SAND2007-3652C

Reduction of Electron Flow Current and Localized Anode Energy Deposition in Transitions from Coaxial Feeds to a Disk

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Electromagnetics and Plasma Physics Analysis

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under contract DE-AC04-94AL85000.

Presentation Outline

- Z-Pinch Inertial Fusion Energy (ZP-IFE)
  - Introduction, simulation goals
  - Simulation setup
  - Current and electron flow time histories
  - Anode temperatures at t = 200 ns (end of simulations)
  - Strategies/results for alleviating anode energy deposition
  - Conclusions

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ZP-IFE Introduction

- ZP-IFE (Z-pinch Inertial Fusion Energy)
- Long range goal: produce an economically-attractive power plant using high-yield z-pinch-driven targets with low repetition rate per chamber (~0.1 Hz)
- Primary source consists of multiple LTD (Linear Transformer Driver) modules, each driving a single coaxial line
  - The preliminary design had 70 - 9 Ω coaxial lines operating at ~7 MV and ~1 MA
  - This configuration yielded high flow currents causing inefficiency and extreme localized anode heating
  - The currently investigated design is 10 - 9 Ω coaxial lines operating at ~9 MV and ~7 MA to deliver 60 MA to the load
- $V_{oc}(t) = V_0 \sin^2 \omega t$, where ω is chosen for a 200 ns pulse width with $V_0 = 19.5$ MV

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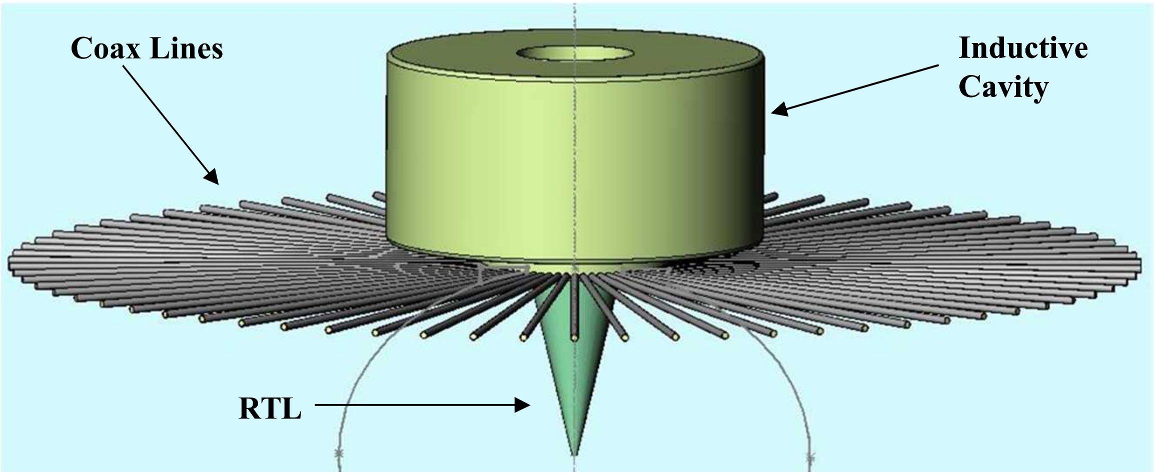
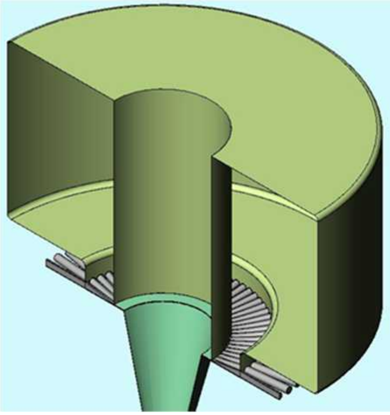
ZP-IFE Conceptual Drawings

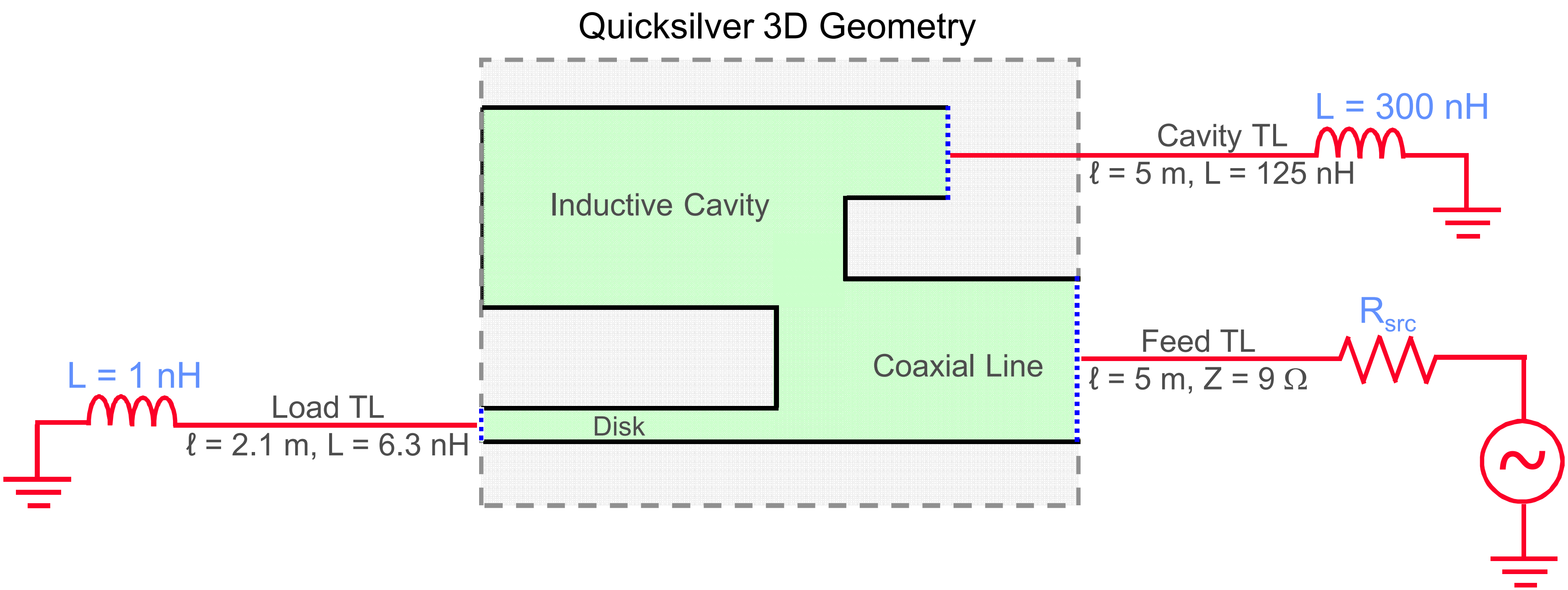




- The configuration of this design is constrained by two decisions:
  - The RTL must be a single-disk feed, i.e. not a triplate line with an extra inner conductor
  - The conductors enclose a sealed volume under vacuum
- The second decision forces the coaxial lines to be coupled to a triplate disk configuration to close the volume and the first decision dictates that the triplate disk must be efficiently transitioned into a biplate disk

Long 1-D transmission lines attach to the 3-D boundaries to model the external system

- Extensive code development for power flow simulations of Z and ZR help with this analysis
  - Long 1-D TLs for modeling parts of the system external to the 3-D geometry
  - Robust algorithms for connecting 1-D TLs to the 3-D geometry
  - Compute electron deposition into all anode surface faces, and the subsequent temperature increase



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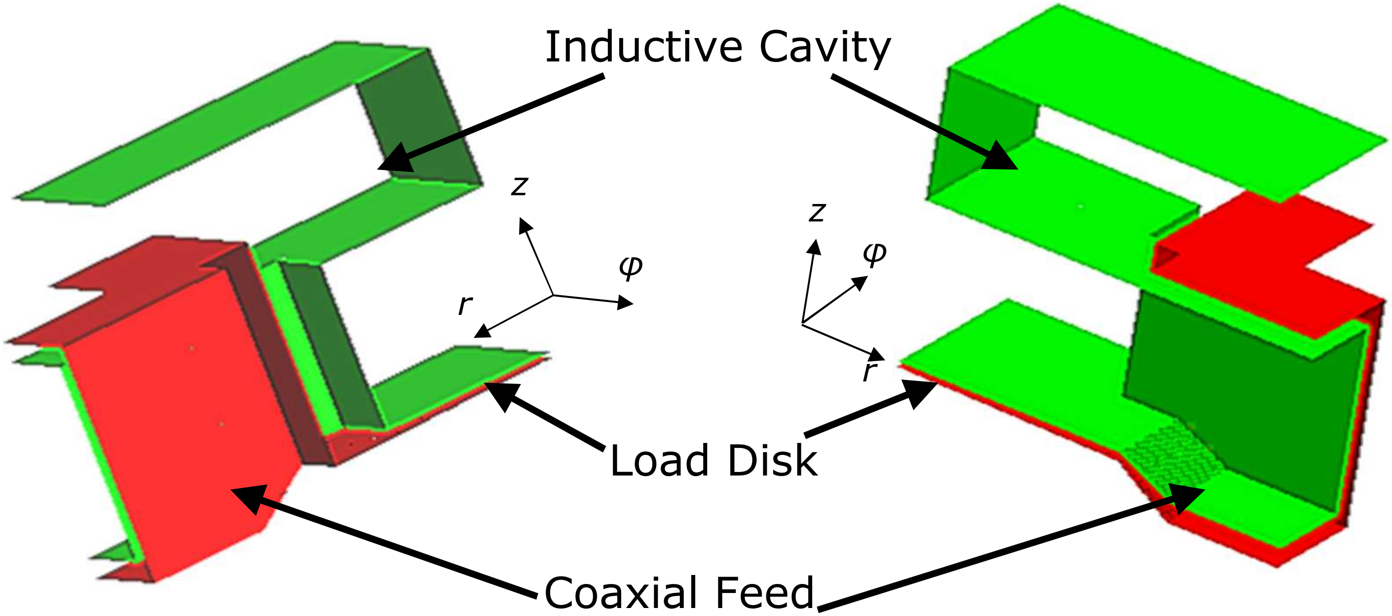
Quicksilver 3D Geometry



- Cylindrical coordinates are used due to the cylindrical symmetry
- Rectangular cross section coaxial lines are used for simplicity

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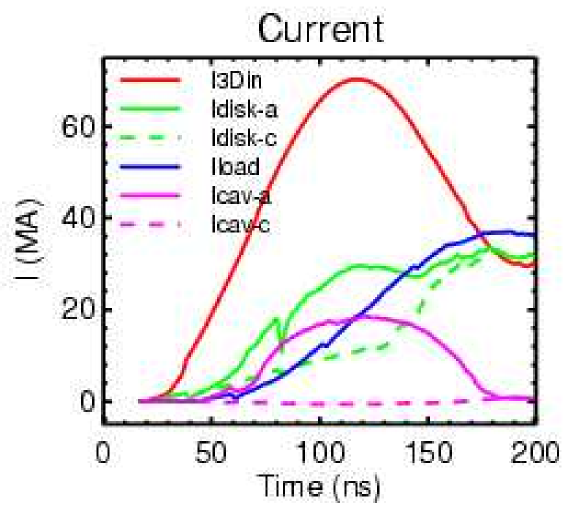
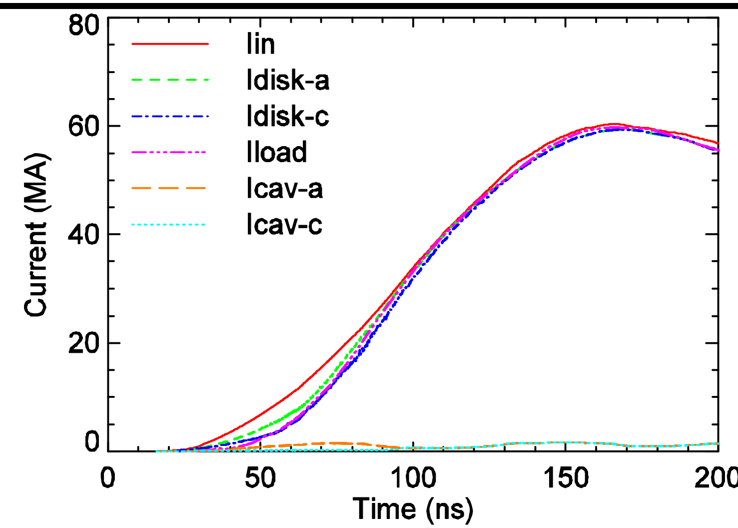
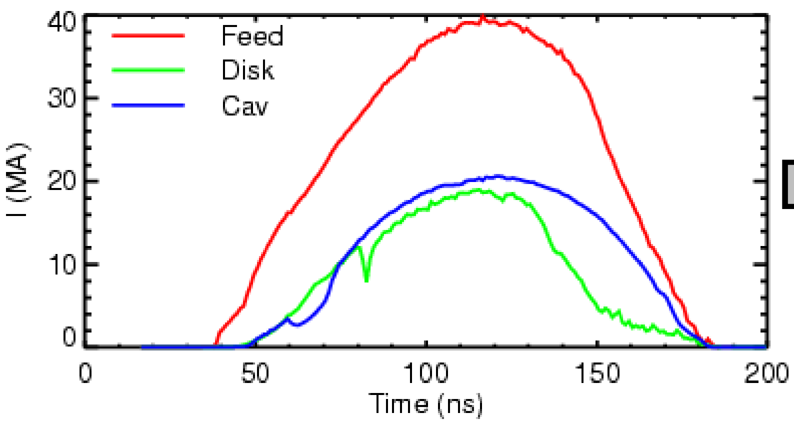
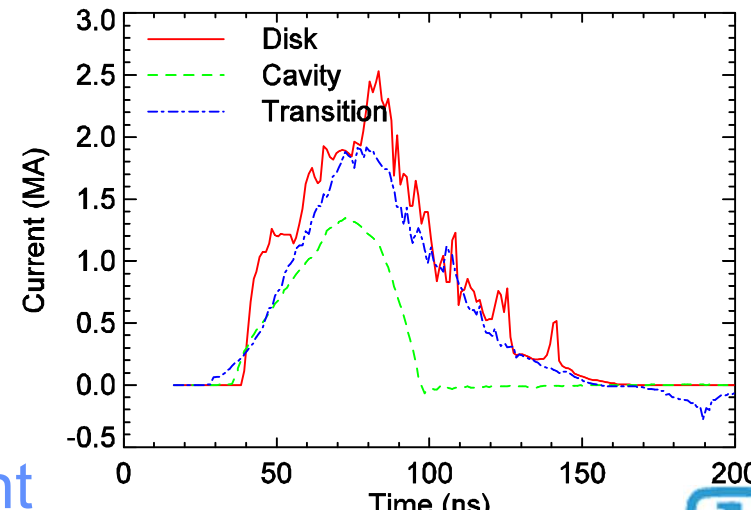
Time History Comparison
70-feed lines (left) vs. 10-feed lines (right)



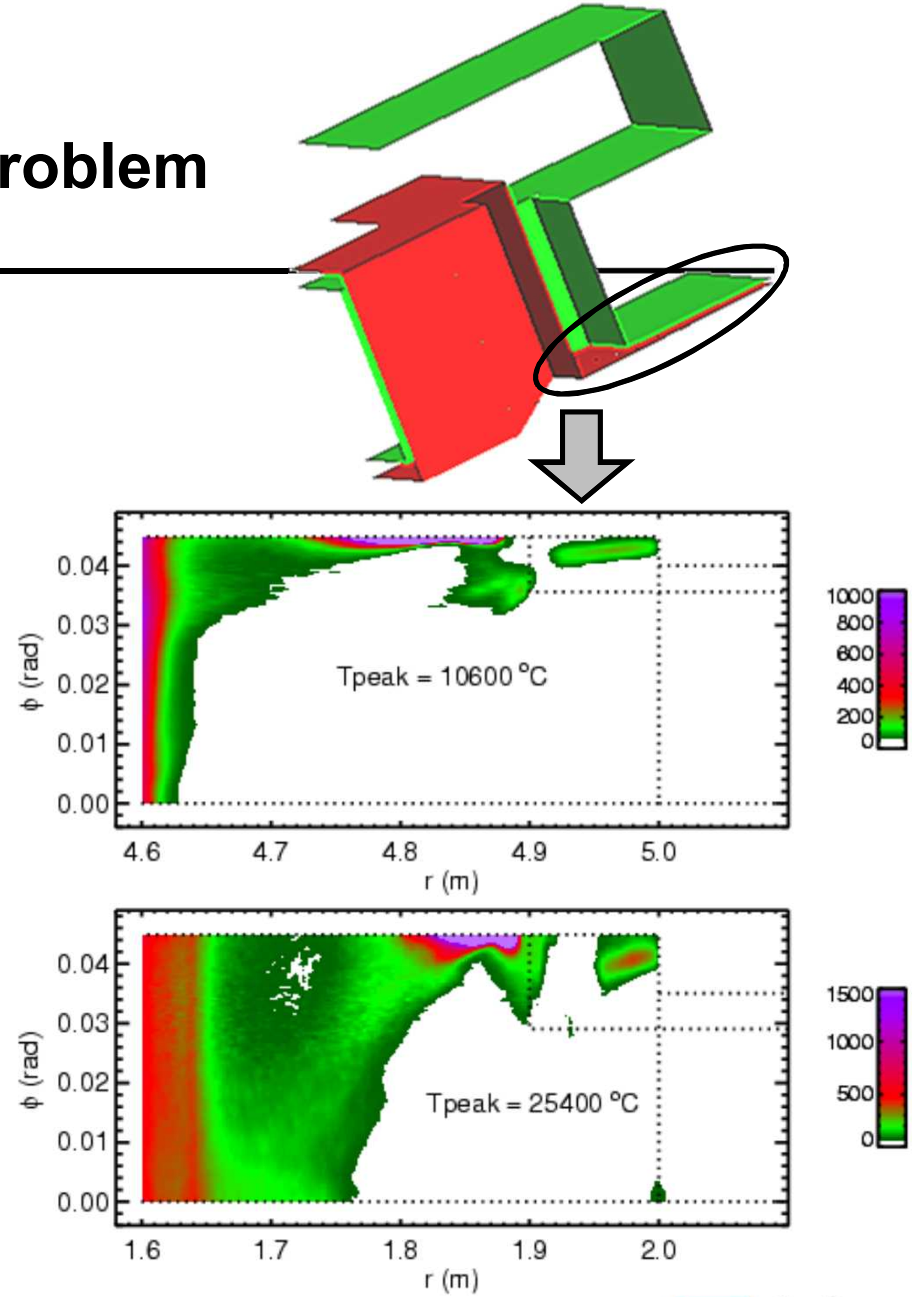






Electron Flow Current

Anode heating is a problem



- Anode heating is a big problem with the 70-feed line structure
- Energy deposition of this magnitude ruins the possibility of achieving the desired repetition rate (~10 sec. between shots)
- The energy deposition model is temperature accurate for stainless steel up to T~800°C
- Above 800°C, the “temperature” from this model should only be considered a qualitative indicator of energy deposition

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Anode Heating and Energy Deposition

- Anode energy deposition should definitely be limited such that the temperature of the anode conductor remains less than the melt temperature of 1430°C.
- Ideally energy deposition to the anode would be limited in a manner such that the temperature of the anode conductor remains less than 400°C.
- This temperature specification is made based on the empirically-based temperature† where impurities on the surface of the metal form a dense plasma on the anode causing the effective A-K gap to become smaller or breakdown completely.

† Cuneo, M. E., "The Effect of Electrode Contamination, Cleaning and Conditioning on High-Energy Pulsed-Power Device Performance," IEEE Trans. on Dielectrics and Electrical Insulation, no. 4, August (1999).

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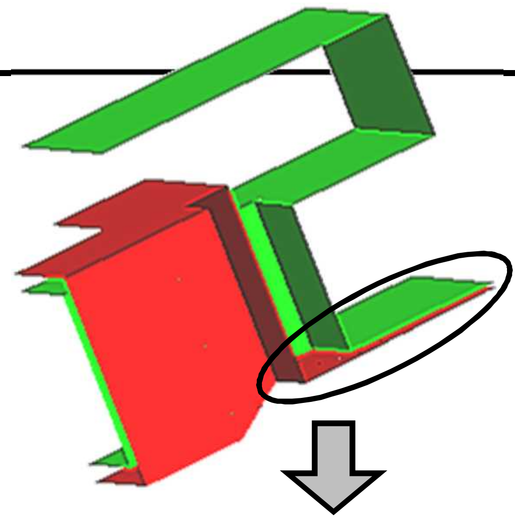
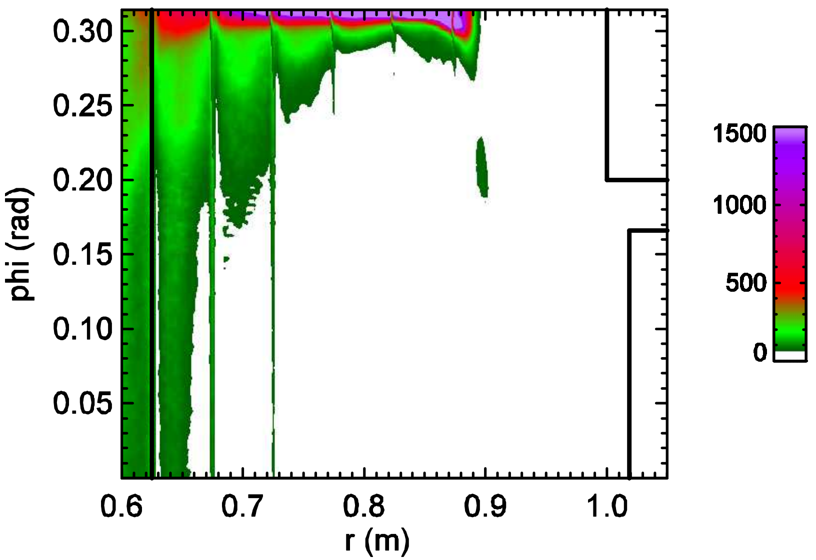
Anode heating is still a problem

- The 10-feed line structure is improved but still not close to the desirable range
- The primary cause of the extreme anode heating is the combination of the abrupt transition from the feed coax to the disk MITL and the influence of the reduced magnetic field between adjacent feed lines
- There is a reduced magnetic field between adjacent feeds because it takes a finite distance downstream of the transition for the current distribution to be azimuthally symmetric





$T_{peak} \approx 9969°C$

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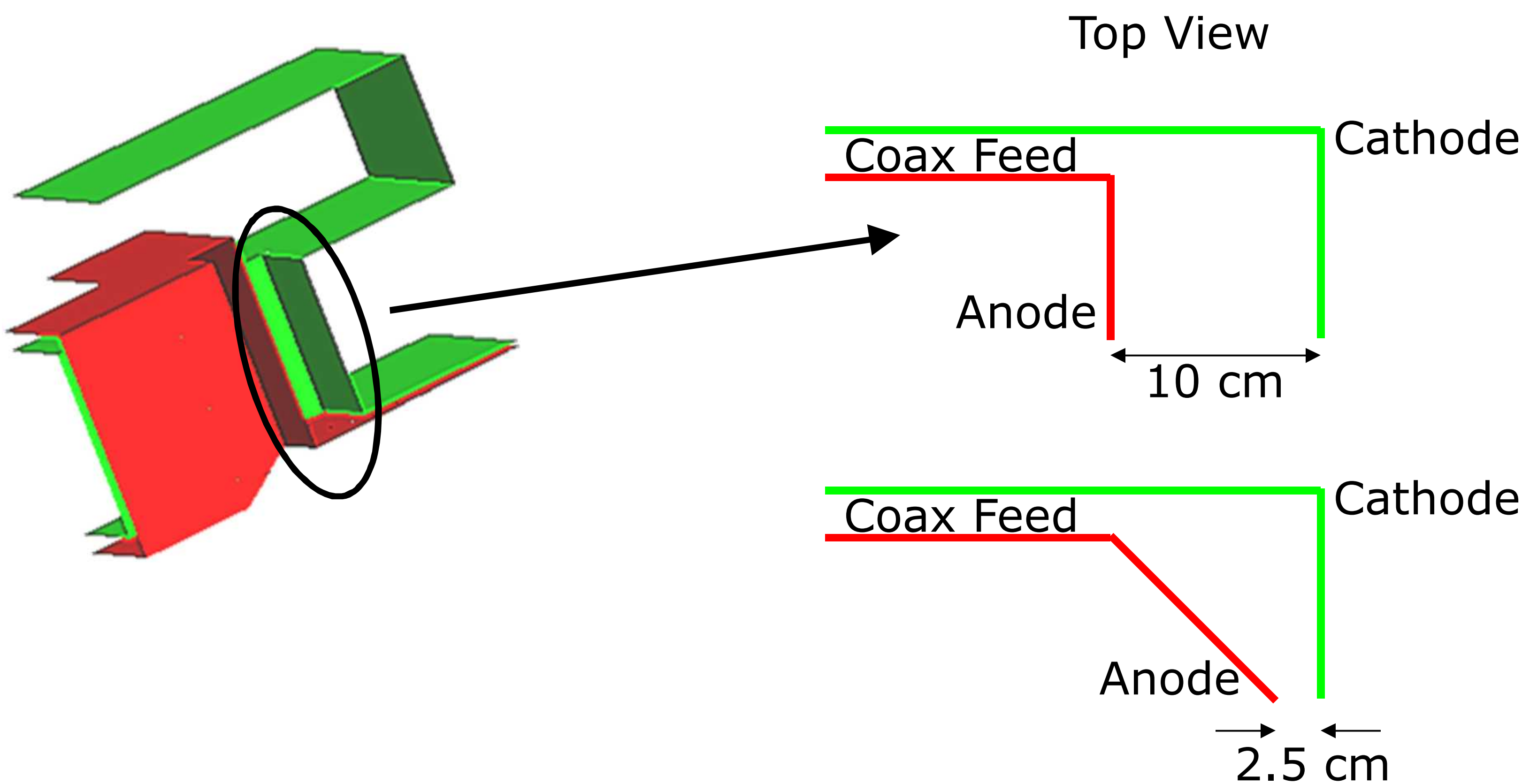
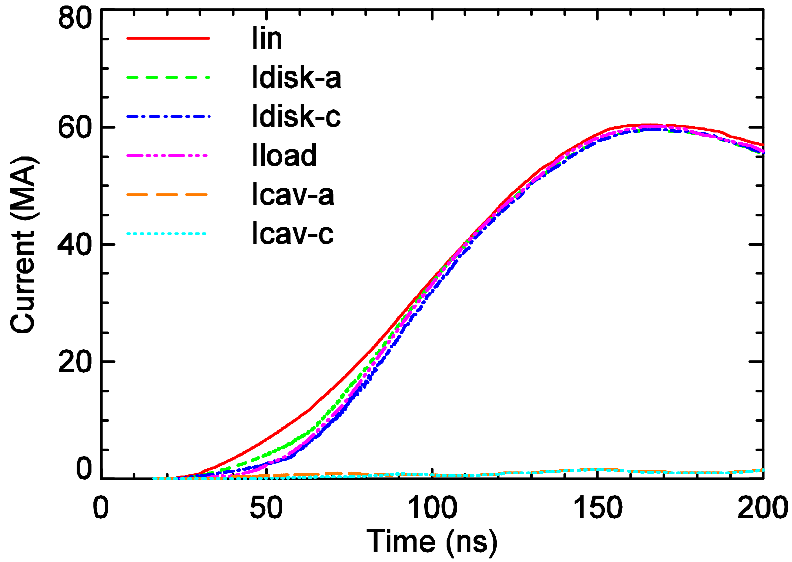
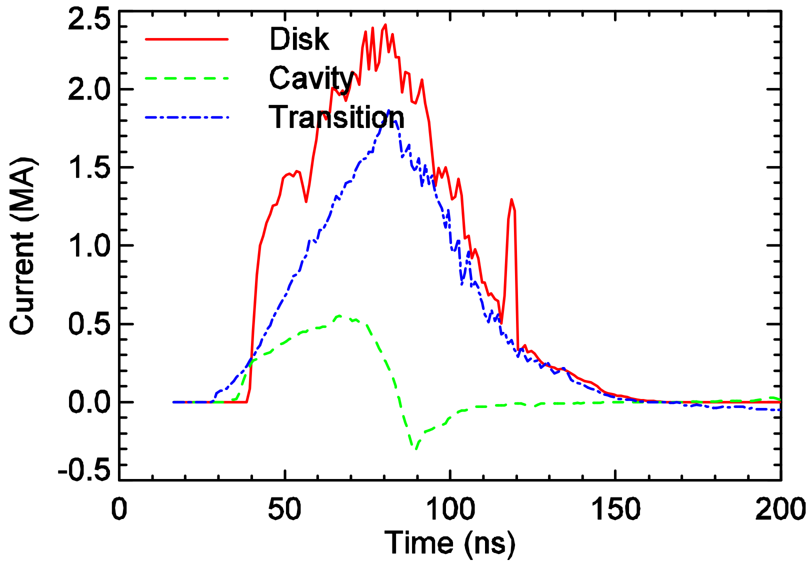
Transition Region Anode Reshaping



The current time histories are largely unaffected by the change . . .





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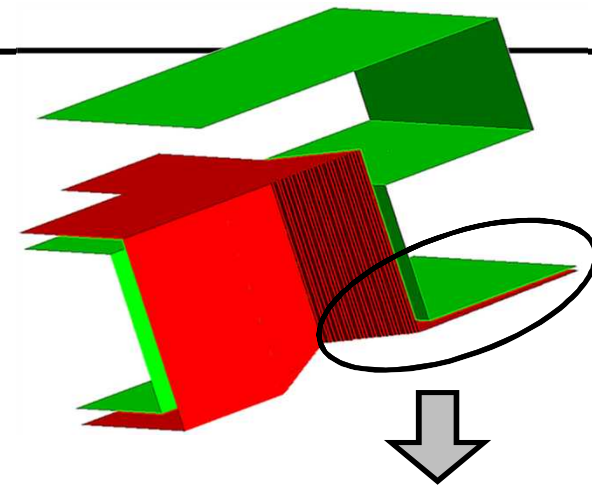
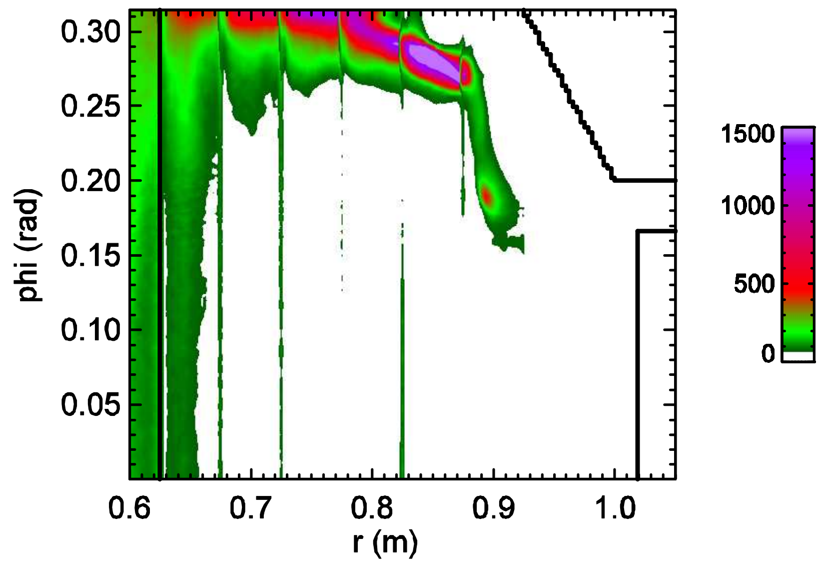
Anode temperature improvement

- Several attempts were made to improve the energy deposition to the anode in the disk and transition regions.
- Most of the changes to the anode and/or cathode yielded at least some modest improvement.
- Angling the anode such that the A-K gap is 2.5 cm (at $\phi = \phi_{max}$) in the transition section provided the best result.

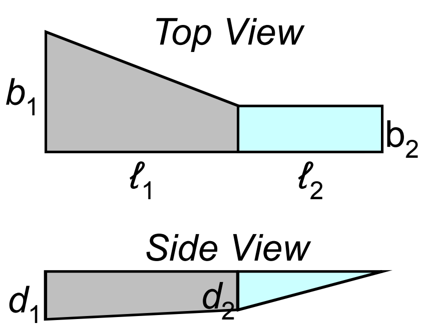




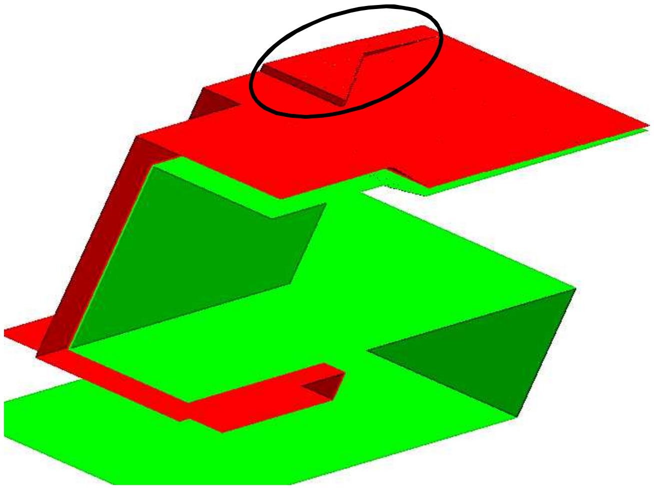
$T_{peak} \approx 3018°C$

Another strategy . . .

- Lengthening the A-K gap in the areas where the energy deposition is occurring has also been reported to help alleviate anode heating/damage‡
- In this case, we chose to use a combination of a triangular region and a rectangular region to cover the areas where we wanted to lengthen the A-K gap as shown below.



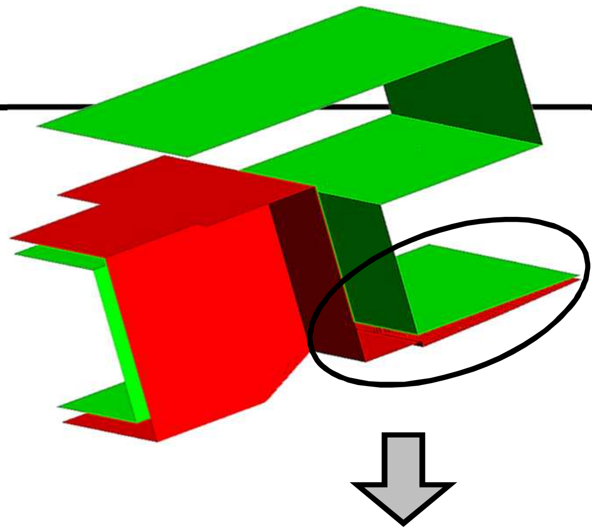
Dimensions
$b_1 \approx 114.2$ mm
$b_2 \approx 29.4$ mm
$\ell_1 = 143.75$ mm
$\ell_2 = 153.125$ mm
$d_1 = 13.5$ mm
$d_2 = 12$ mm

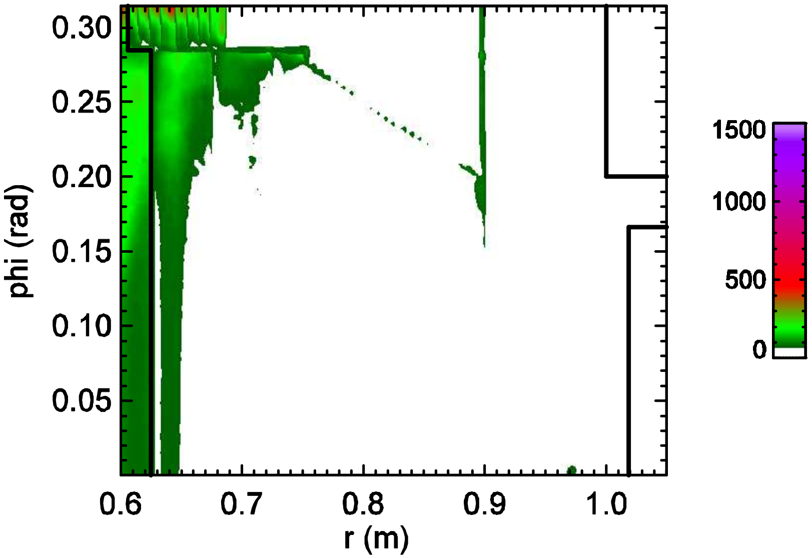


‡ C. W. Mendel, Jr., T. D. Pointon, *et al.* "Losses at magnetic nulls in pulsed-power transmission line systems," *Physics of Plasmas* **13**, 043105 (2006).

Drastic improvement!

- In this case, lengthening the A-K gap where the anode heating occurs leads to a drastic improvement in the peak anode temperature.
- Different configurations were used but this configuration yielded the best result for lowering the peak anode temperature.
- Lengthening the A-K gap did not change the current time histories appreciably.





$T_{peak} \approx 596°C$

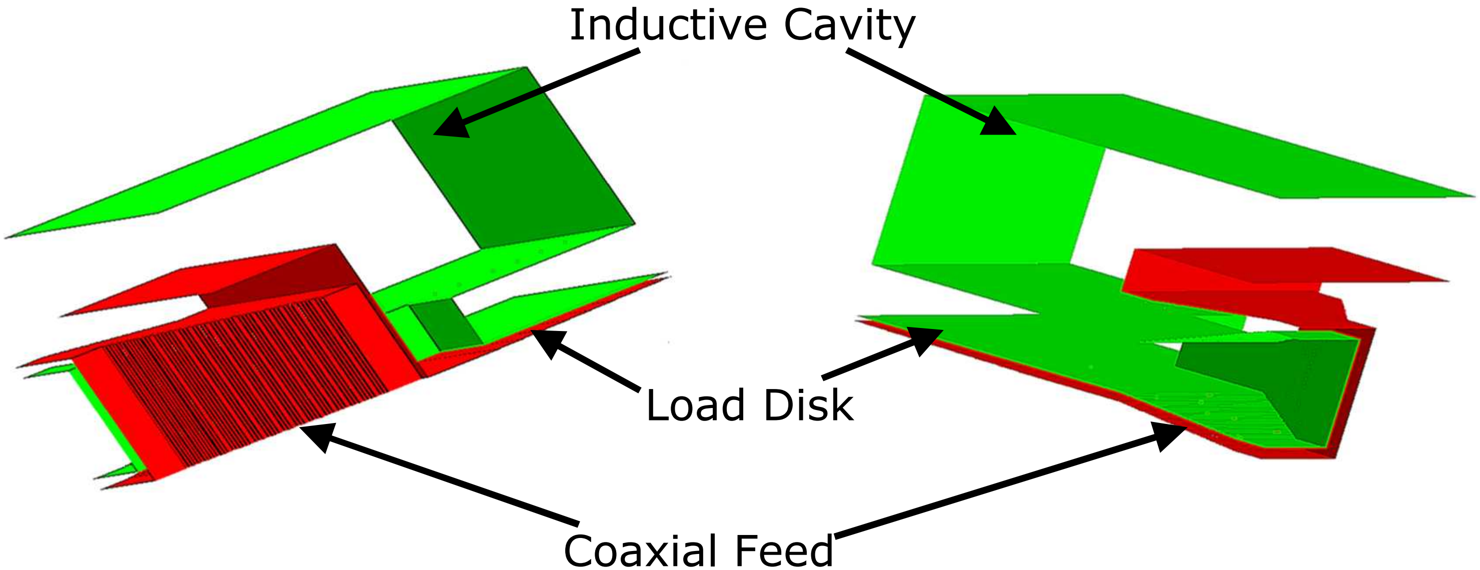
Modified Geometry

- One of the problems with the original geometry was the abrupt transition from the coaxial feed line to the disk MITL.

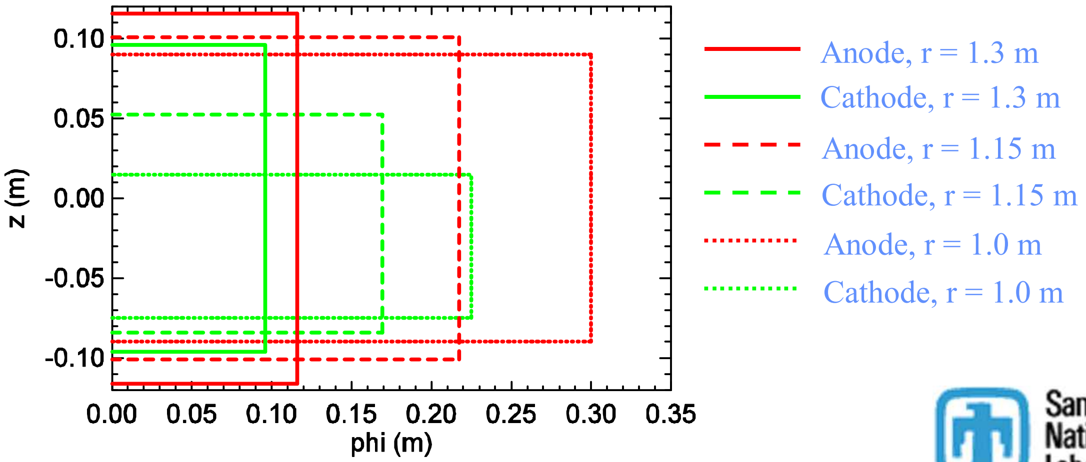
- One way to make this transition smoother is to begin the transition in the coaxial line before it connects to the disk section by widening and flattening it so the transition to the disk is less abrupt.

- This idea led to a new geometry that is similar to the previous geometry but incorporates a “morphing” coaxial line.

Modified Geometry



Coaxial Line Cross-section



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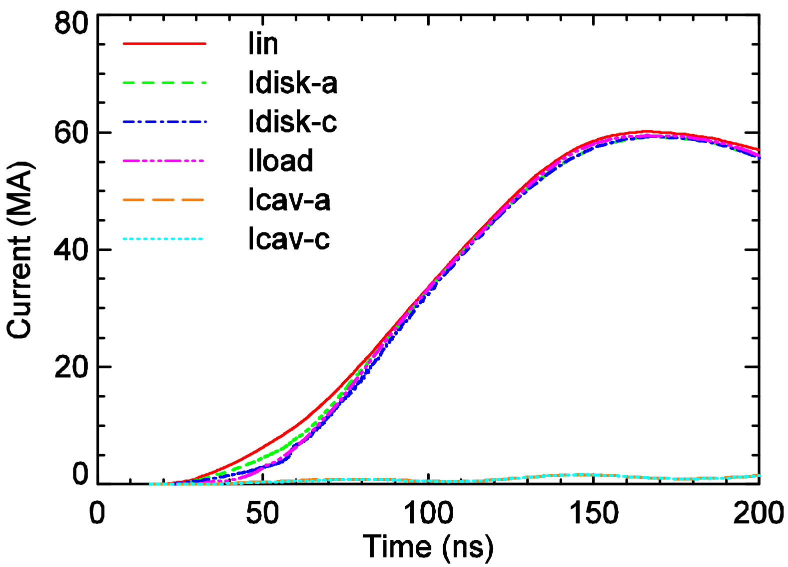
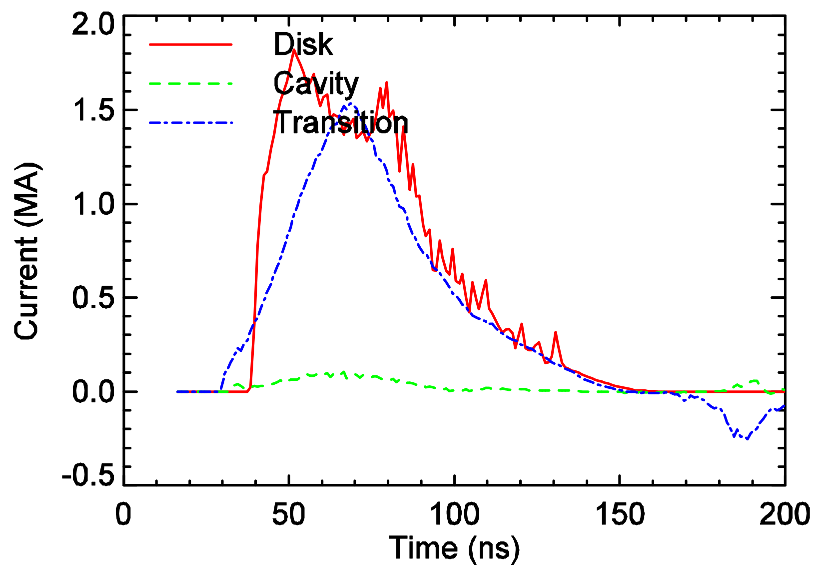
The current time histories are largely unaffected by the change again . . .



But the electron flow current has been reduced further by ~0.5 MA



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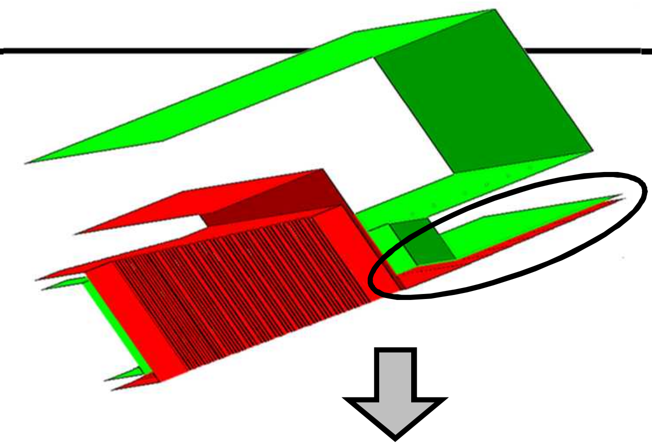
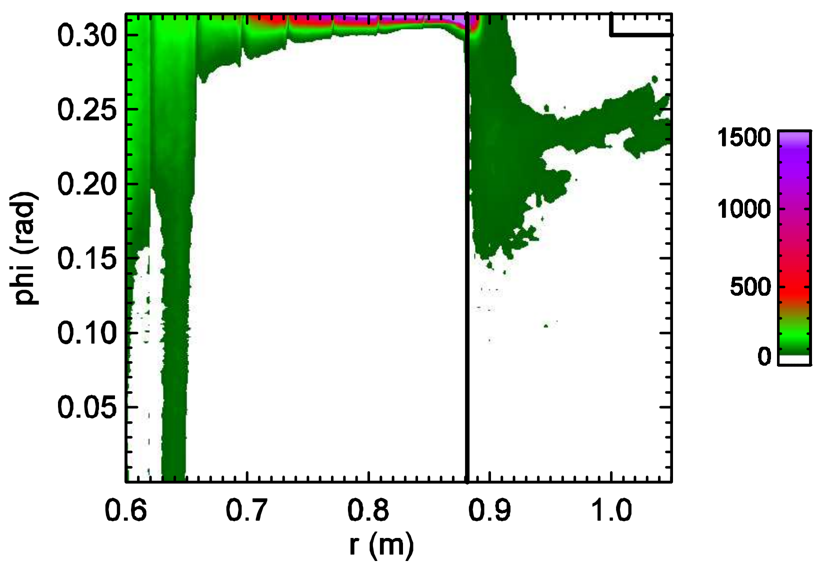
~24% reduction in peak temperature versus the original structure

- The anode heating is extreme but not as bad as the original 10-feed line structure.
- The area of anode heating is very localized to the area near $\phi = \phi_{\max}$ for $0.7 < r < 0.9$ m.
- The localization of the anode heating makes this structure a good candidate for lengthening the A-K gap in this area to reduce the anode heating.





$T_{peak} \approx 7592°C$

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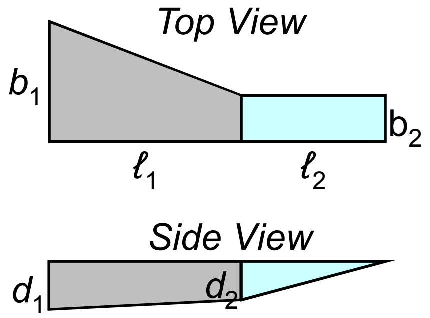
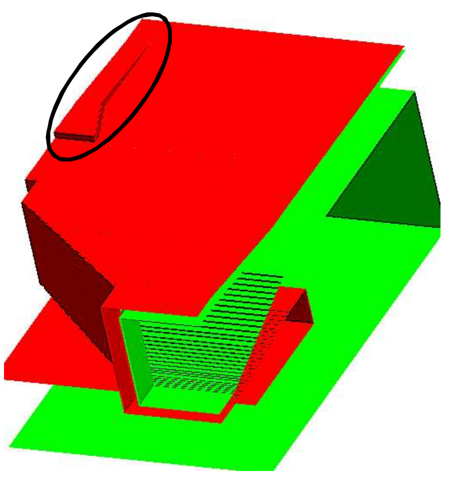
Lengthening the A-K gap . . .

- The same geometrical configuration is used as before but with different dimensions.
- For this structure the lengthening of the A-K gap does not need to cover as large an area to achieve the desired result.



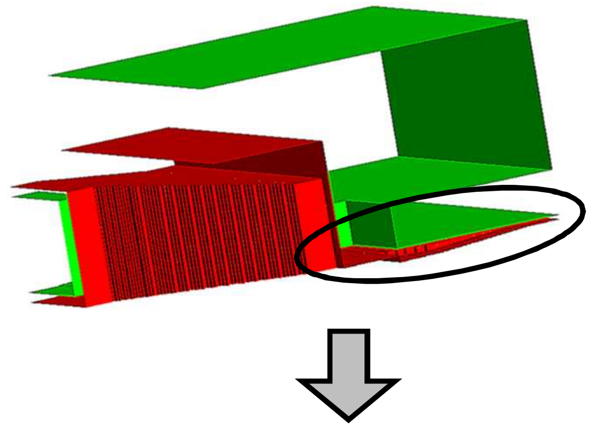
Dimensions

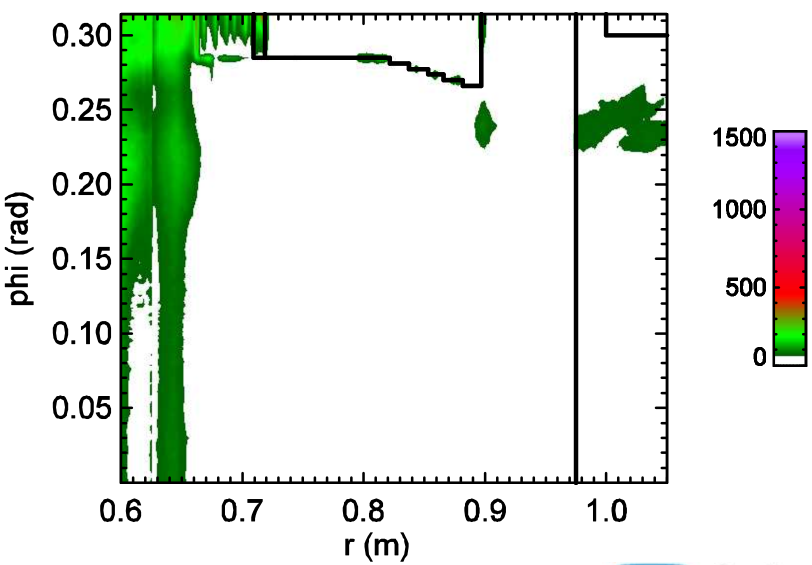
$b_1 \approx 47.9$ mm
$b_2 \approx 29.2$ mm
$\ell_1 = 75$ mm
$\ell_2 = 159.375$ mm
$d_1 = 13.5$ mm
$d_2 = 12$ mm



A-K gap lengthening works again

- Lengthening the A-K gap for this structure provided a similar reduction in peak anode temperature.
- The structure without gap lengthening saw a decrease of ~24% (versus the original 10-feed structure)
- The peak anode temperature for this structure has decreased by a similar amount (~26% versus the original 10-feed structure with gap lengthening)





$T_{peak} \approx 443°C$

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Conclusions

- The simulation results show that switching to a 10-feed line structure (versus a 70-feed line structure) yields a vast improvement in (lowering of) the electron flow current.
- Unfortunately, this reduction in electron flow current only translates into a modest improvement in the energy deposition on the anode in the transition and disk regions.
- A couple of different methods of reducing this energy deposition were simulated with largely good results.
- The best results were obtained by lengthening the A-K gaps in the localized areas where anode heating was occurring.
- Anode temperatures as low as ~ 440°C have been achieved in simulations using this technique.
- Even better results may still be possible by moving the disk transition out to larger radius or by using more complex models with smoother conductor surfaces and transitions.

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