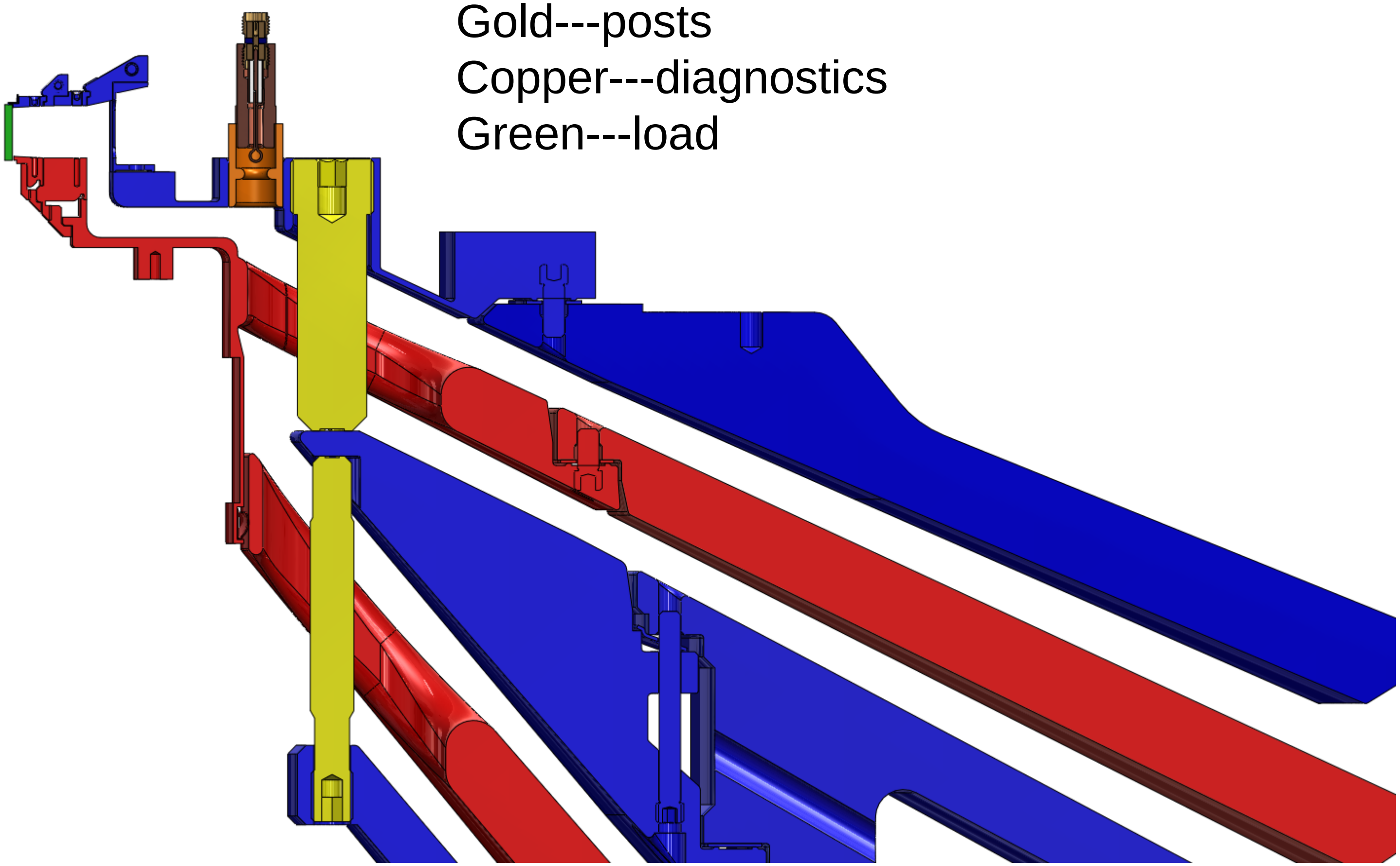
Sandia’s Z machine is a large pulsed-power accelerator used to create extreme conditions of high energy density. Research areas of Z include dynamic properties of materials, radiation and electromagnetic effects on materials and systems, and inertial confinement fusion. In its current embodiment, four magnetically-insulated radial transmission lines (MITLs) are combined at a double post-hole convolute (PHC). Current loss in the convolute can be quite large (20% of peak load current) for certain pulse shapes and physics loads, thus there is need for a simple physics-based model of this current loss in order to accurately predict load-current waveforms using a transmission-line circuit model of Z in the BERTHA code) Sources of charged particles and plasma in the post-hole convolute are believed to consist of electrons from Child-Langmuir space charge limited field emission from the cathode, as well as cathode and anode plasma production from adsorbed contaminants. The generated loss current path is the subject of some debate, but the result of experiments and PIC simulations indicate that cathode plasma forms initially due to emission from the sides of the cathode hole, then fills a magnetic well downstream of the post, effectively reducing the AK gap there. Current subsequently flows across this plasma-filled gap to complete the circuit. We shall describe the physics contained in the simplified models, show some preliminary results, and discuss how we try to incorporate experimental observations and PIC simulations in our model. We will also describe the inherent uncertainty in the electrode conditions, and how that affects the model results. Based on the model and its integration with BERTHA, recommendations for reducing the current loss will be offered.

Motivation

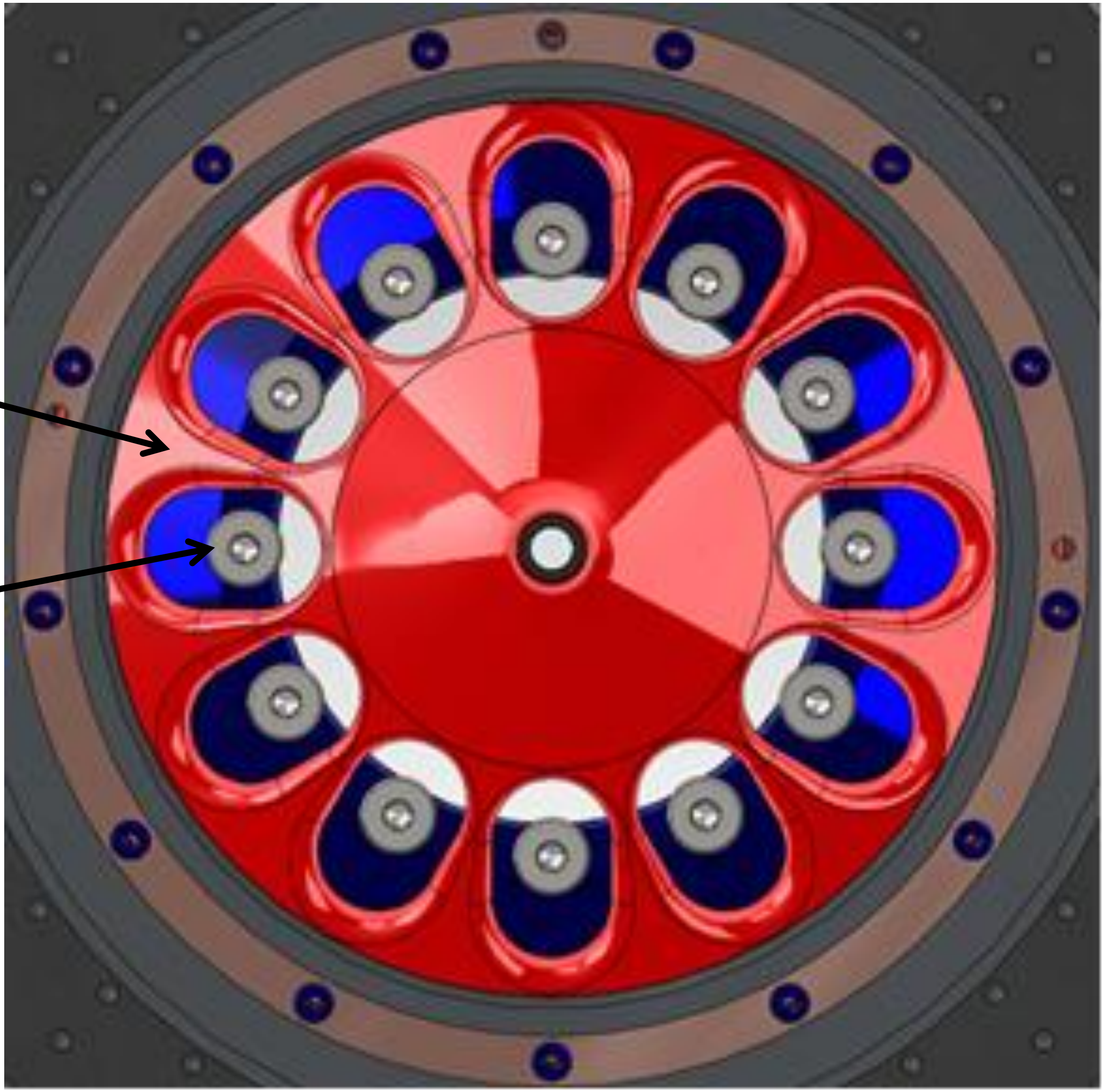
- Post-hole convolute geometries are used on the present ZR system in order to add the currents from multiple MITL levels, while maintaining overall low impedance.
- This particular geometry unfortunately has magnetic nulls at small radius where strong magnetic insulation is absent. These nulls introduce the possibility of parasitic currents reducing the final current to the physics load, thereby reducing performance.
- The results of experiments and particle in cell simulations suggest that additional current paths may exist on the inboard side of the convolute post-holes away from the nulls.
- It motivates us to describe the issues and models we have considered of cathode plasma production in the post-hole convolute region.
- The models are of a reduced dimensionality so they can be implemented in a circuit code model such as Bertha for the purpose of prediction and ‘post diction’ of desired or observed machine current pulse shapes.

Geometry

Blue—anode
Red----cathode
Gold---posts
Copper---diagnostics
Green---load

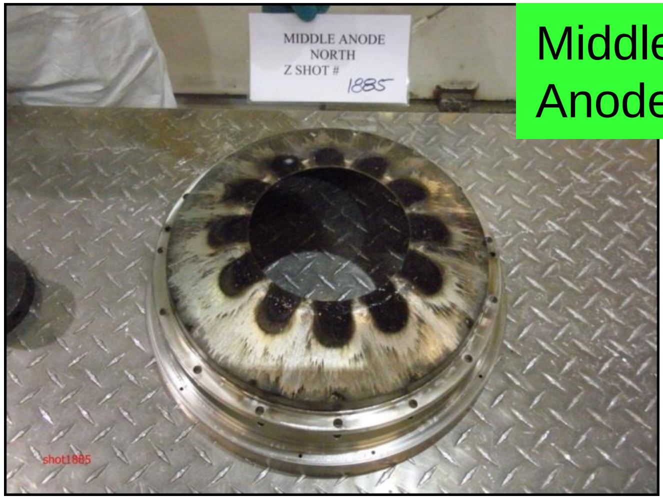


Convolute—top view



Post-Shot Components

Upper Cathode

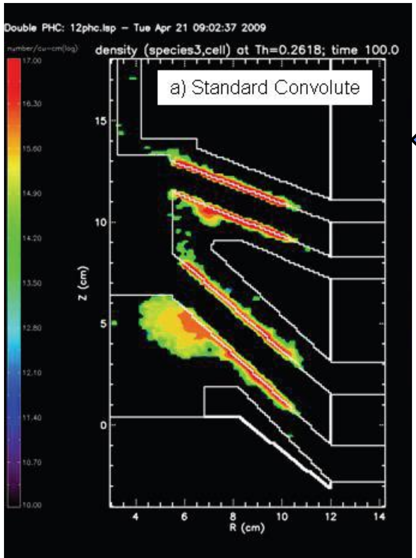


Middle Anode

Lower Cathode

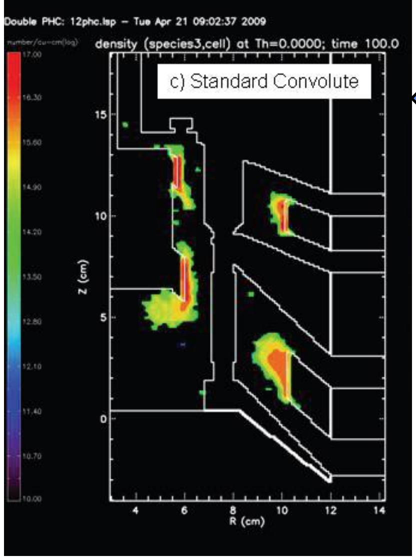
Lower Anode

Particle in Cell Simulations with Cathode Plasma Formation (Rose, *et al*.*)



Between hole view

The final mechanism for inboard (high field) gap closure is not entirely understood from the PIC simulations, hence making a *reduced* model for it somewhat difficult.

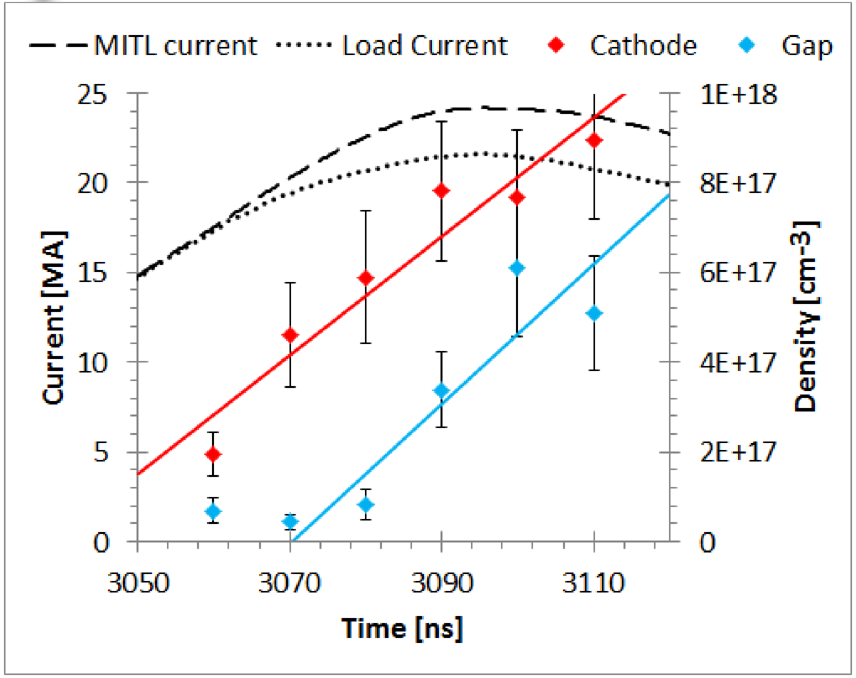


Slice through anode post

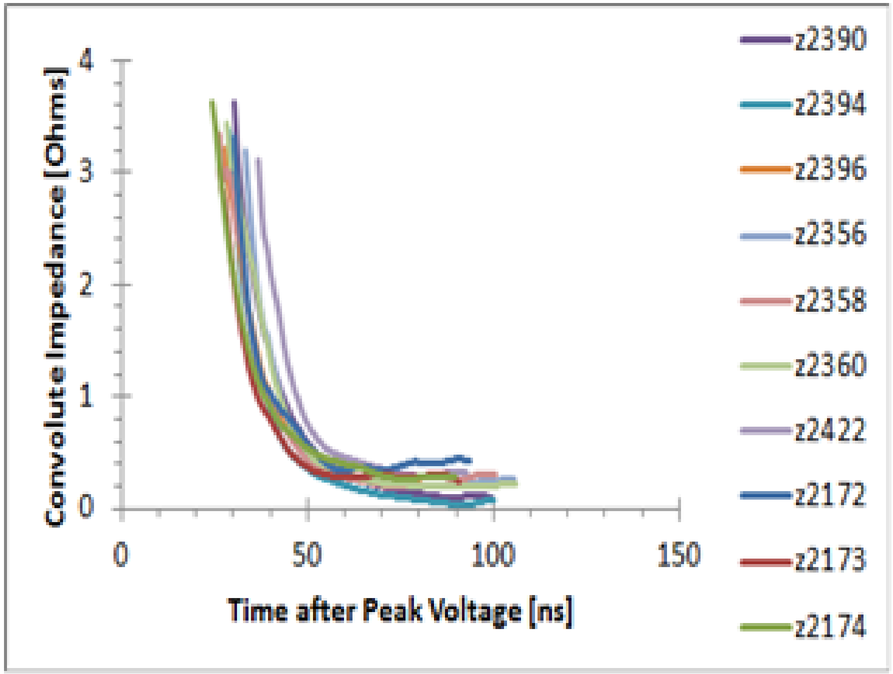
Plasma forms on inboard and outer cathode hole surfaces.
Enhanced current loss found on inboard AK gap.

*PPC 2009, p. 1153.

Experiments (Gomez, et.al.)



Gap closure velocity is inferred by density time history at cathode and in gap (Δ = 0.44cm). 17-20 cm / μsec



Inferred convolute impedance, while consistent in shape, the floor varies by a factor of 20 for the same configuration. 0.02-0.4 Ohms. Significant uncertainty in losses inferred.

Possible models

- Fluid model to compute fill time of downstream post hole reservoir. Give delay time from null current loss to inner gap current loss. (pursued many models for the fill time downstream, none seemed adequate)

- Hybrid model (kinetic/fluid) for plasma formation on surfaces and null and inner gap closures.

- Vickers (AWE) has claimed that pure fluid models to not describe the closure process. Rose (Voss) has shown that a kinetic or 2-fluid model can reproduce measured current losses on several different convolute configurations.
- Hybrid models would not be (remotely) fast enough to include in BERTHA
- We need a higher level, heuristic model for current loss for use in BERTHA.

Desired Model Features

- Fast computational time for 10’s of thousands of evaluations in BERTHA
- Probably should have closure at outer and inner post hole gaps per experiment and simulation, the null closure occurring first. .
- Time delay for inner (high-B) closure, based on a critical density being reached.
- Data can suggest what this delay might be.
- Final mechanism for inner hole closure not understood thoroughly.
- Suggests a physics motivated functional form consistent with experiment and simulation, but with the ability to account for variation of surface conditions (roughness, adsorbed contaminants)

Model form

We consider a sum of Child Langmuir (CL) space-charge-limited emission and gap closure. Applied to both null loss and inner gap loss and combined as parallel resistances, R_j:

$$R_j = \left\{ C\,\{1-[(t-t_{0j})/\tau]\}^2 + D\,[(t-t_{0j})/\tau] \right\} / A_j(t),$$

where t_0 is the CL turn on time, determined by the local electric field exceeding the CL threshold (240 kV/cm for Al). Dimensionality, surface roughness, and surface cleanliness are accounted for by a profile of field enhancement factors that cause the CL emission to initiate at different times.

With area $A_j(t)$ a linearly increasing function of $(t-t_{0j})$, resistance profiles like those measured appear naturally. Coefficients C and D have hidden physical dependencies and are chosen to bracket the envelope of measured resistance.

Model Test

- Consider several shot tests, all dynamic material (DM) pulse shapes, real and dummy loads.

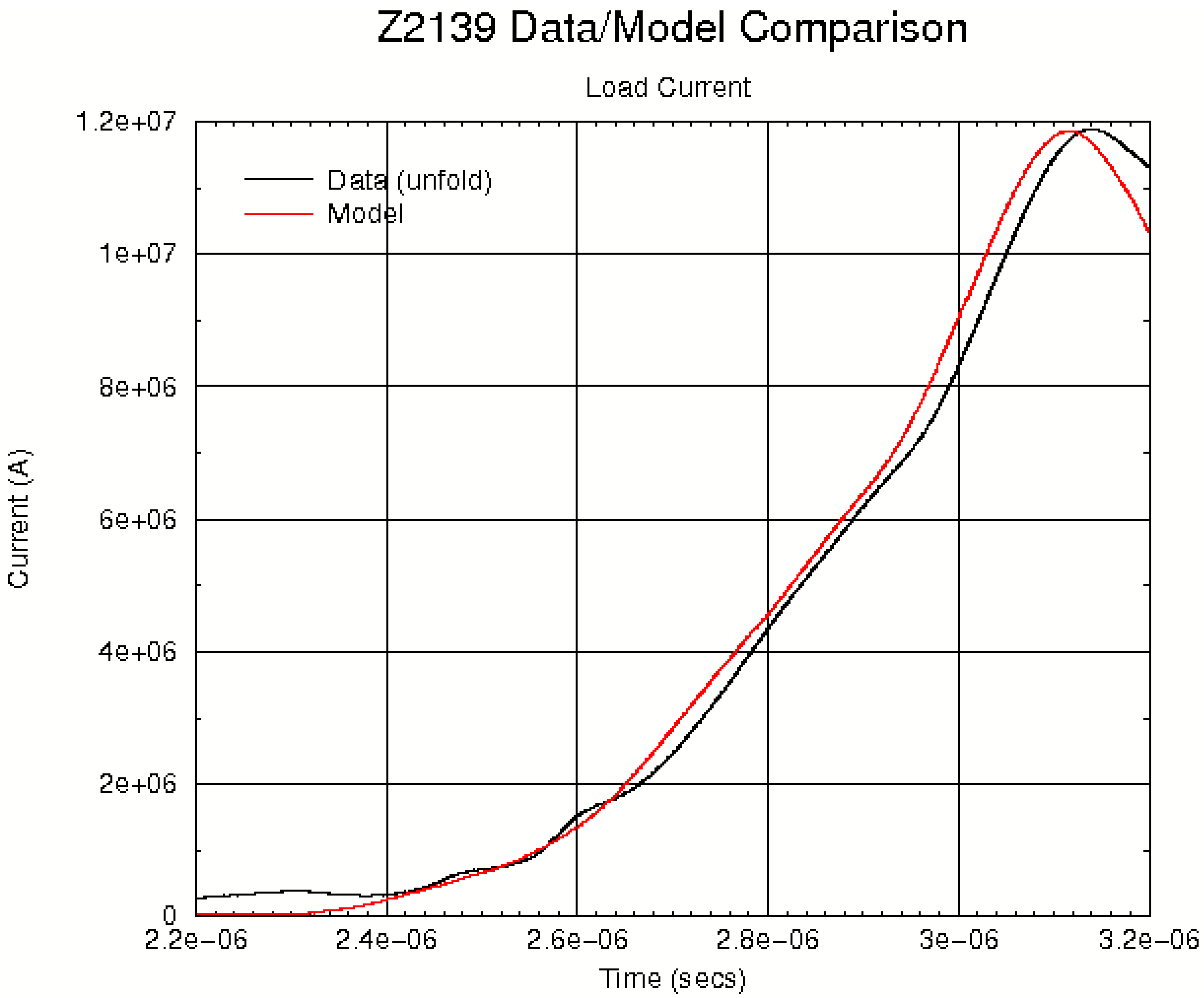
- Each shot has a current unfold using VISAR data and 2D ALEGRA simulations. Load B-dots were not fielded on DM shots.

- Model profiles of convolute resistance were derived from ICF type pulse shapes and loads (quite different from DM). If losses are bracketed by this model, adds to credibility that it more widely applicable.

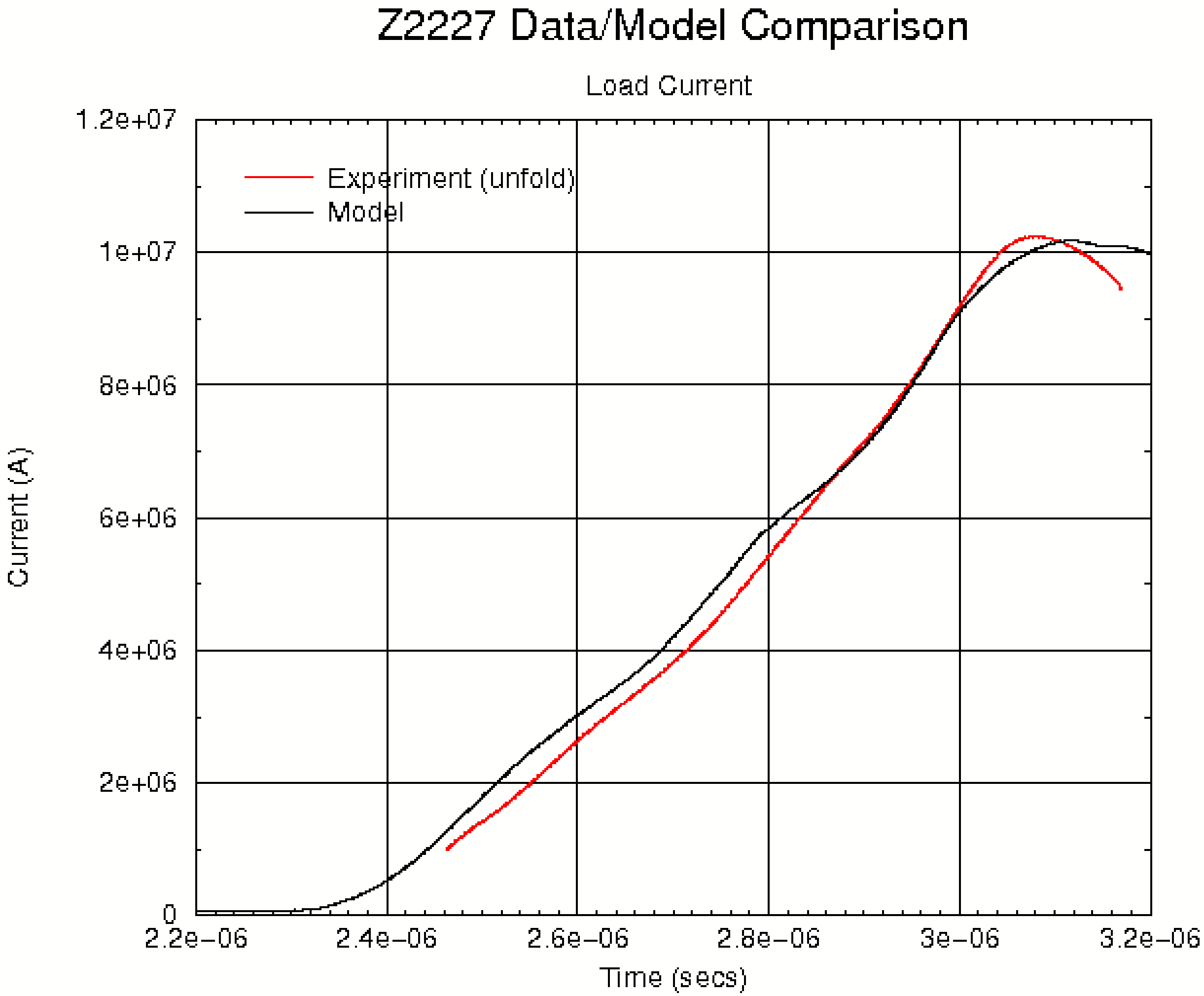
- Shots 2139, 2227, 2303, 2304, 2333, 2450.

- Comparison layout for each shot: Unfolded current per ALEGRA, compared to model computed losses. Have leeway in coefficient choice so long as it lies in the envelope of resistance profile experimentally derived.

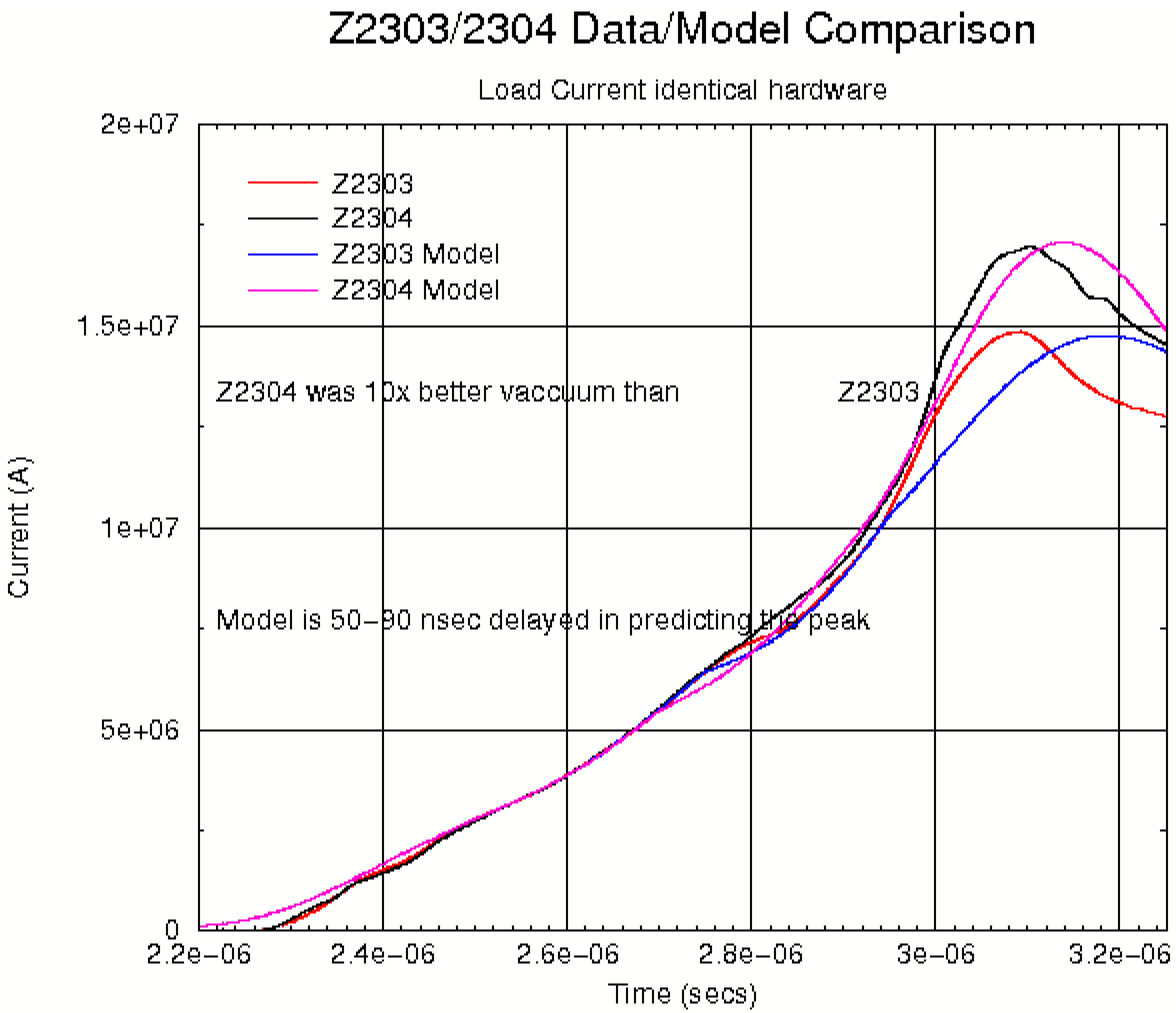
Shot 2139


Z2139 Data/Model Comparison
Load Current
Data (unfold)
Model
Current (A)
Time (secs)
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
0
2.2e−06
2.4e−06
2.6e−06
2.8e−06
3e−06
3.2e−06

Shot 2227


Z2227 Data/Model Comparison
Load Current
Experiment (unfold)
Model
Current (A)
Time (secs)
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
0
2.2e−06
2.4e−06
2.6e−06
2.8e−06
3e−06
3.2e−06

Shots Z2303/2304



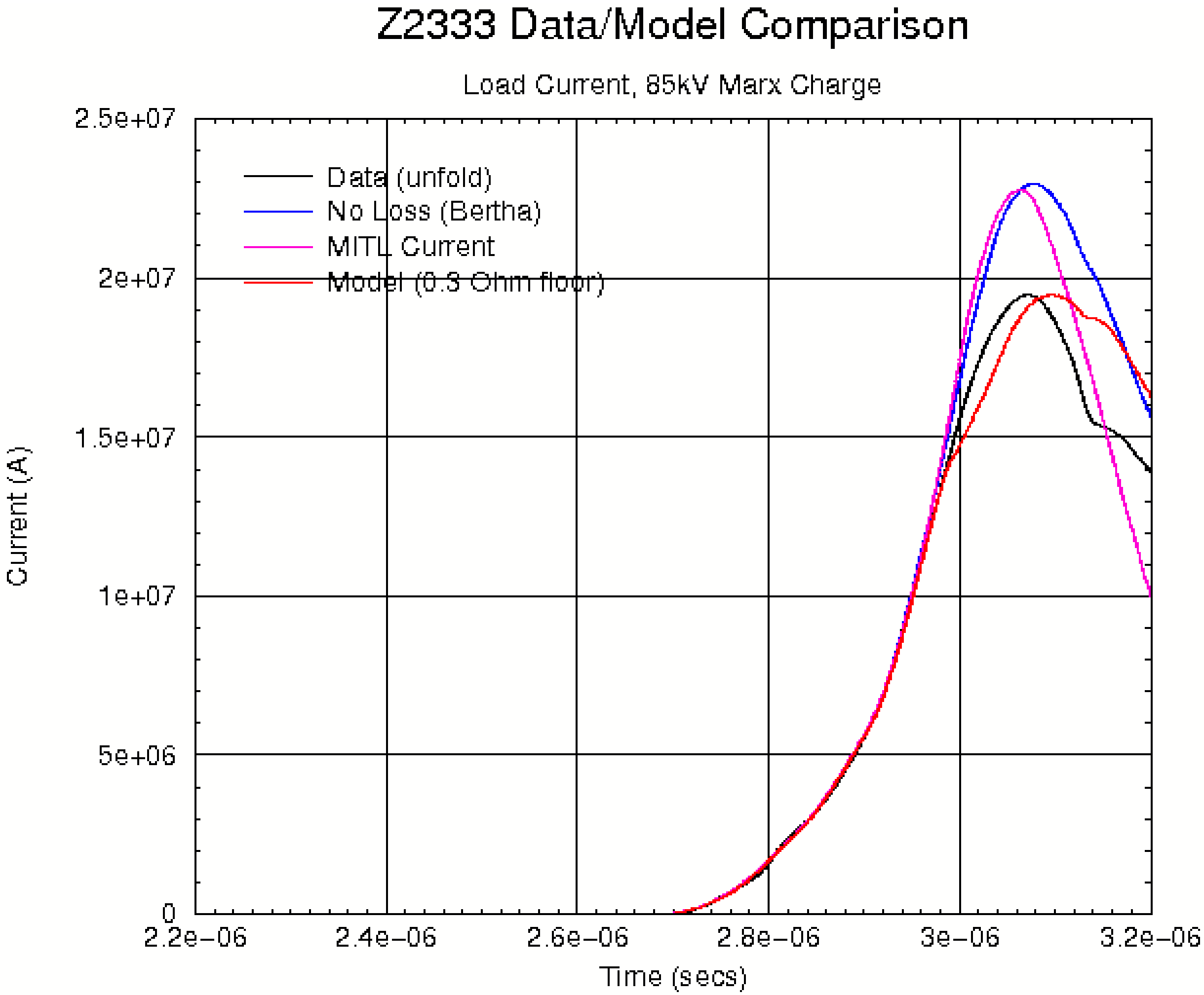
Z2303/2304 Data/Model Comparison

Load Current identical hardware

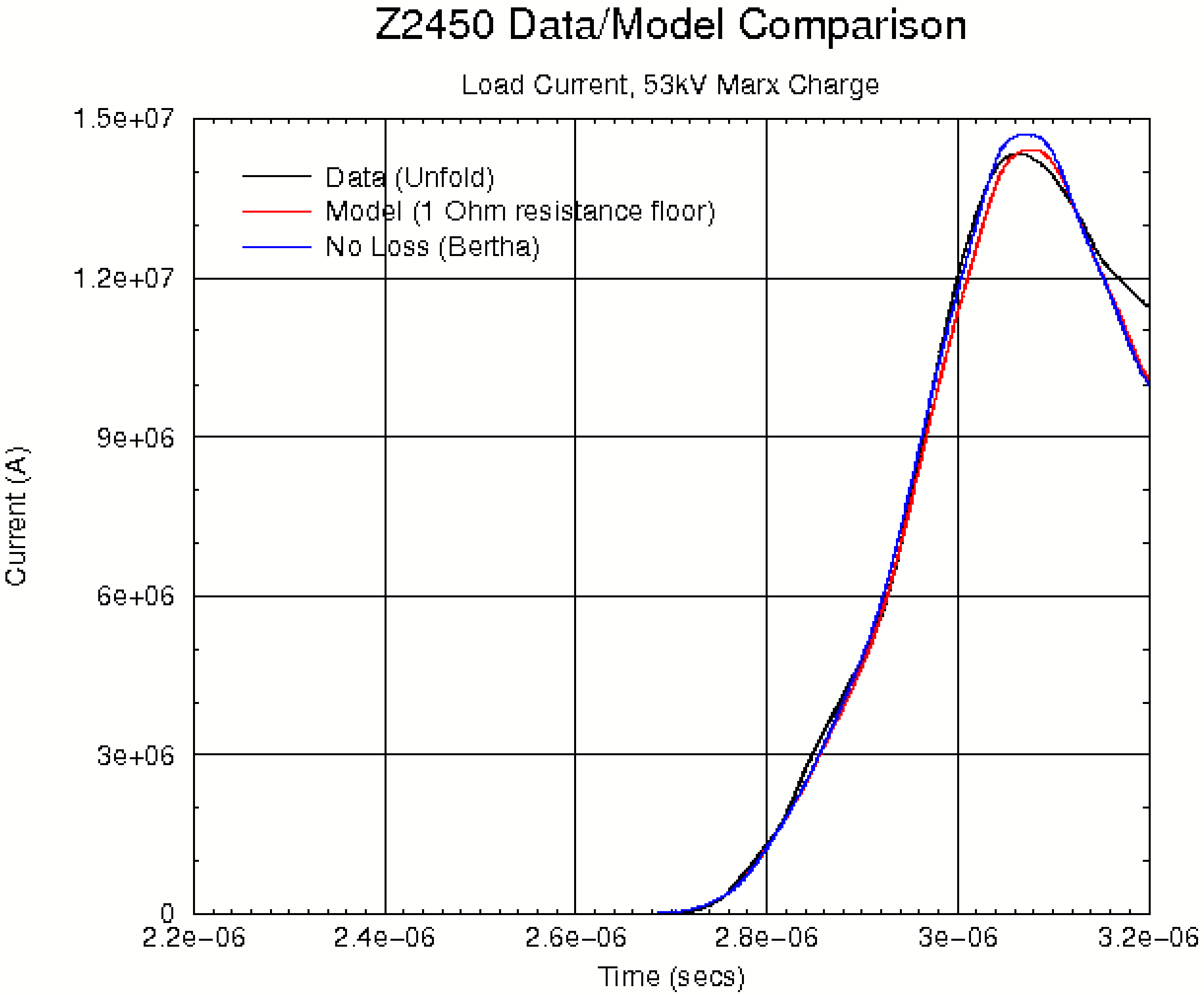
Z2304 was 10x better vaccuum than Z2303

Model is 50–90 nsec delayed in predicting the peak

Shot Z2333


Z2333 Data/Model Comparison
Load Current, 85kV Marx Charge
Data (unfold)
No Loss (Bertha)
MITL Current
Model (0.3 Ohm floor)
Current (A)
2.5e+07
2e+07
1.5e+07
1e+07
5e+06
0
2.2e−06
2.4e−06
2.6e−06
2.8e−06
3e−06
3.2e−06
Time (secs)

Shot Z2450


Z2450 Data/Model Comparison
Load Current, 53kV Marx Charge
Data (Unfold)
Model (1 Ohm resistance floor)
No Loss (Bertha)
Current (A)
1.5e+07
1.2e+07
9e+06
6e+06
3e+06
0
2.2e−06
2.4e−06
2.6e−06
2.8e−06
3e−06
3.2e−06
Time (secs)

Comments

- The semi-empirical model derived from ICF-like shots is consistent with the observed losses of the dynamic materials experiments.

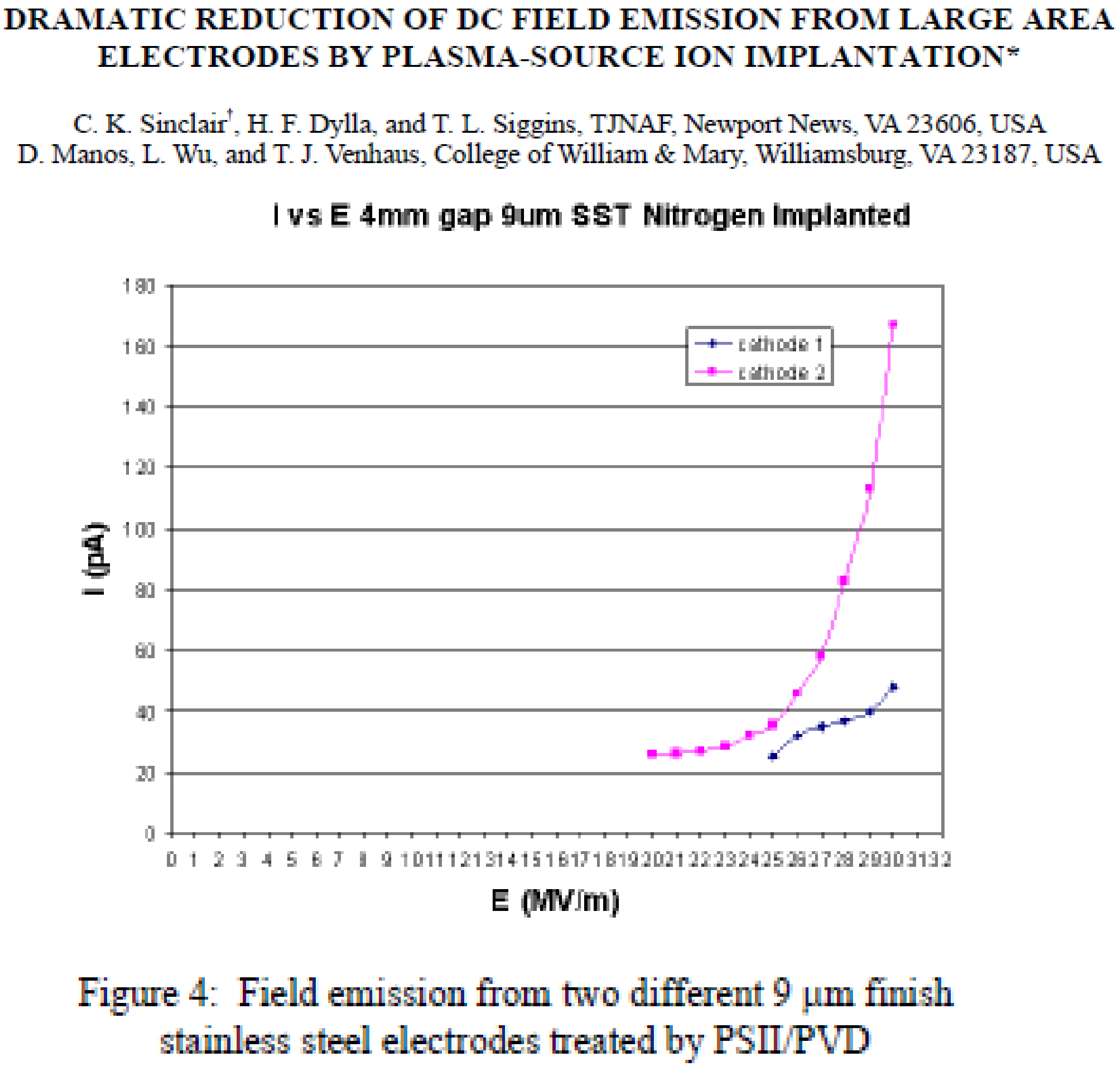
- The variation in losses for seemingly identical hardware setups can be large for both ICF and DM shots. This of course suggests that the root causes of the convolute losses should be identified and ameliorated, rather than focus on describing the 'symptom'.

Focus on the root causes of the losses-*surface conditions*

- Clean up surfaces
  1. Glow discharge cleaning
  2. Dry Nitrogen fill/purge
  3. Lower spec for center section vacuum. Now typically 2 e-5 torr, order 2.e-6 torr can make measureable differences (i.e. Z2303 versus Z2304)

- Modify the bare surfaces
  1. Gold plating (some of this has been tried, but not consistently)
  2. Ion implantation with nitrogen ions (Sinclair, Dylla, et.al. 2001)

Ion implantation creates smooth surfaces and can raise the field emission threshold.



DRAMATIC REDUCTION OF DC FIELD EMISSION FROM LARGE AREA ELECTRODES BY PLASMA-SOURCE ION IMPLANTATION*

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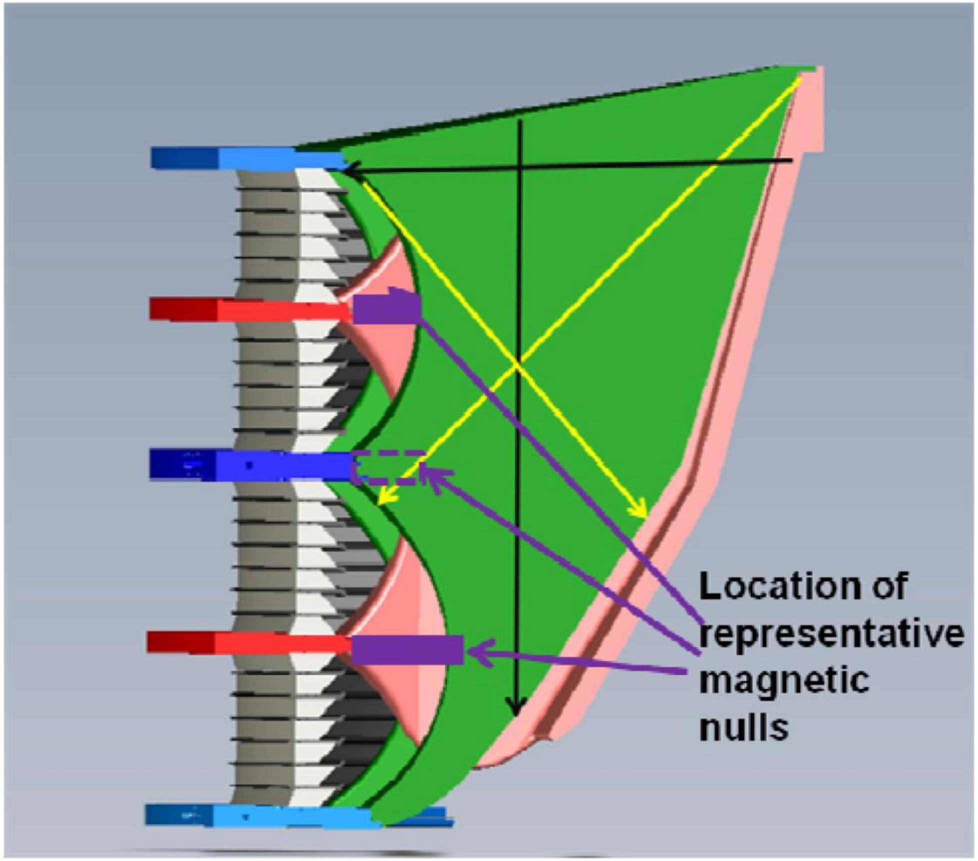
I vs E 4mm gap 9um SST Nitrogen Implanted

Figure 4: Field emission from two different 9 μm finish stainless steel electrodes treated by PSII/PVD

“New” designs could affect the convolute losses favorably.

Clam Shell MITL will be a drop-in replacement for the Z MITL and Convolute. (Pace VanDevender, 2008)

- **Moves the nulls out to much lower fields.**
- **Removes the inboard side ‘reservoir’ for buildup of cathode plasma**



Experiments were done in 2011-The CSMITL behaved electrically as the conventional design, with higher peak current and power

Figure 4. Photograph of the Saturn CSMITL anode (bottom) and cathode (top). The cathode is shown inverted from its operational condition to show the MITL surfaces and the pattern of metal erosion from electron loss along the ridgeline line of the tents.

NEW SELF-MAGNETICALLY INSULATED CONNECTION OF MULTI-LEVEL ACCELERATORS TO A COMMON LOAD

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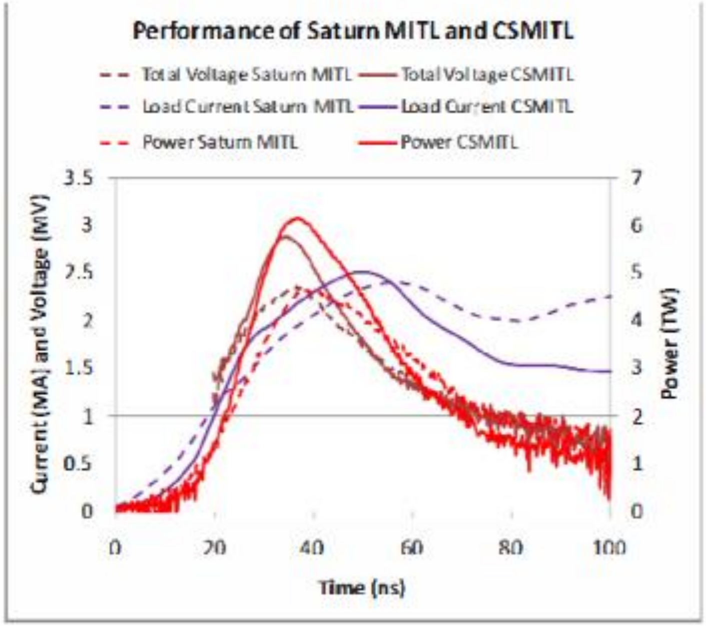

Figure 6. Comparison of the total voltage, load current, and power for the conventional Saturn MITL (dashed lines) and the CSMITL (solid lines).

Conclusions

- The processes in play in the Z convolute are sufficiently complex and stochastic that a physics-based predictive model is elusive.

- The semi-empirical model can reproduce the features of the current loss, within the range of measured resistance temporal profiles.

- To solve the convolute current loss problem, more attention to root causes rather than try to simulate the rather rich variation of the ‘symptoms’

- Root causes (for fixed load inductance) is surface cleanliness and bare surface properties.