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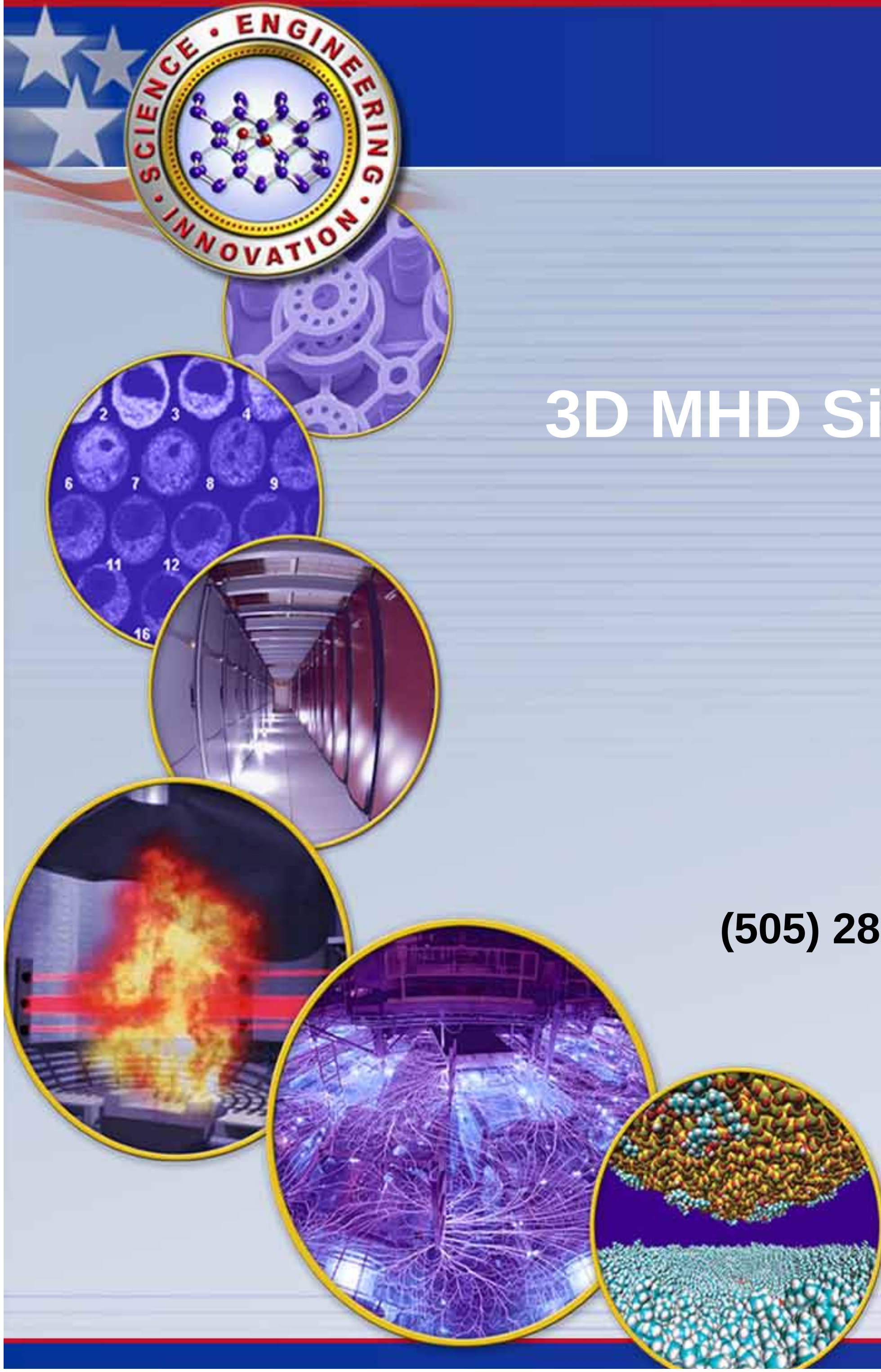

3D MHD Simulations of Wire Array Z-pinches

UCSD seminar

Chris Jennings

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Sandia National Laboratories

Acknowledgements / Outline

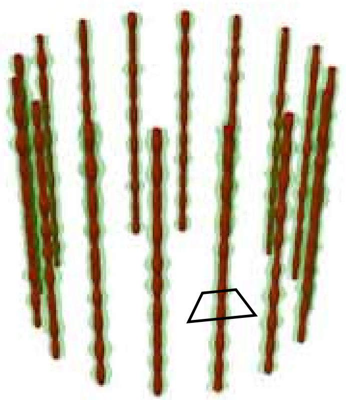
Acknowledgements:

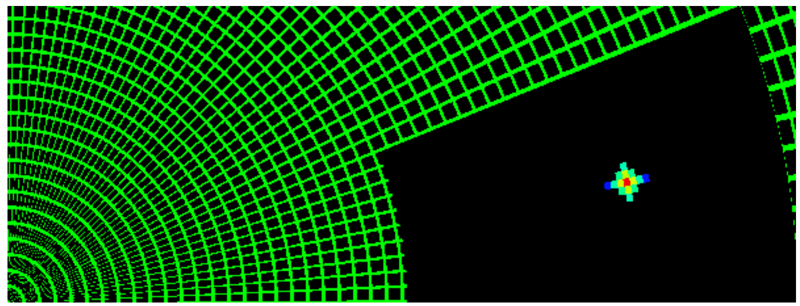
Jerry Chittenden, Mike Cuneo, Ray Lemke, Tim Pointon, Eduado Waisman, Mike Jones

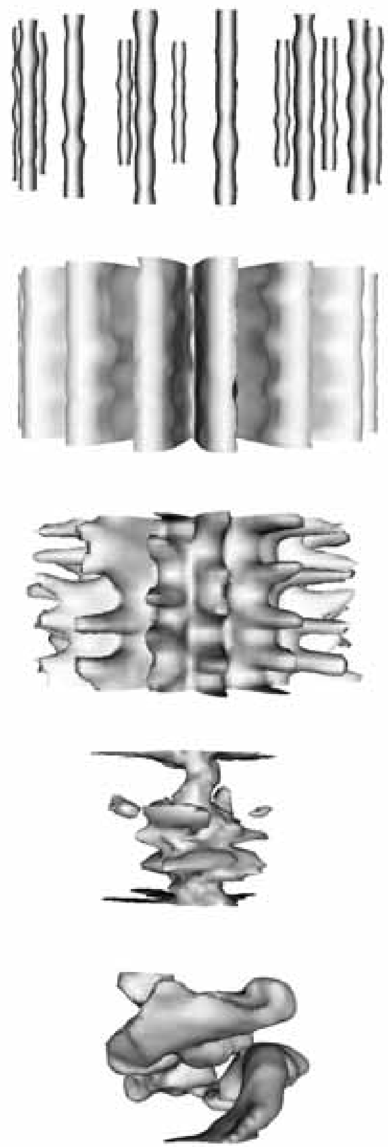
Outline

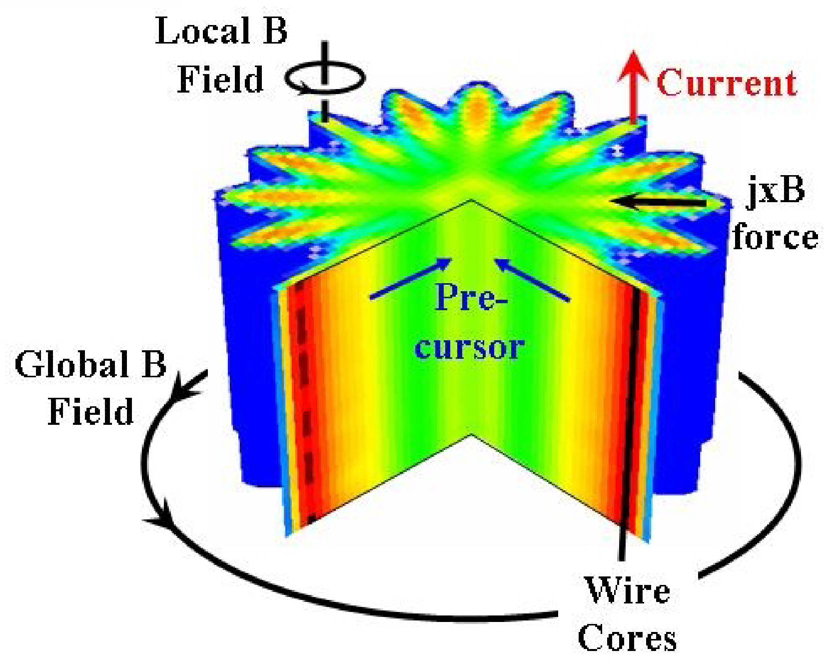
- **Introduce MHD code gorgon**
- **Transmission Line Circuit model**
- **Phenomenological convolute model**
- **Modeling of Mass Scan**
- **Modeling ZR shot 1787**
- **Return to Mass Scan**
- **Comparison with Radiography**
- **Modeling nested arrays**

Wire Array Z-pinch on MAGPIE (~1MA)

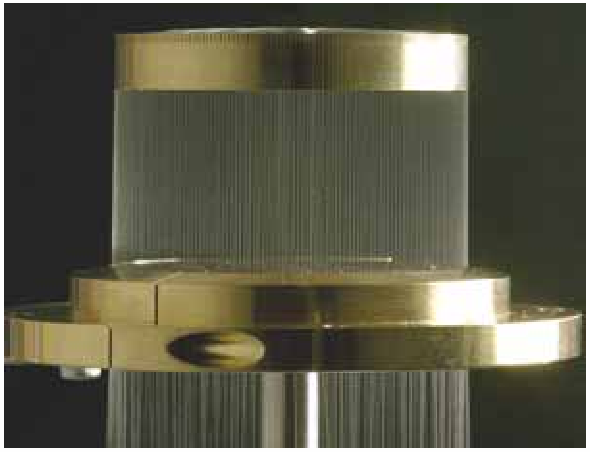


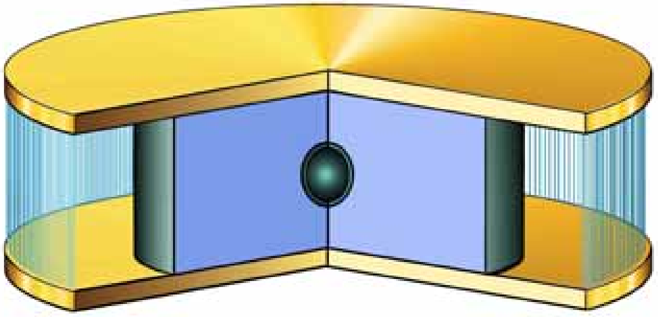


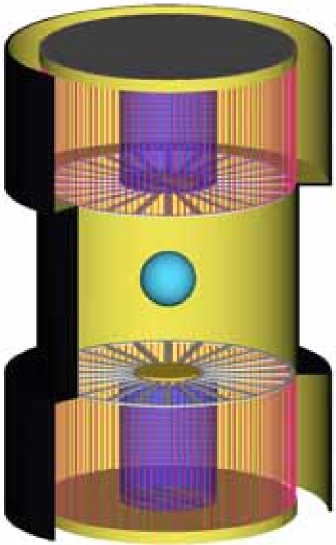




Wire Array Z-pinch on Z







Modelling the Z-pinch

GORGON – 3D Resistive MHD

Fixed square grid finite volume hydrodynamics

Single fluid – separate electron and ion temperatures

Explicit electro-magnetic field solution (wave equation in vacuum / diffusion equation in plasma)

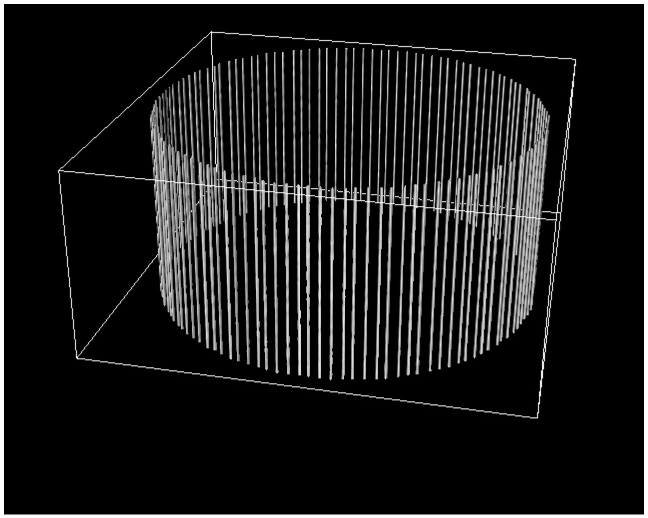
Thomas-Fermi Ionization

Van Leer Advection

Constrained Transport for Magnetic Field Advection

Single group radiation diffusion (not used for these calculations)

Simulation Setup



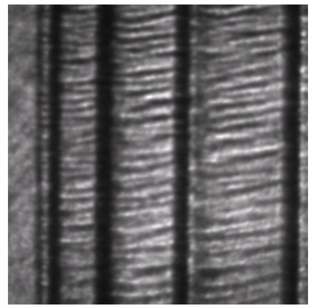
3D Full Circumference Calculation

•120 wires substituted for 300 in simulation

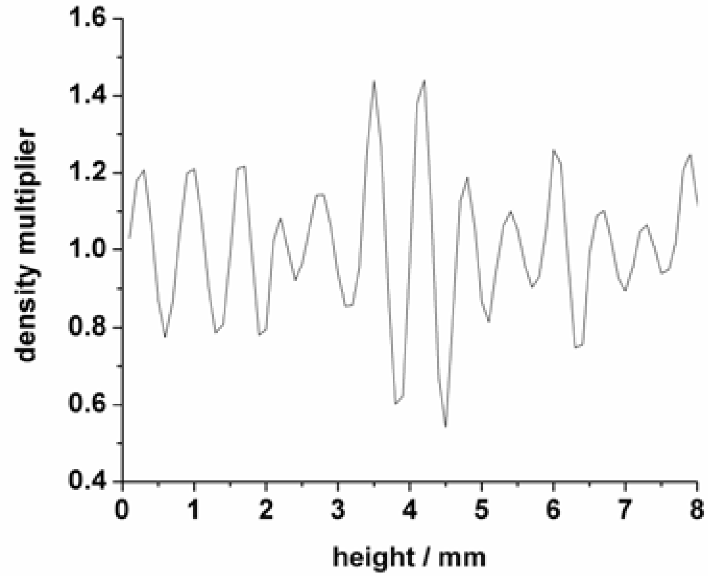
•Computational box 10 x 24 x 24 mm

•Cell resolution – 110 micron square cells

•2 – 4 day runtime on 16 nodes



Initial wires given a mass perturbation in the axial direction to mimic ablation structure

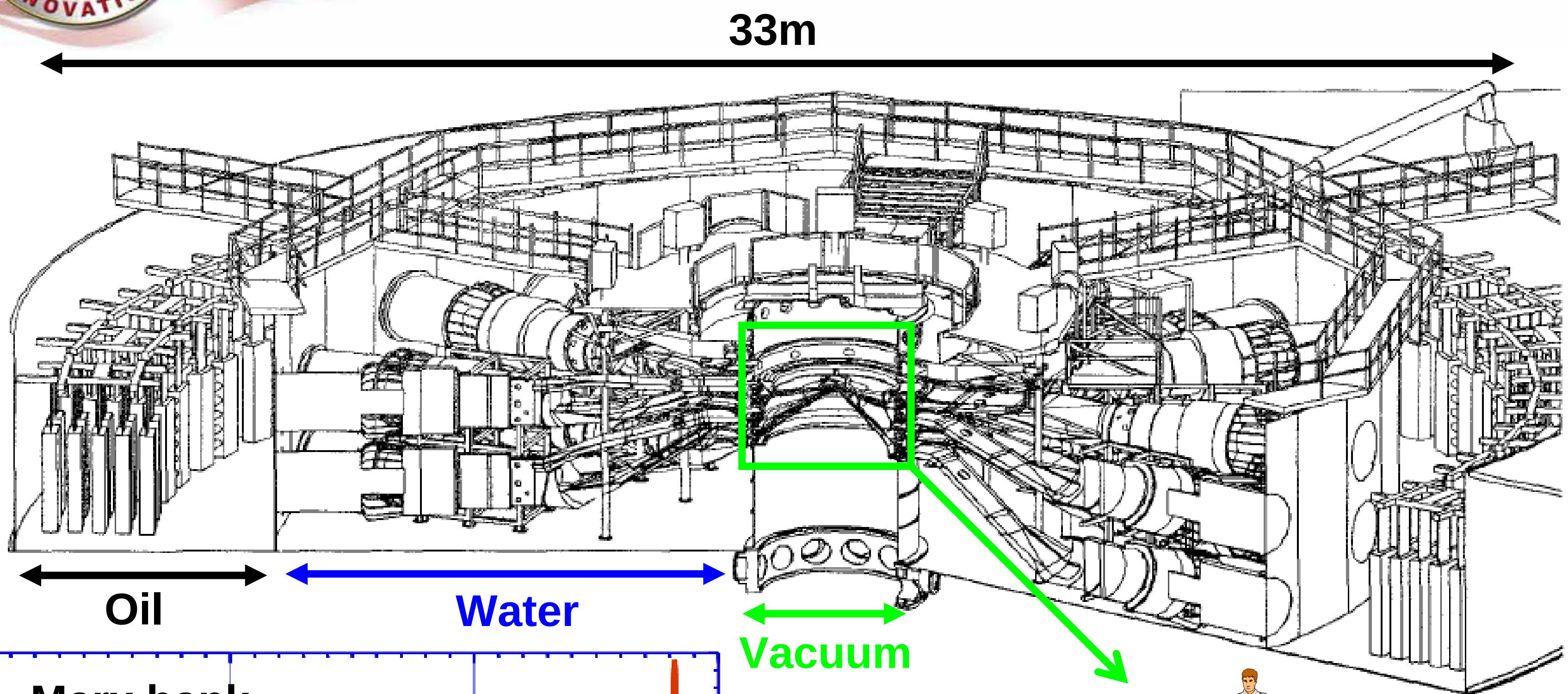


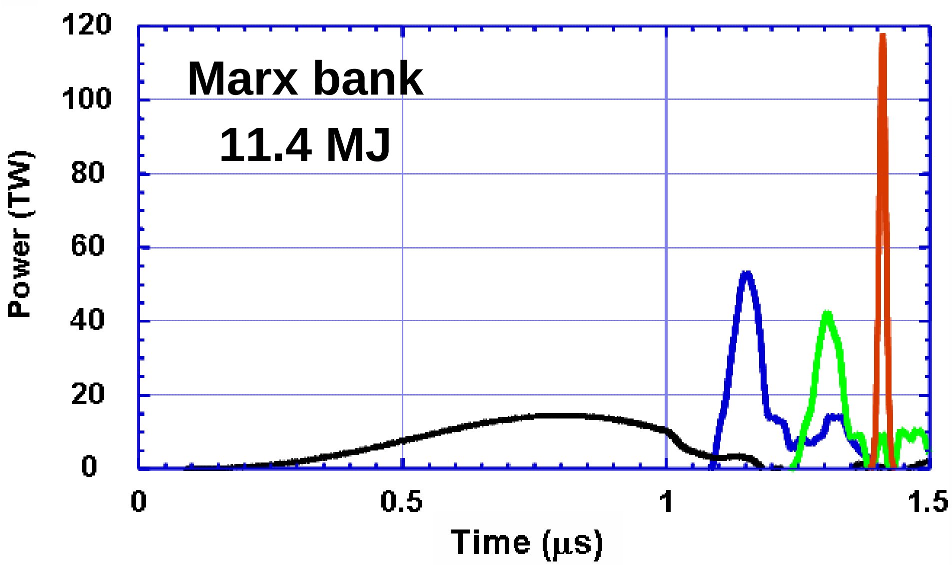
Example density perturbation file

+/- 5 % mass perturbation used

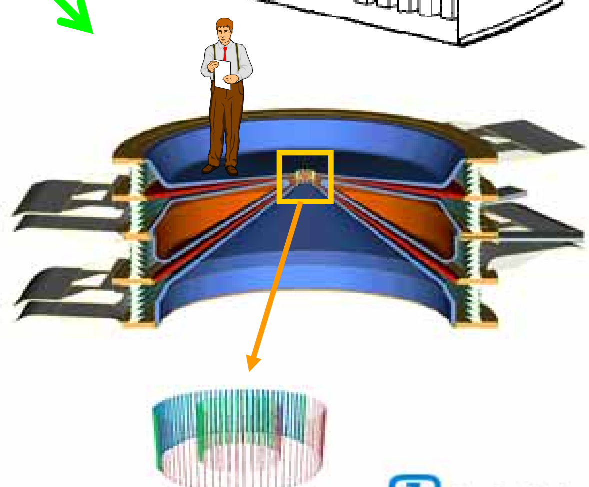
Numerical sensitivities exist, e.g. resolution / vacuum cut-off / artificial viscosity, but MHD model is now fixed – no parameters are changed or tweaked. Only the initial array mass is varied in accordance with what was fired

The Z Generator





X-rays
>1.5 MJ
>250 TW
η ~ 15%
(electrical to x-ray)



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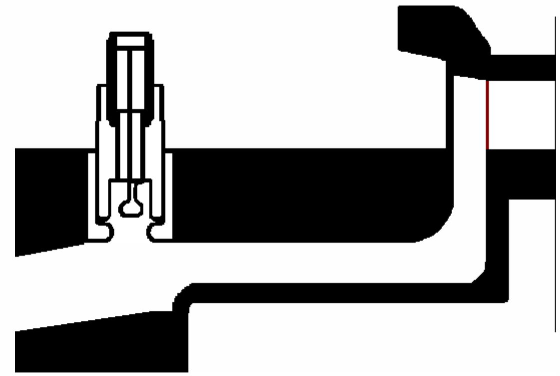
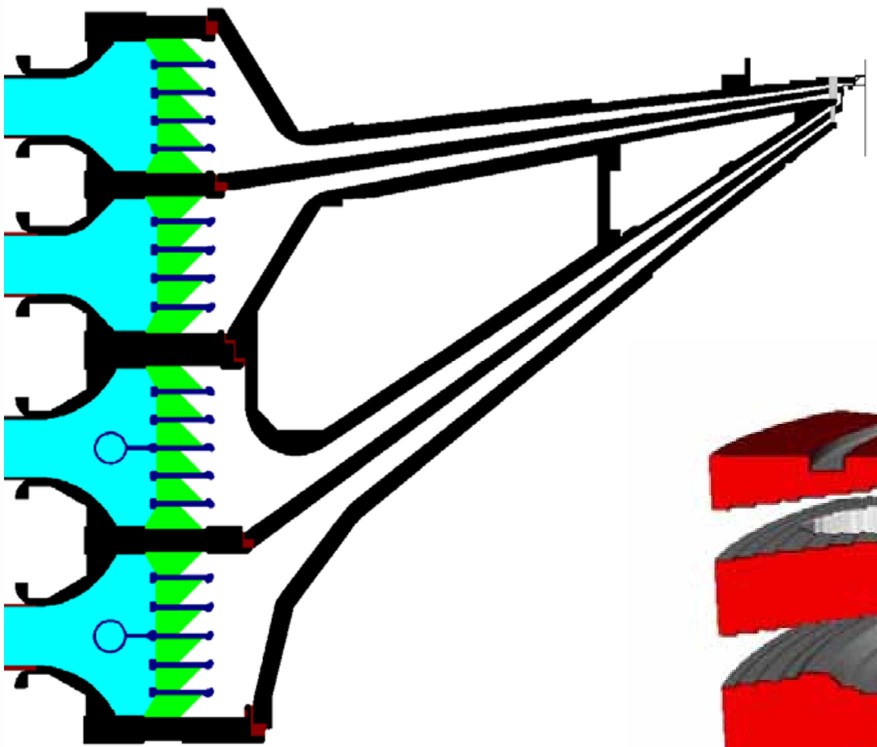
Hardware to include in the model

Feed to load



4 level MITL

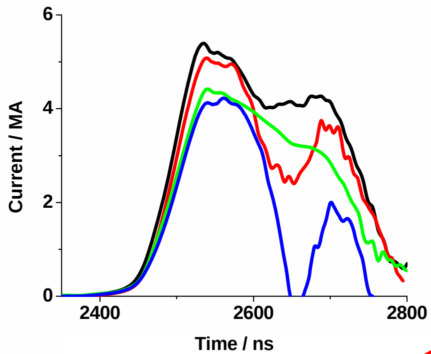


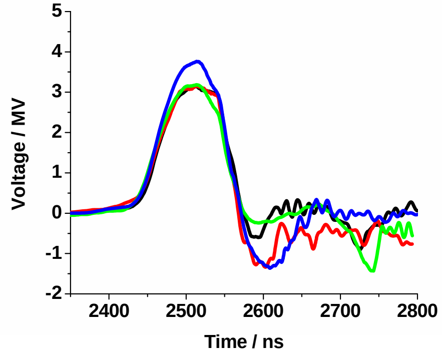
Double post hole convolute

Wire Array Z-pinch

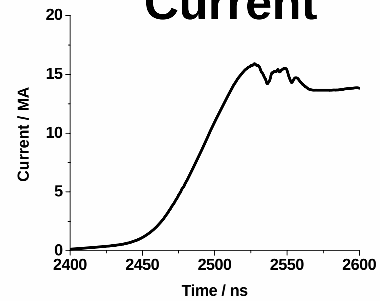
Measurements to Use and Compare Against

Stack Current / Voltage

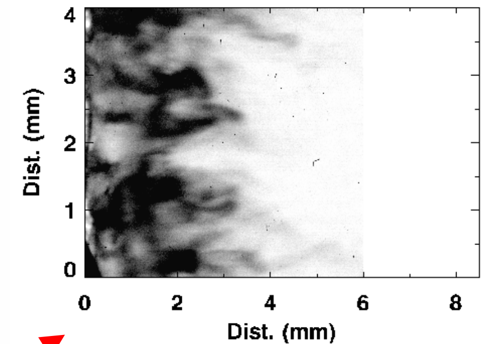


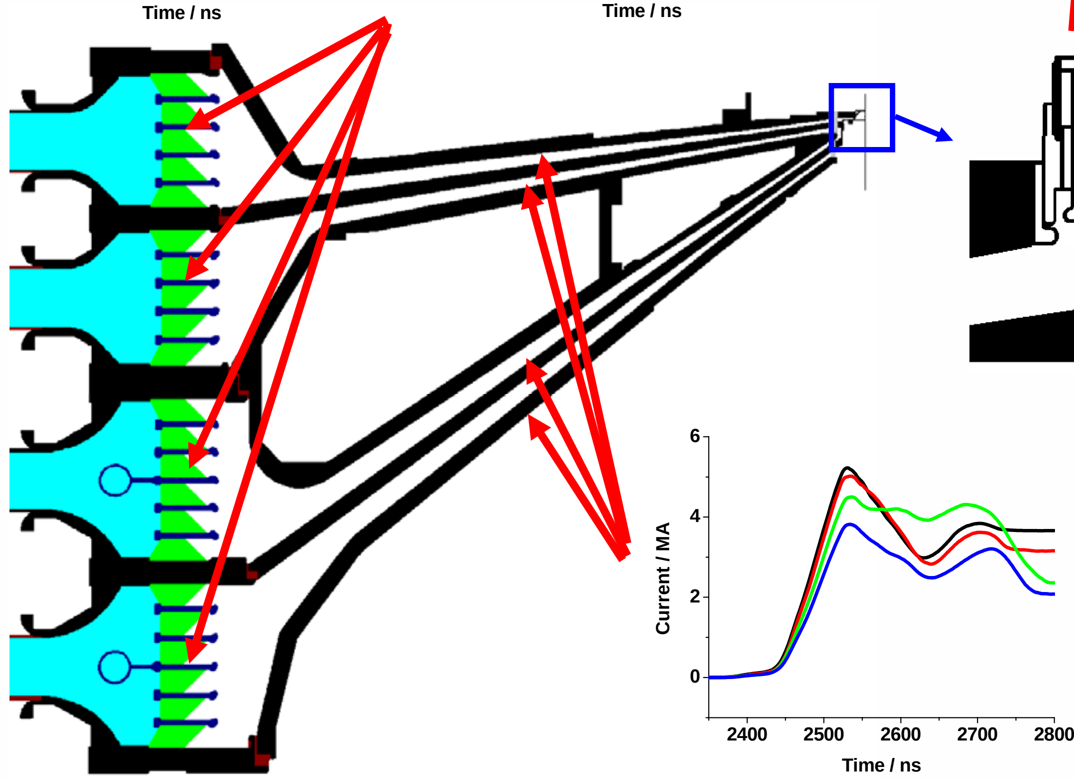


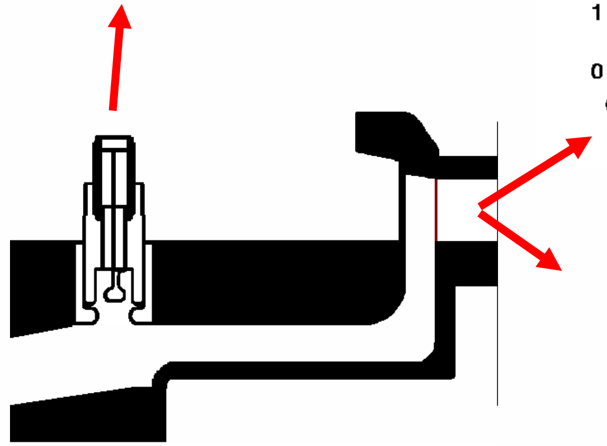
Load Current

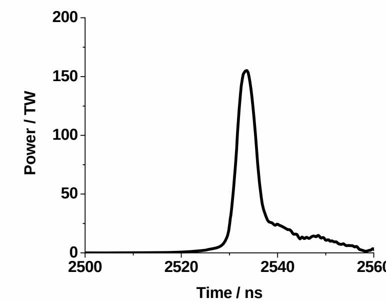


Radiography









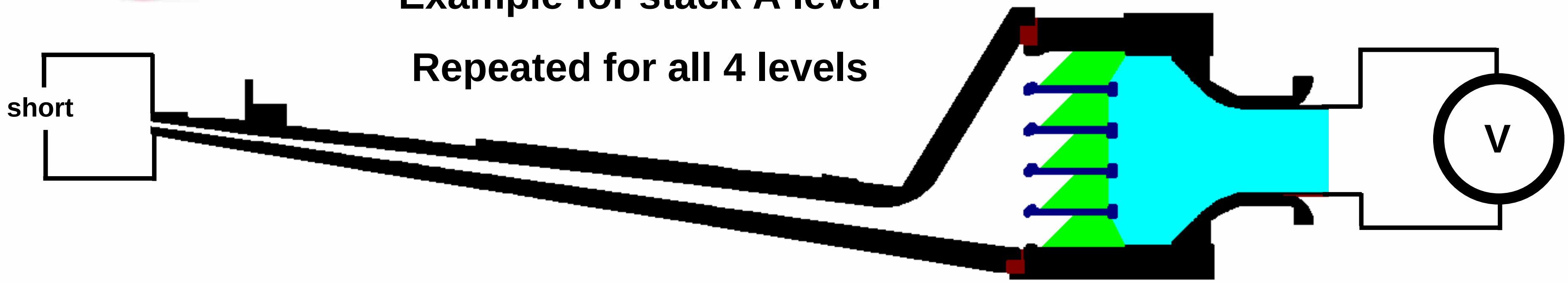
X-ray

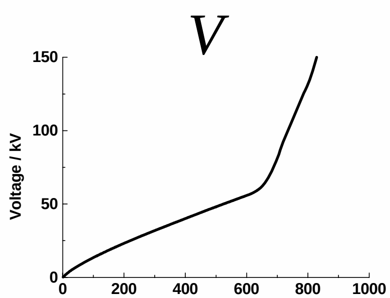
MITL Currents

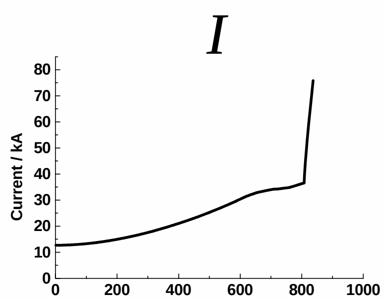
Electrode Configuration reduced to lumped element transmission line through EM simulation

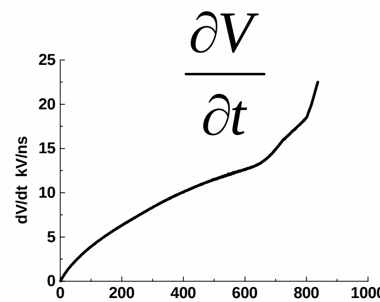
Example for stack A level

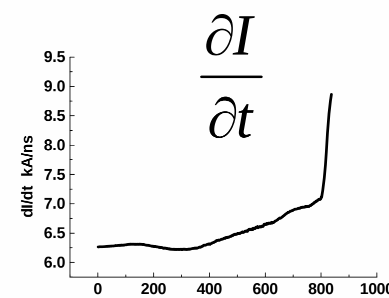
Repeated for all 4 levels







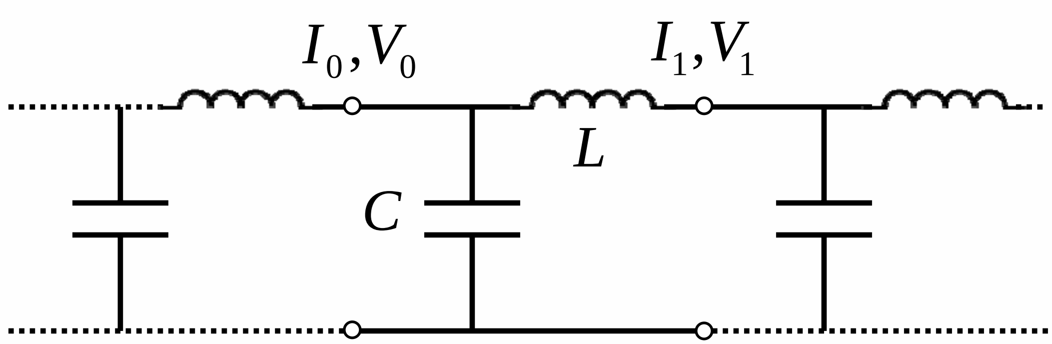




Telegraphers Equation

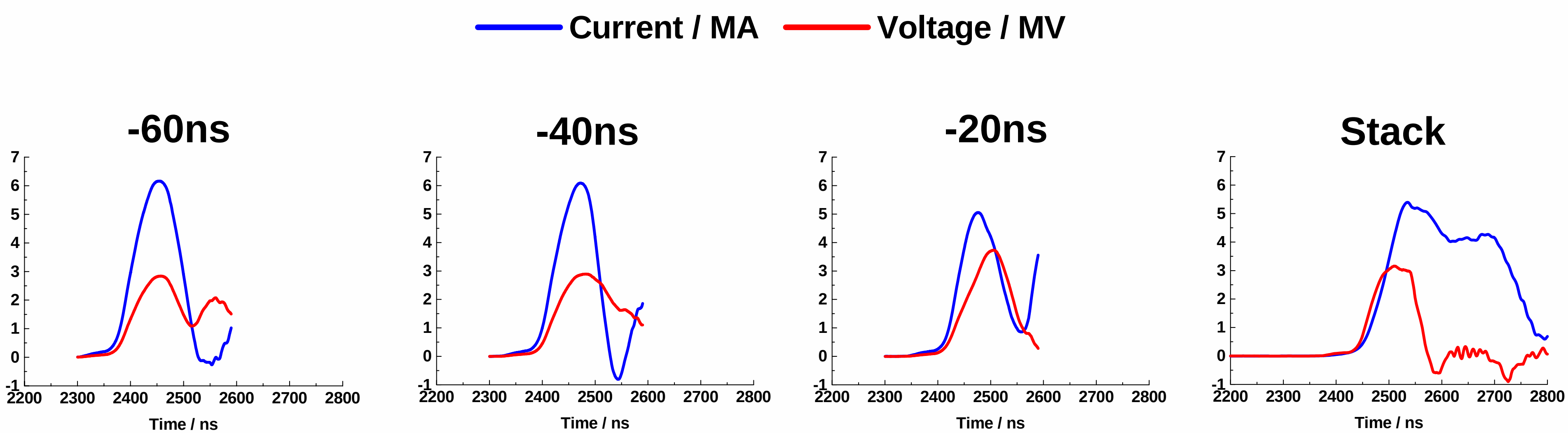
$$I_1 = I_0 - C\Delta r \frac{\partial V_0}{\partial t}$$

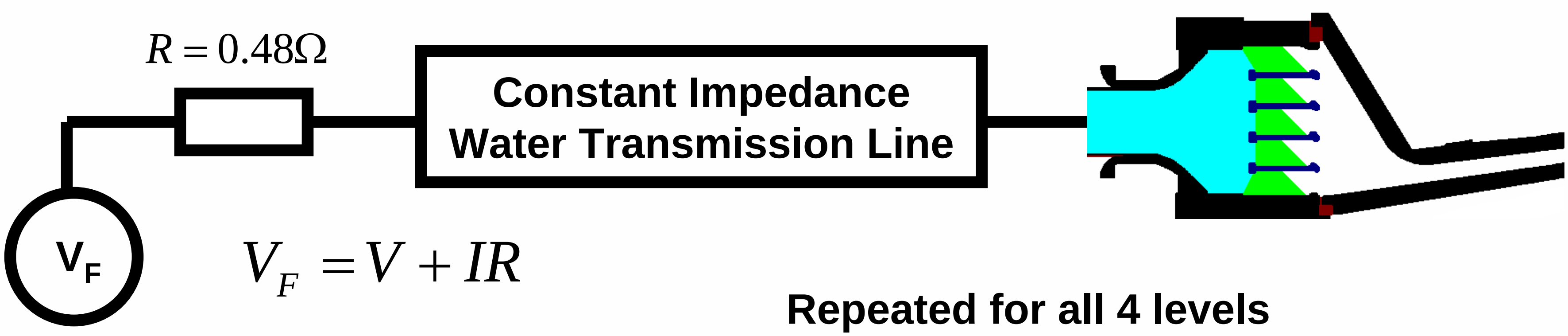
$$V_1 = V_0 - L\Delta r \frac{\partial I_1}{\partial t}$$



Lumped element transmission line

Voltage Source translated from stack measurements

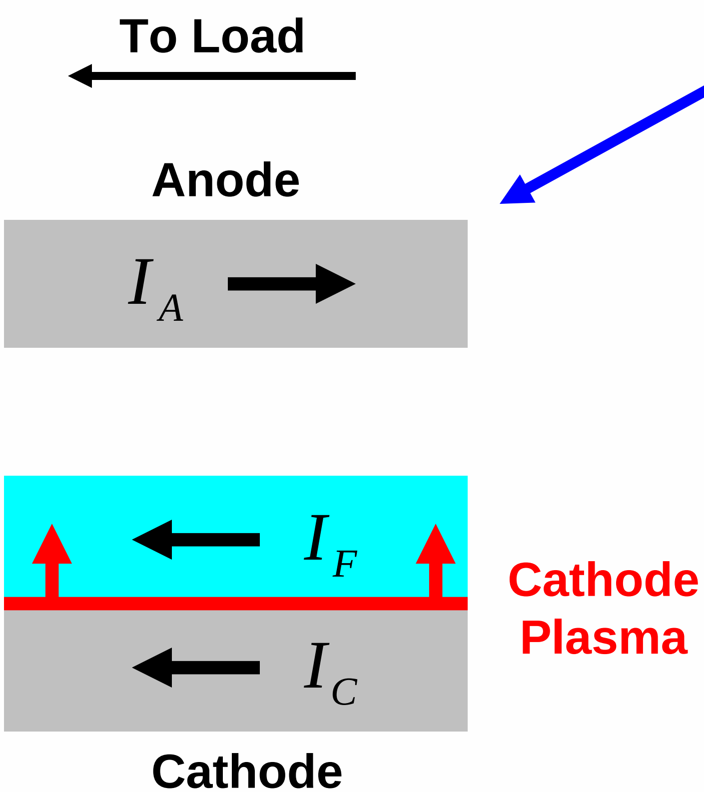




$$V_F = V + IR$$

Repeated for all 4 levels

Electron Flow in Transmission Lines



- Cathode plasma forms for E > 250kV/cm
- Emits electrons which are magnetically confined forming electron flow layer
- Electrons in electron flow layer ExB drift towards load region

$$I_A = I_C + I_F$$

$$V = Z_0\sqrt{I_A^2 - I_C^2} - \frac{mc^2}{2e}\frac{\left(I_A^2 - I_C^2\right)}{I_C^2}$$

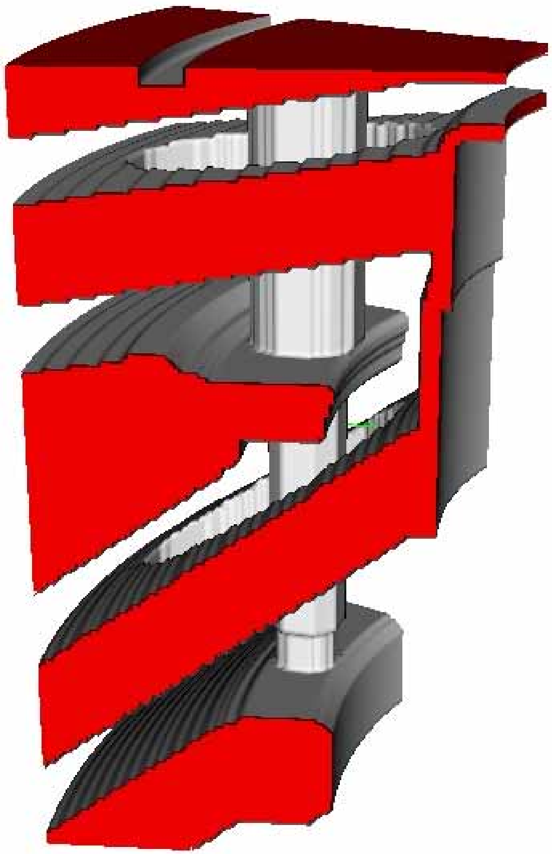
Mendel's Pressure Balance

Corrected for cathode plasma expansion

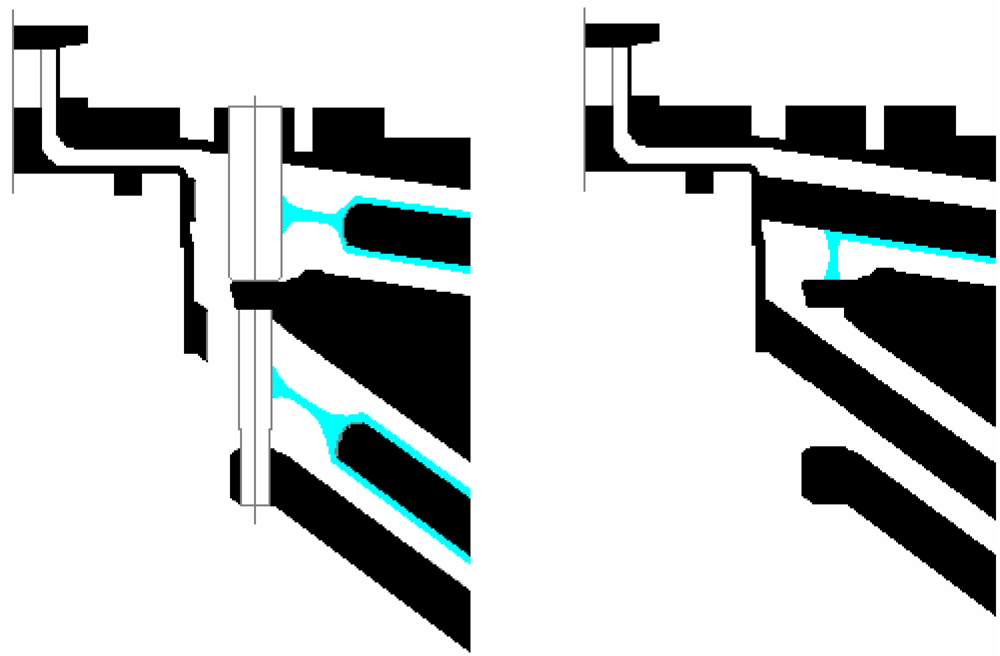
(Stygar 1997 IEEE Proceedings 11th international pulsed power conference pg. 591)

$$V = Z_0\left(1 - \frac{vt}{g}\right)\sqrt{I_A^2 - I_C^2} - \frac{mc^2}{2e}\frac{\left(I_A^2 - I_C^2\right)}{I_C^2}$$

Electron flow current lost through magnetic nulls

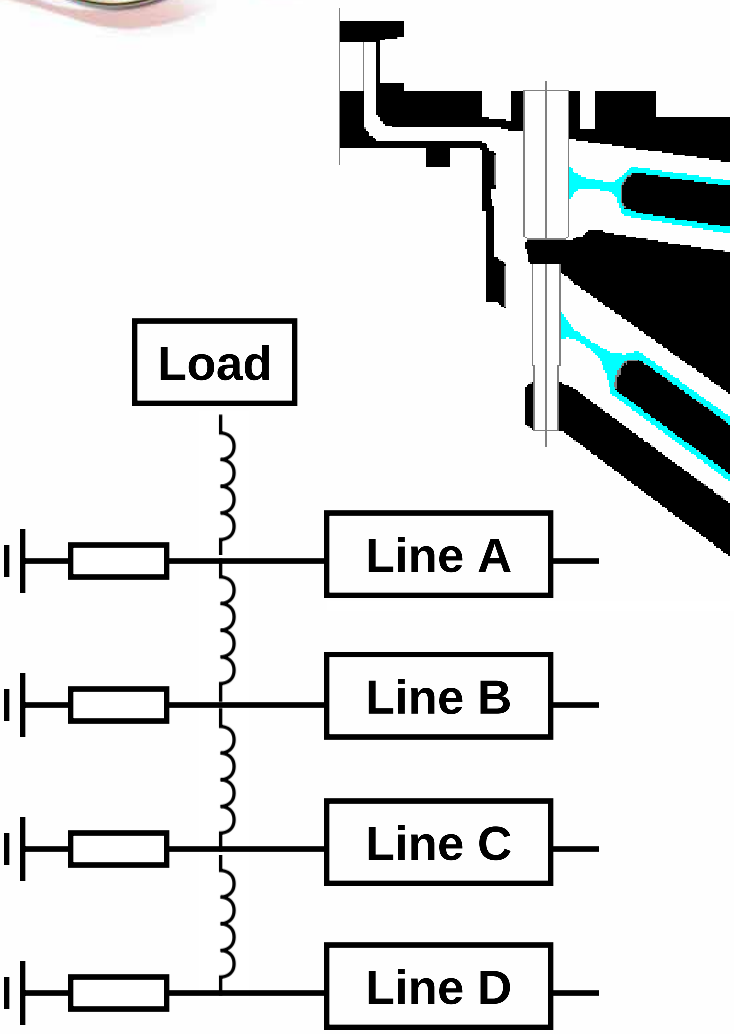


Current added through double post hole convolute



Magnetic insulation breaks down at magnetic nulls, so electron flow current is lost to the anode

Flow loss characterized by 4 loss resistances for the end of each line



$$Z_f = \frac{V}{\sqrt{I_A^2 - I_C^2}} \qquad Z_v = Z_0\left(1 - \frac{vt}{g}\right)$$

$$V = Z_v\sqrt{I_A^2 - I_C^2} - \frac{mc^2}{2e}\frac{\left(I_A^2 - I_C^2\right)}{I_C^2}$$

$$Z_f = \frac{Z_v}{2} + \frac{Z_v}{2}\left(1 - \frac{2mc^2V}{eZ_v^2 I_C^2}\right)$$

P. Ottinger, Phys Plas 13, 063189

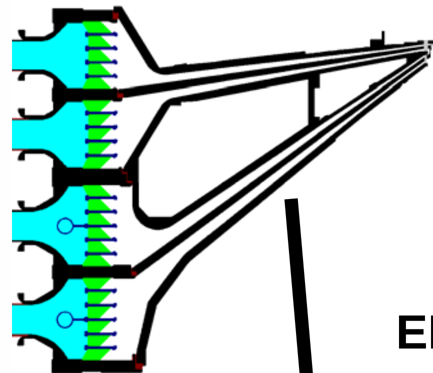
If all electron flow current lost then downstream current is just the cathode current and upstream is the total current

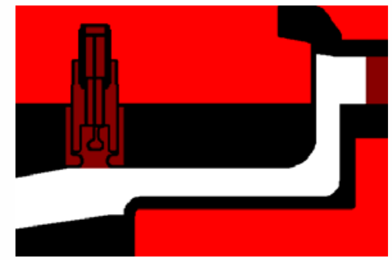
$$R = \frac{Z_f}{\alpha}\sqrt{\frac{I_{up} + I_{down}}{I_{up} - I_{down}}}$$

Simplified convolute model is fast to run with MHD

Simple circuit replaced by 4 line equivalent

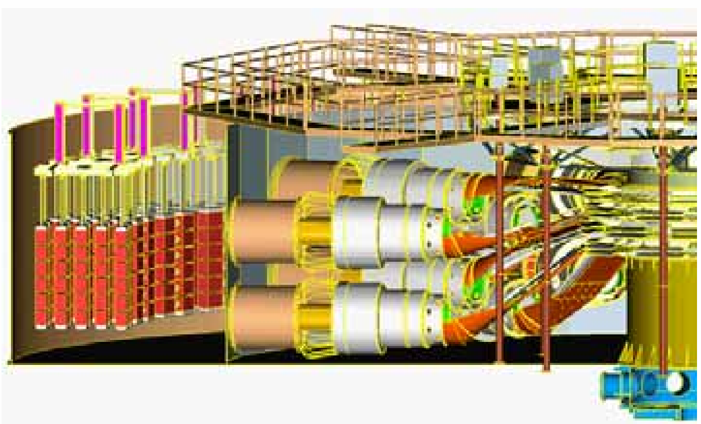
Constant impedance water line

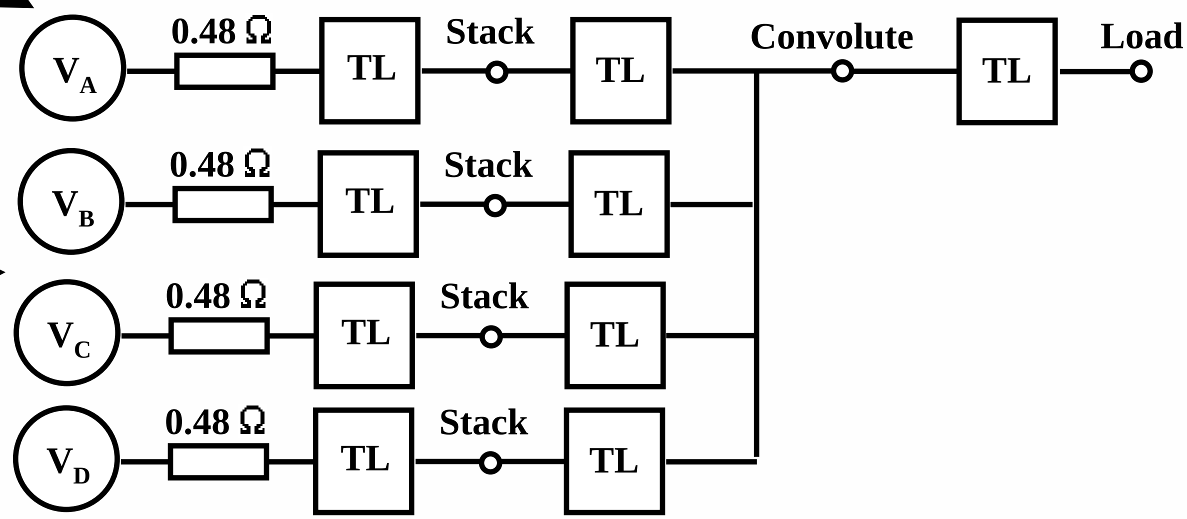




Reconstructed from stack measurements

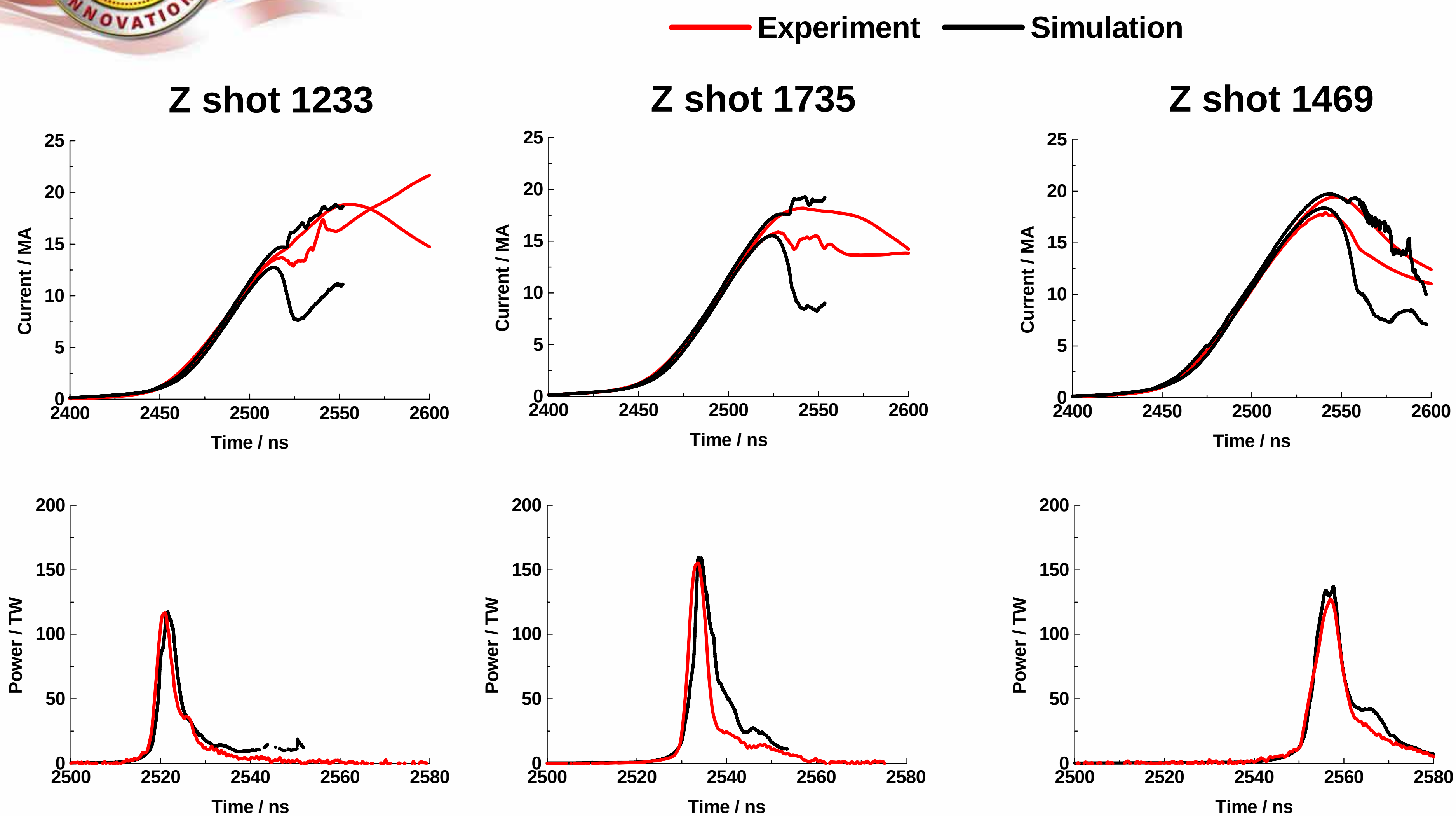
EM calc.





Circuit parameters calculated from hardware and measurements – main unknown is the cathode plasma expansion velocity

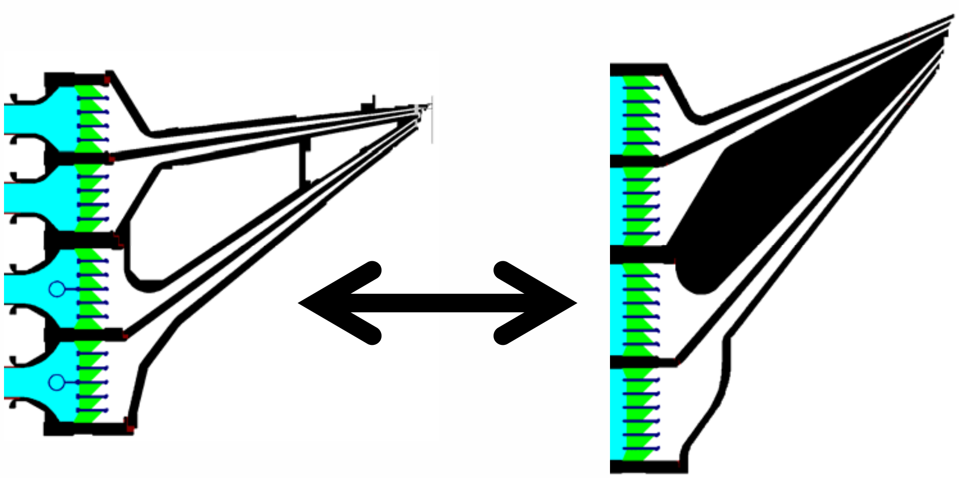
Mass scan assuming cathode plasma expansion rate of 7 cm / micro s

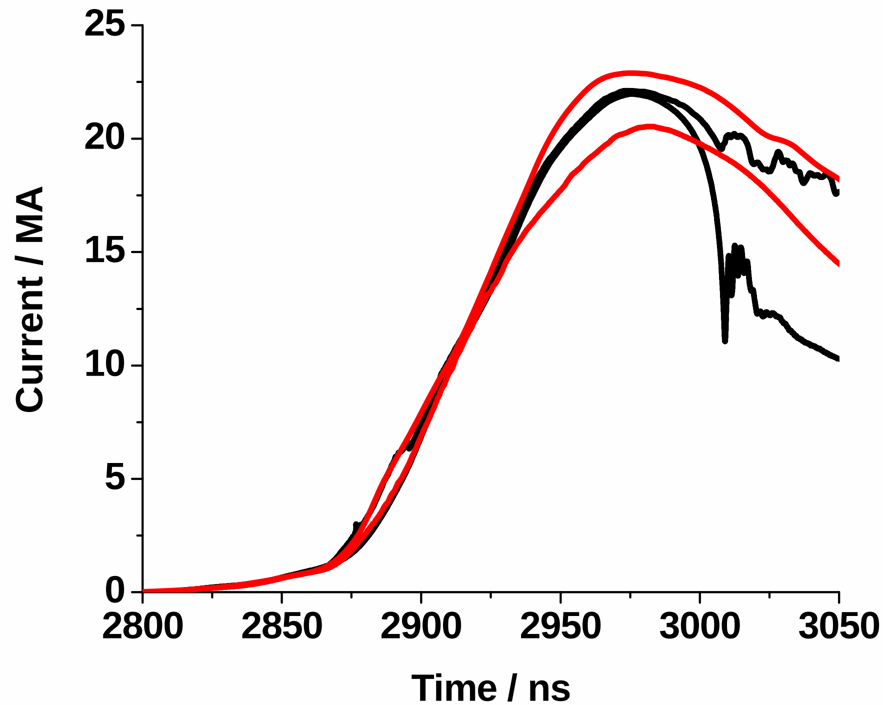


Good agreement but cathode plasma expansion velocity a bit high. Should perhaps be nearer 2.5 – 3 cm / micro s

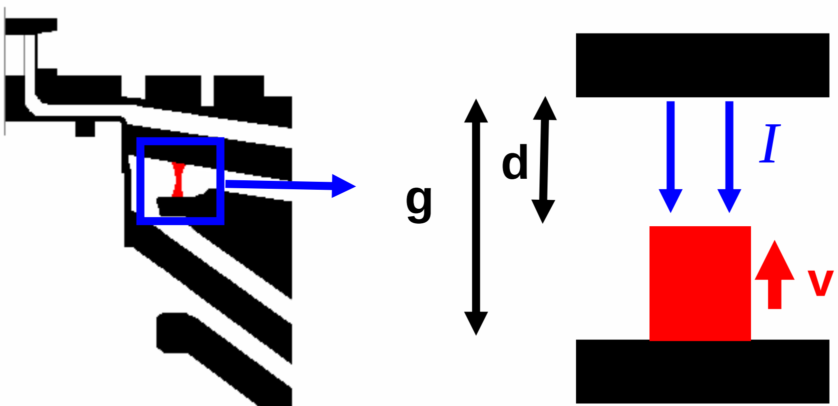
Electron flow insufficient to explain ZR shot 1787 (19.5mg single array) ZR data M. Jones

Swap out hardware in the code for ZR and recalculate voltage source from stack measurements taken back through a constant impedance water line





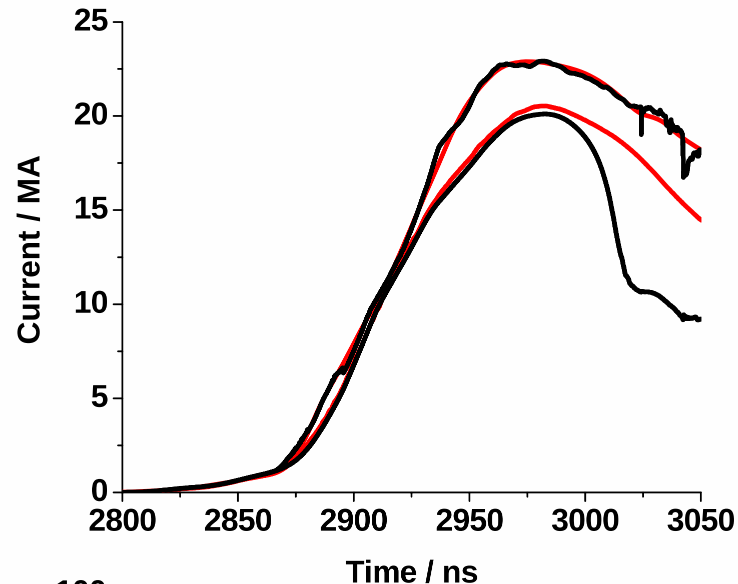
Invoke resistive short closing at 20 cm / micro s to recover correct circuit behavior and x-ray pulse

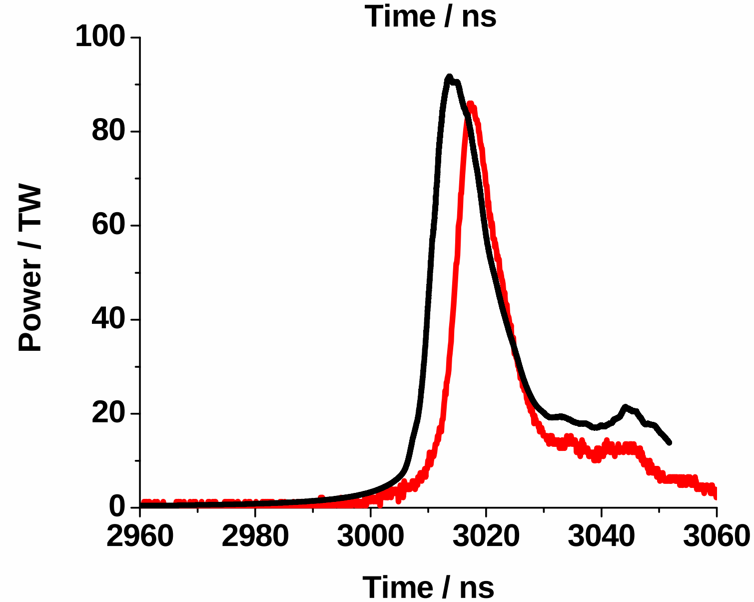


$$\eta = 0.04$$

$$I = \frac{AkV^{1.5}}{d^2}$$

$$R = \frac{d^2}{Ak\sqrt{V}} + \frac{\eta(g-d)}{A}$$





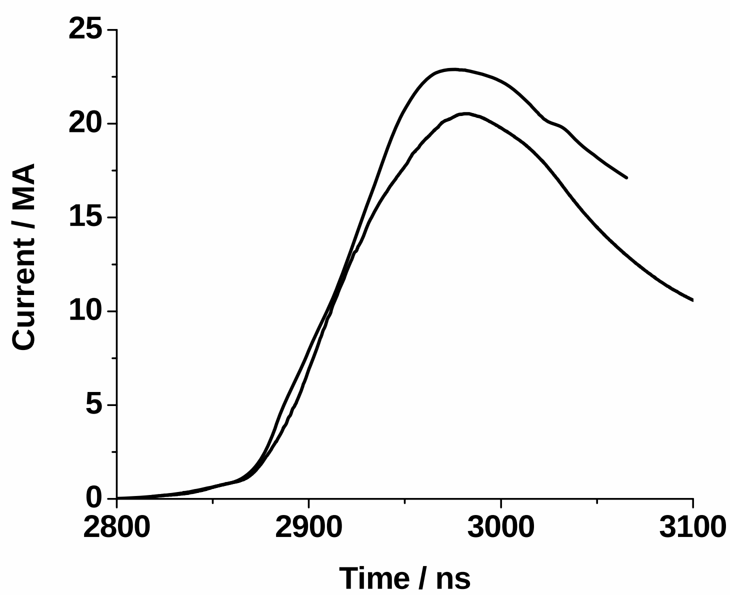
If electron flow current deposited into anode heats surface sufficiently a plasma forms.

Electron flow calculations by T.Pointon indicate this null has the largest area and is most rapidly heated.

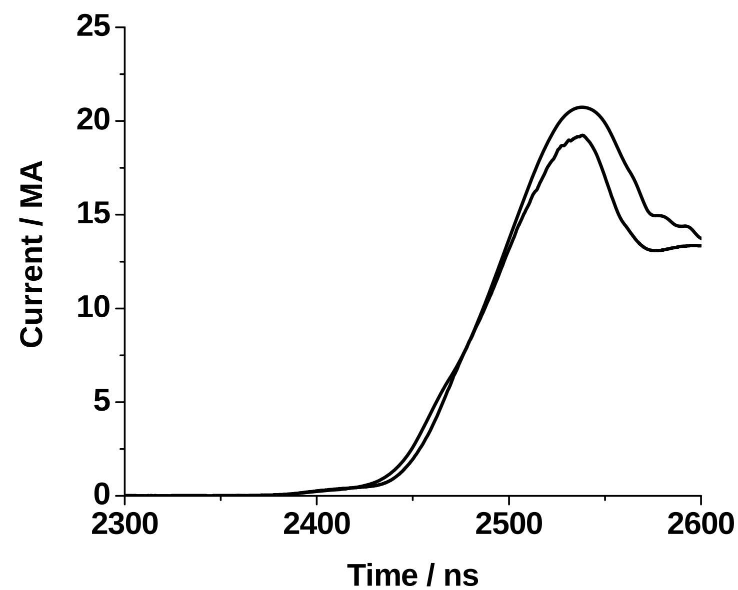
Circuit element just describes a plasma closing a gap – would be equivalent to cathode plasma expansion described by D.Rose last weeks seminar

Behavior of currents qualitatively the same for ZR and Z

Z shot 1787 (19.5 mg ZR)



Z shot 1097 (6 mg Z)



Re-tune ZR shorting model for Z

ZR

Expansion velocity 20cm/μs

Effective area 15cm^2

Z

Expansion velocity 17cm/μs

Effective area 5cm^2

Can put cathode plasma expansion velocity back to 2.5 cm/μs

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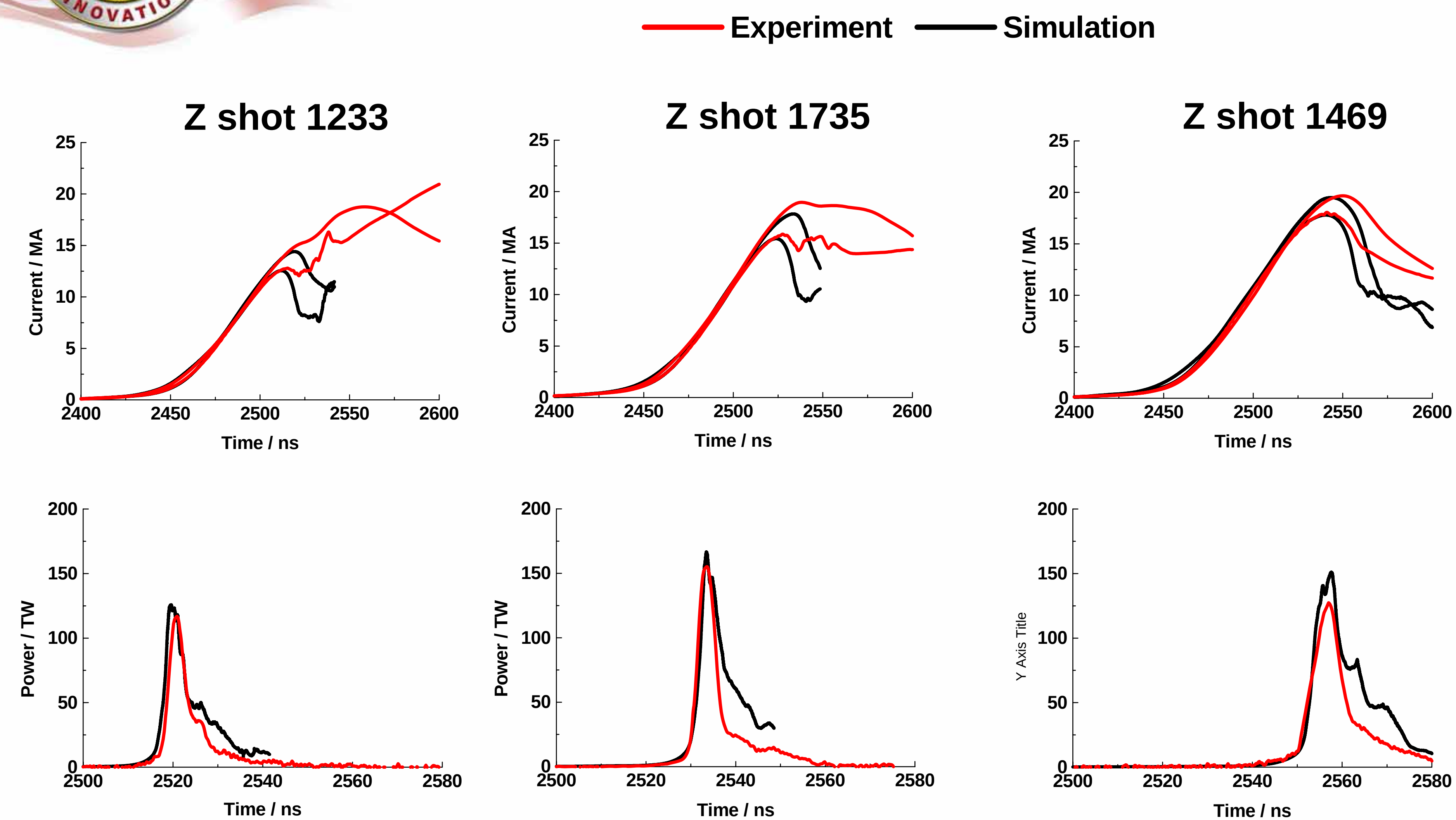
Retain good agreement for mass scan



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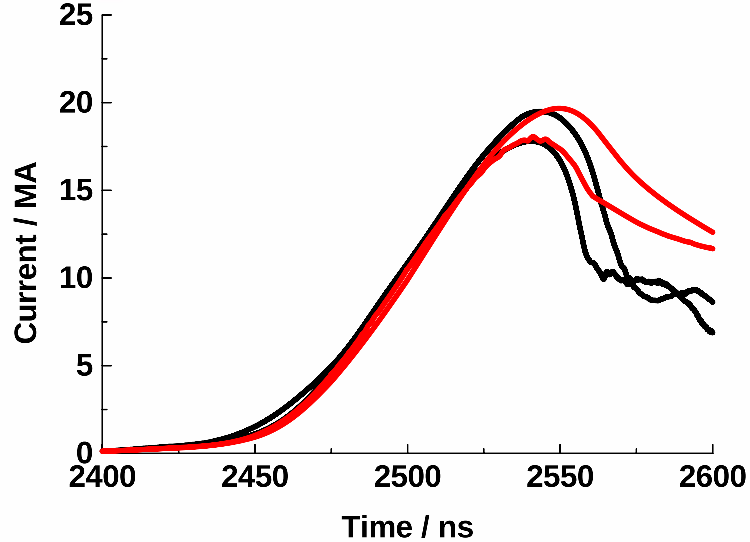
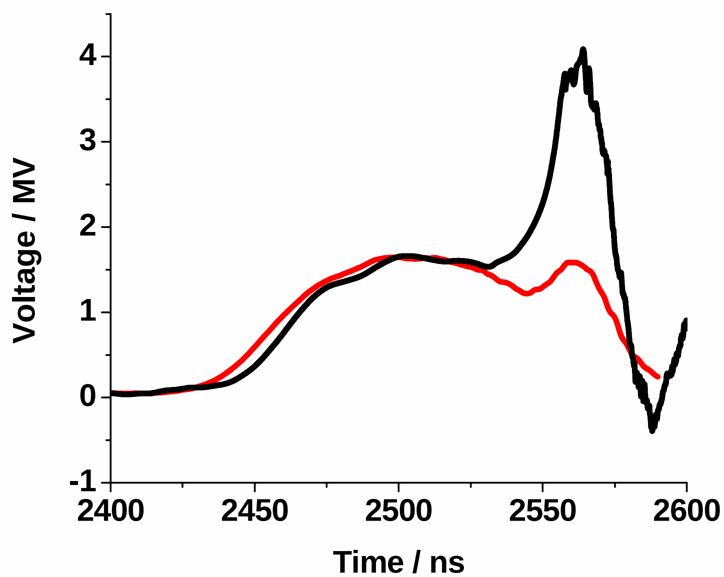
Can Compare to Convolute Voltage Measurement

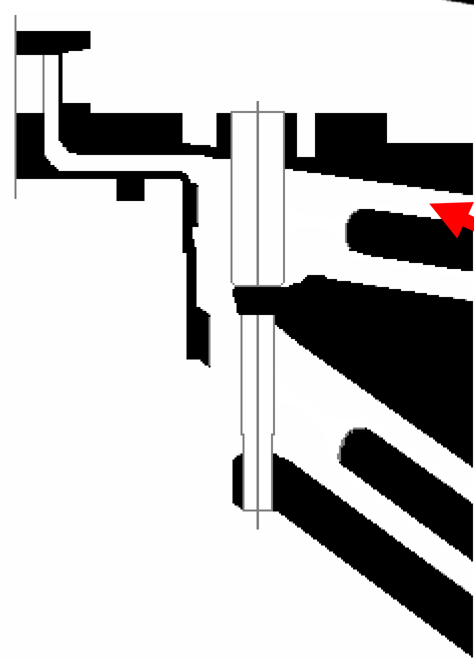
Experiment — Simulation

Z shot 1469





Translate stack measurements forward on A level to get convolute voltage



Voltage Measurement

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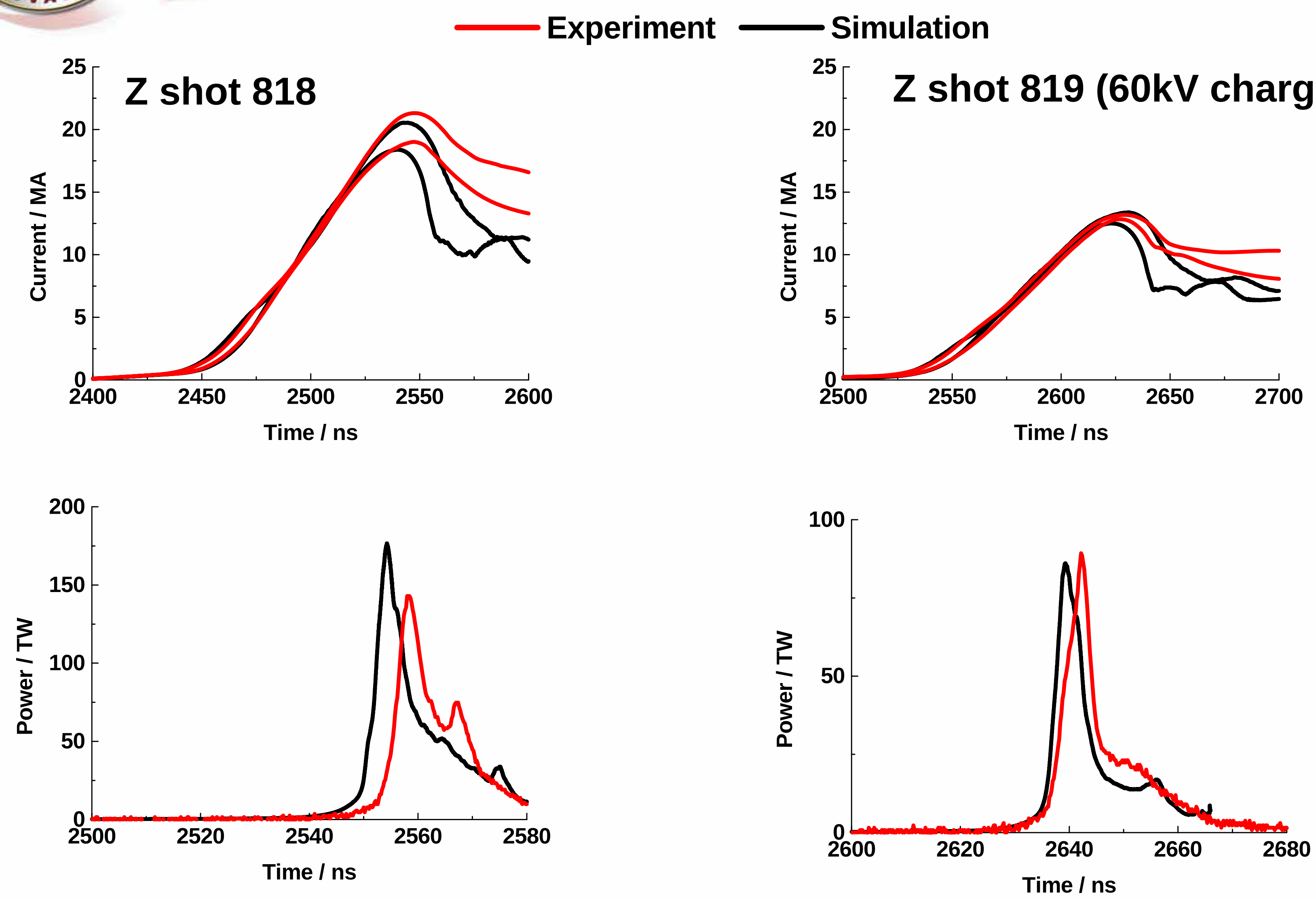
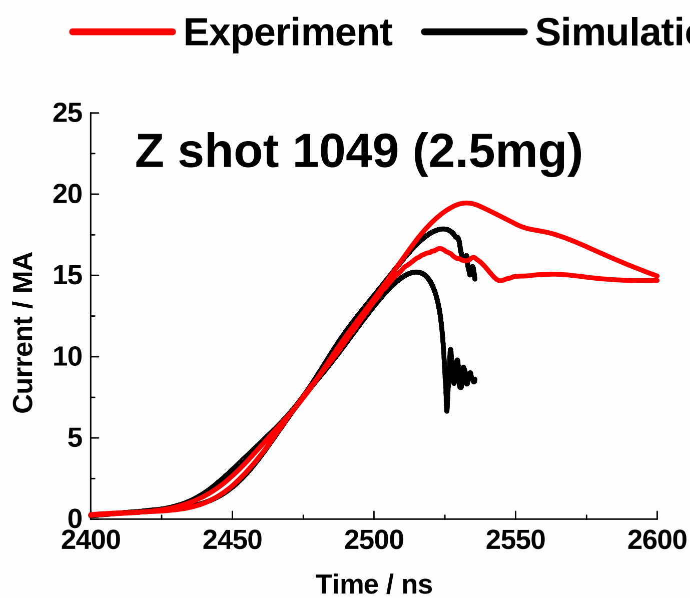
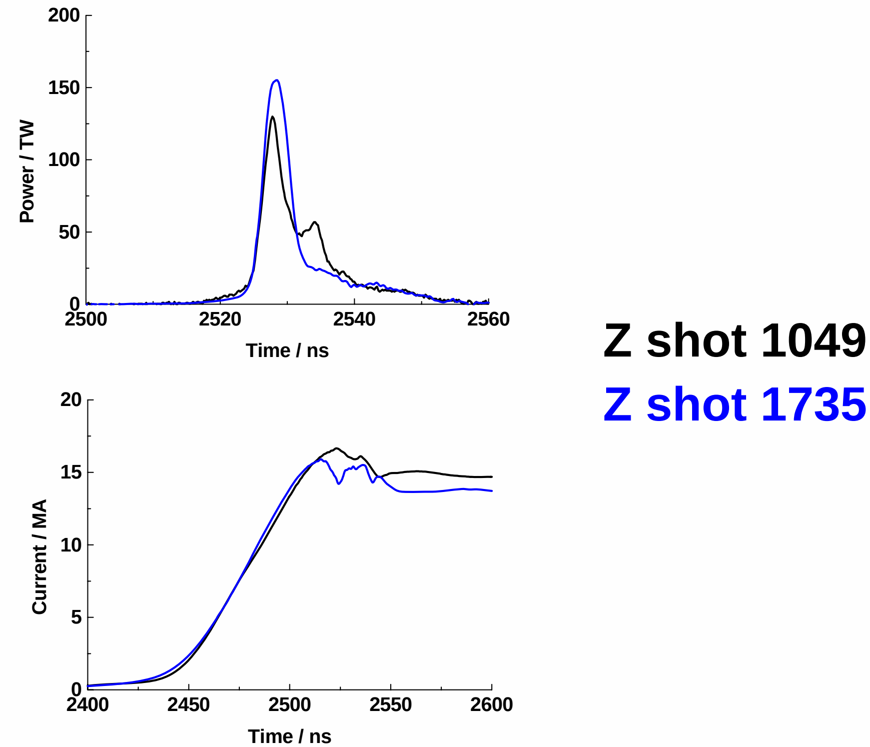
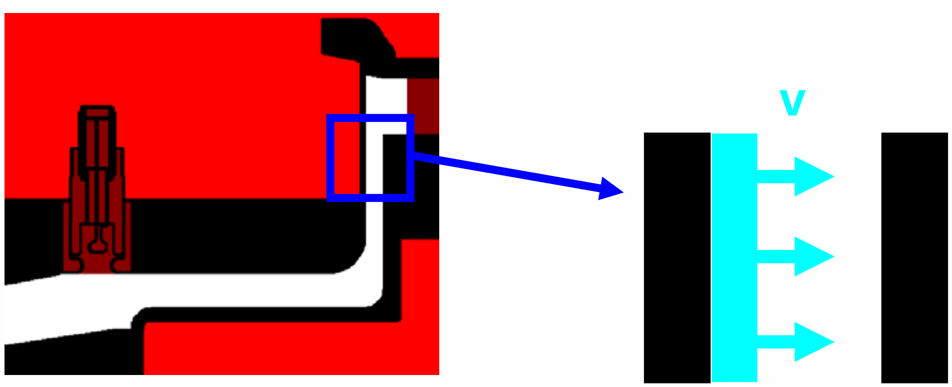
Reasonable agreement for Stygar current scan



Simulated currents low for smaller AK gap of high L mass scan

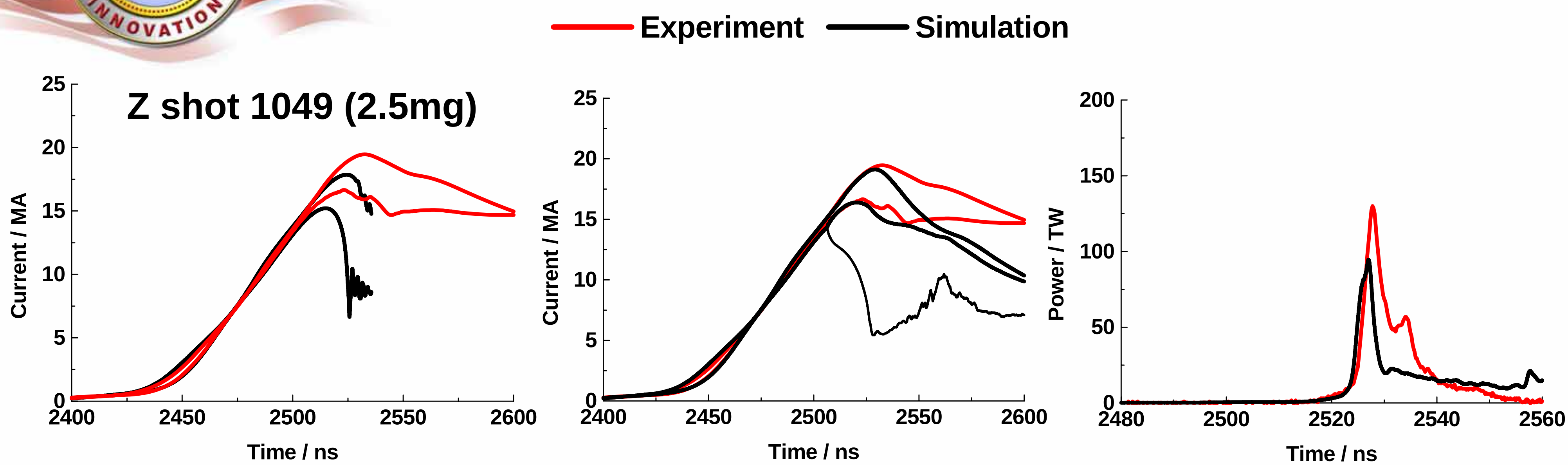


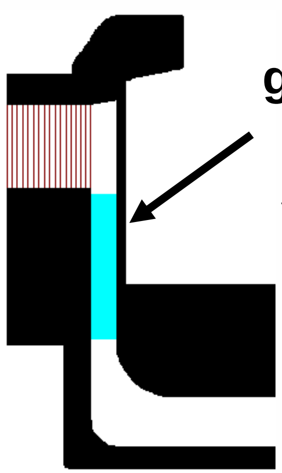




If we assume cathode plasma starts at 250 kV/cm and expands at 2.5cm/μs, then it is able to close 3mm AK gap before peak current for 2.5mg array implosion.

Resistive short in the feed gap recovers correct circuit behavior





At point where AK gap closes we put a resistive plasma short into the feed

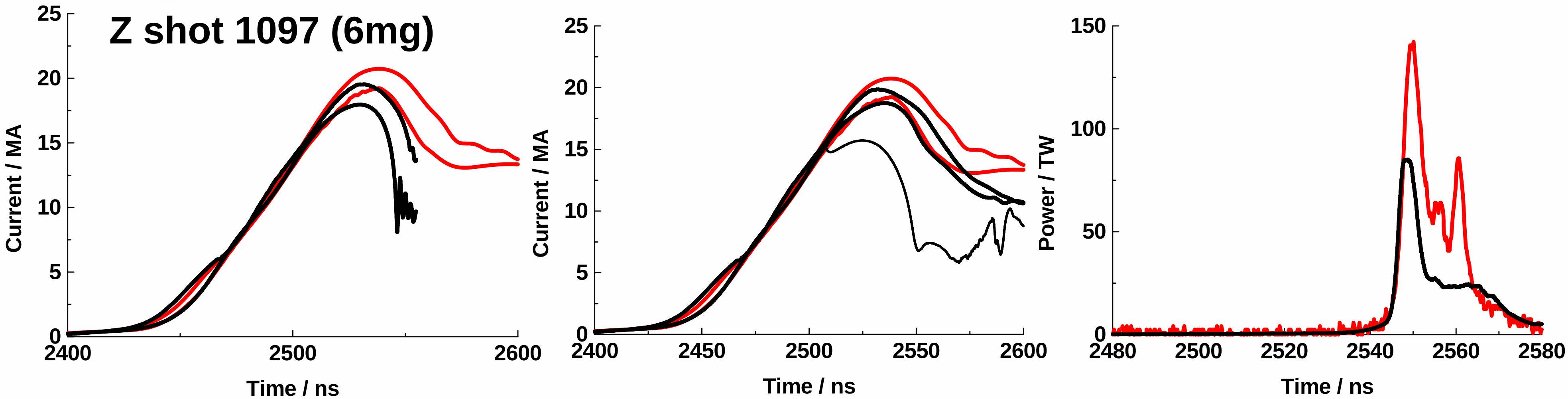
Can imagine mechanisms to raise resistivity after the gap shorts

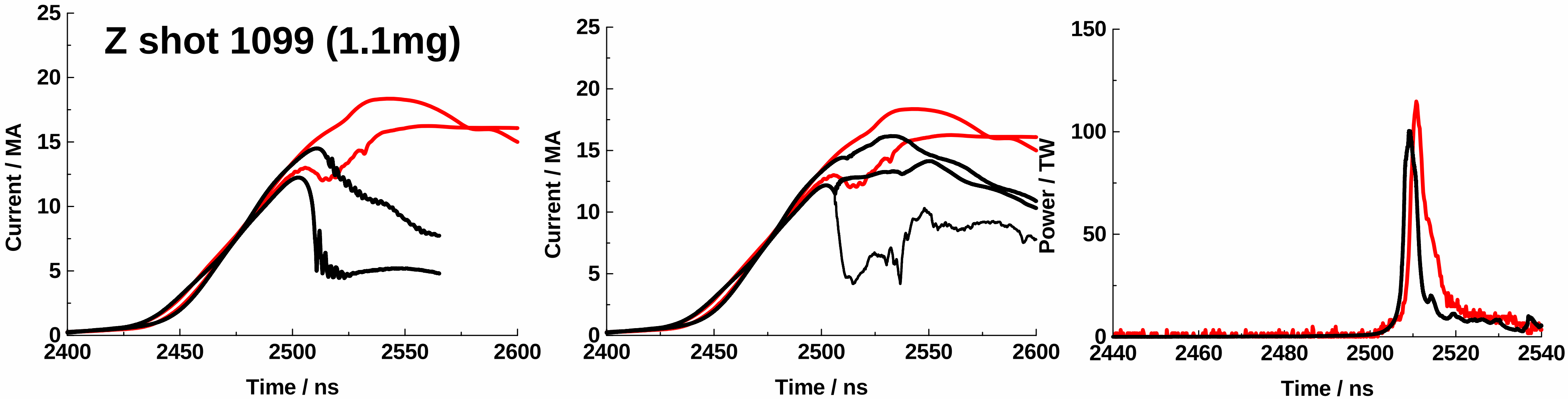
Current limited by ion acoustic turbulence ?

jxB self clears feed by accelerating plasma ?

With more considered approach to shorting mechanism can probably recover agreement with x-ray pulse

1.1 mg load is unaffected by the short in the feed





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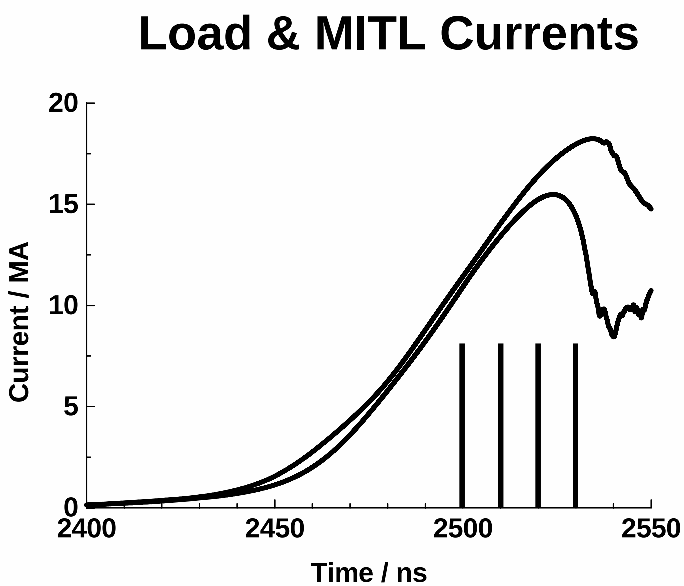
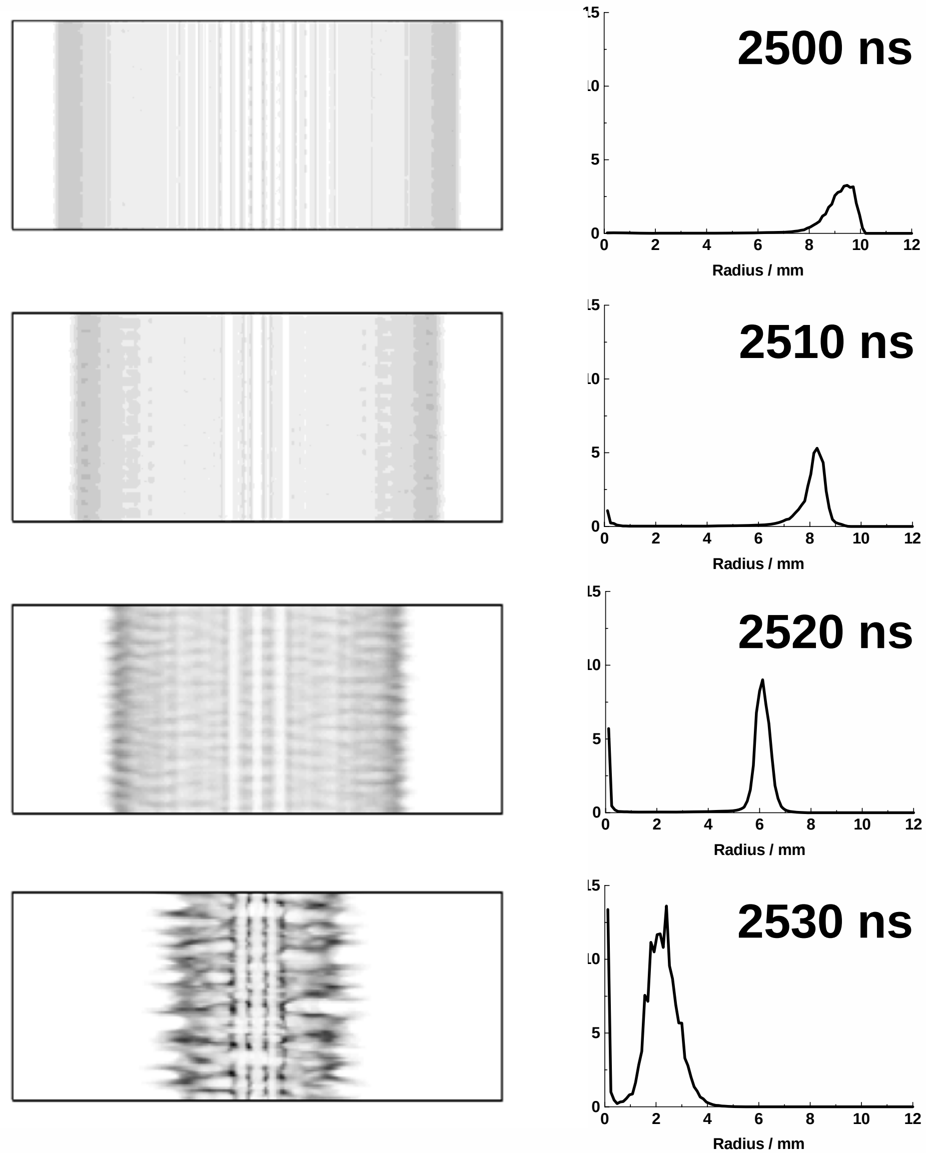
Density distribution for 2.5mg array implosion. Code results





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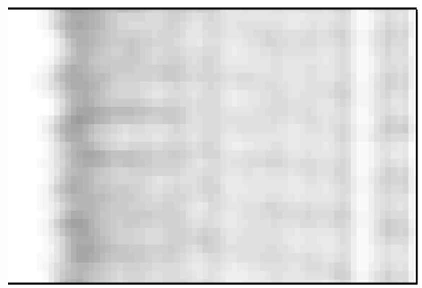
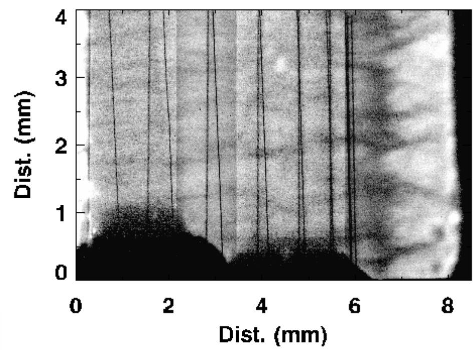
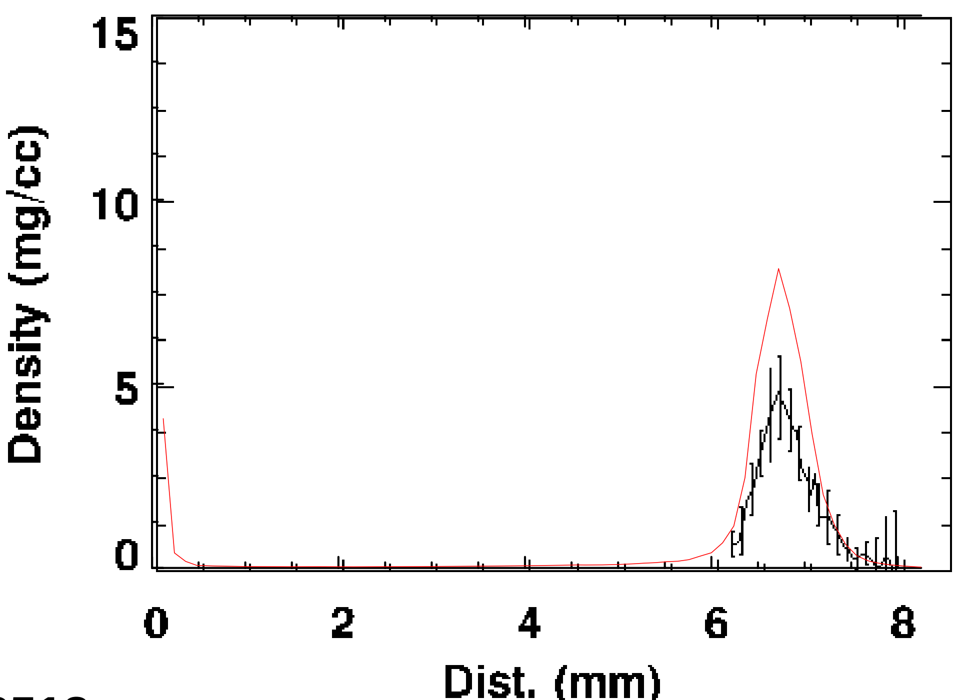
Good match to radiography measurement

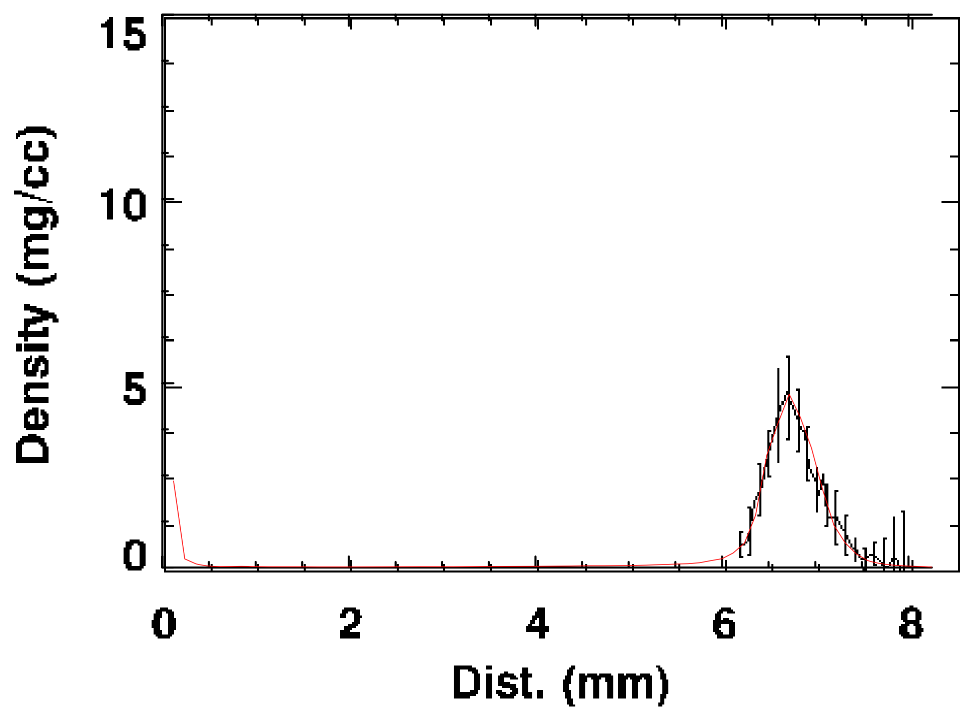
Simulation | **Experiment**





Simulation normalized to radiograph integrated mass of 1.4 mg

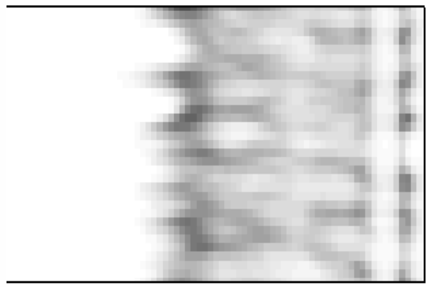




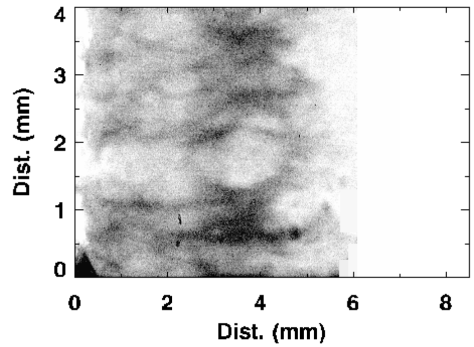
2518 ns

Not so good a match

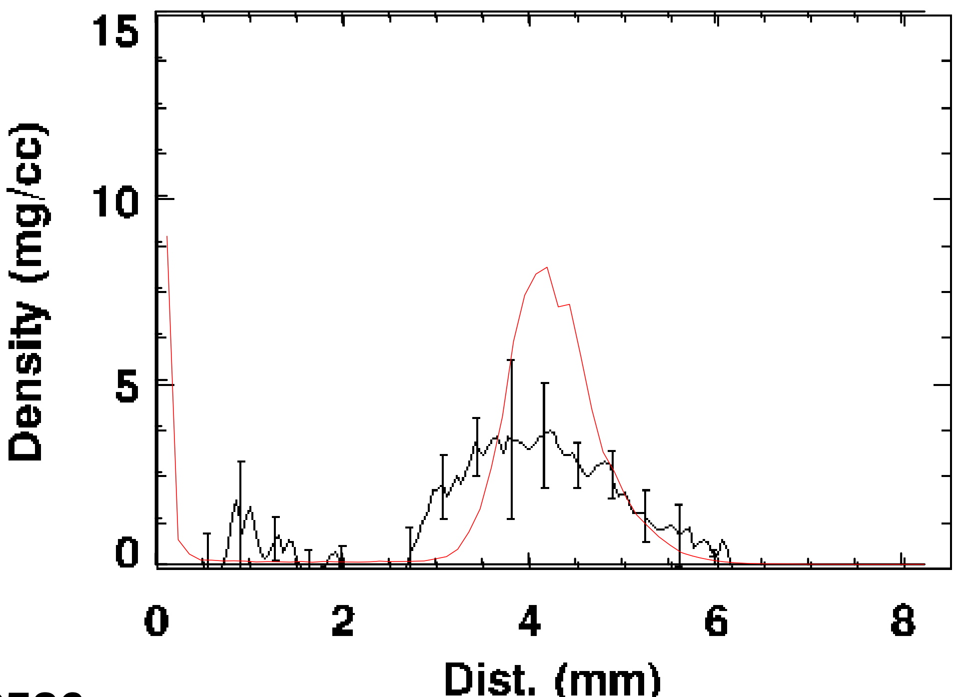
Simulation

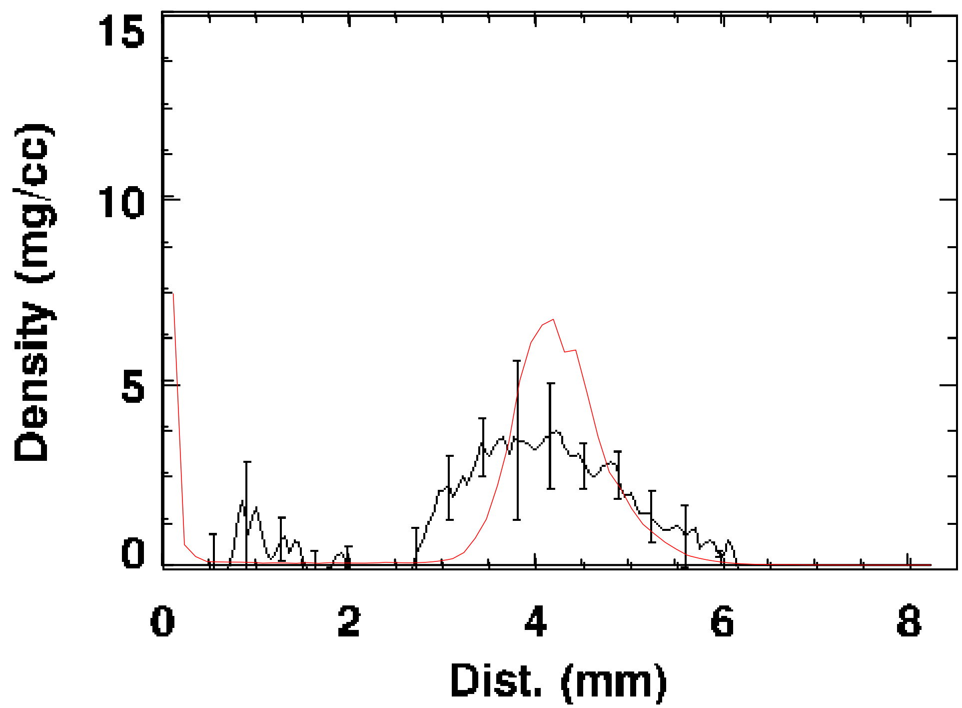


Experiment



Simulation normalized to radiograph integrated mass of 2.0 mg



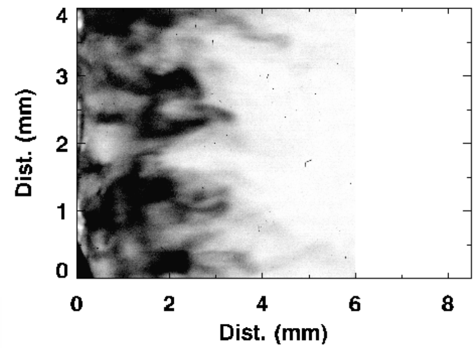


2526 ns

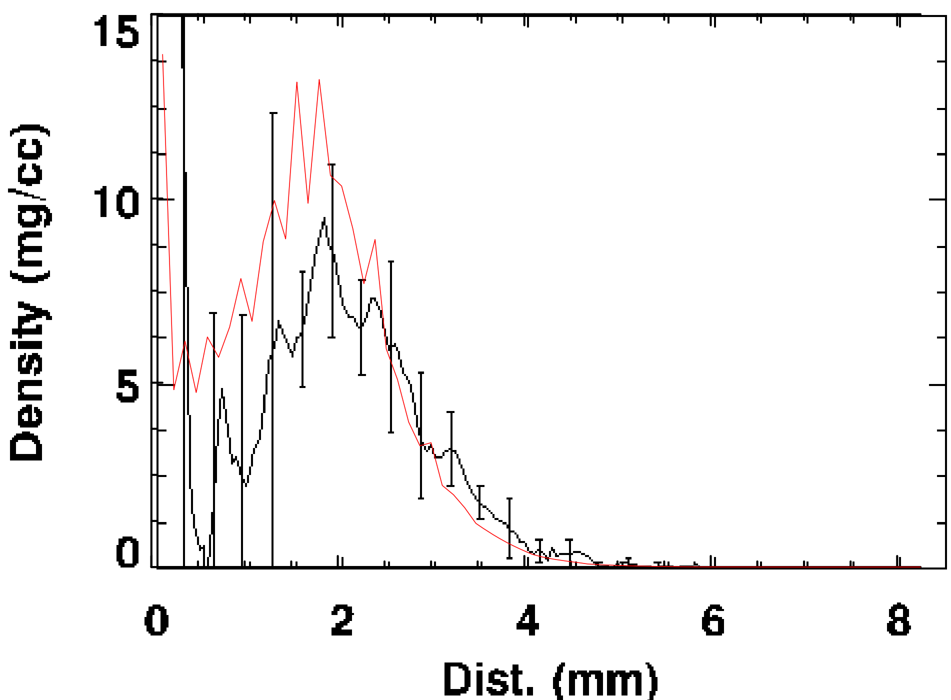
Good match to radiography measurement

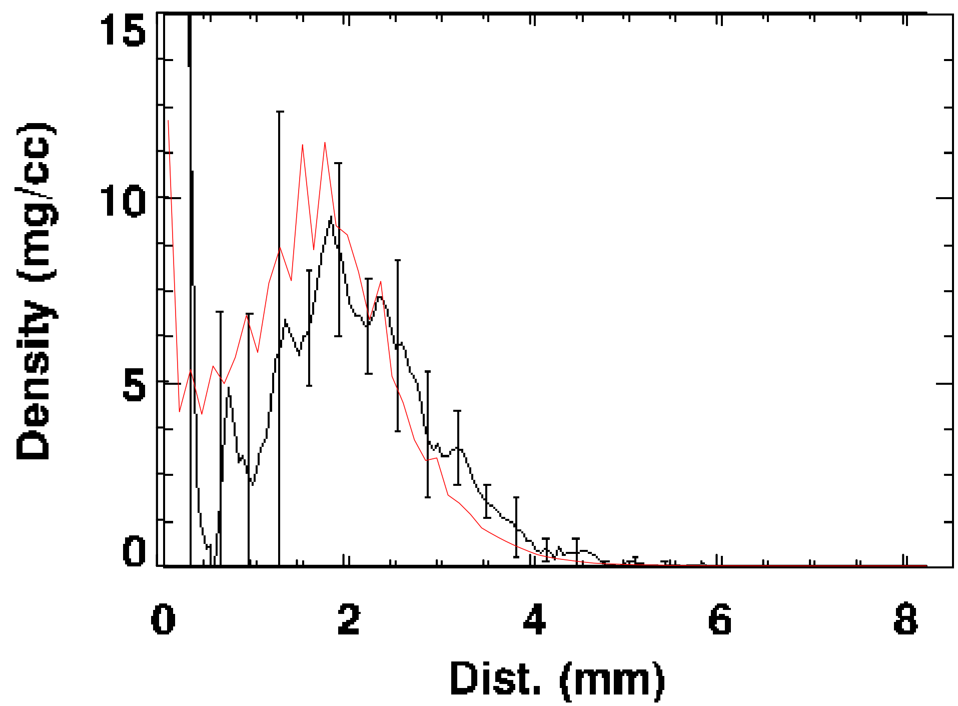
Simulation

Experiment



Simulation normalized to radiograph integrated mass of 2.1 mg

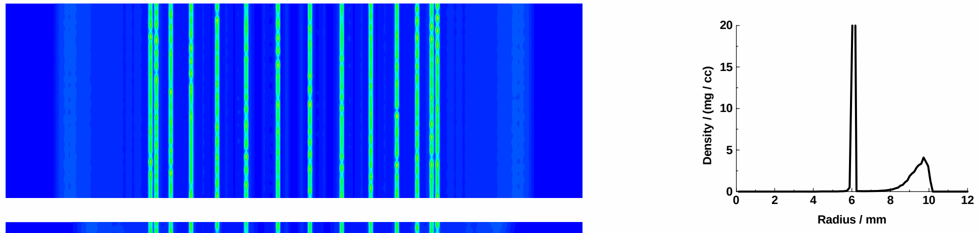




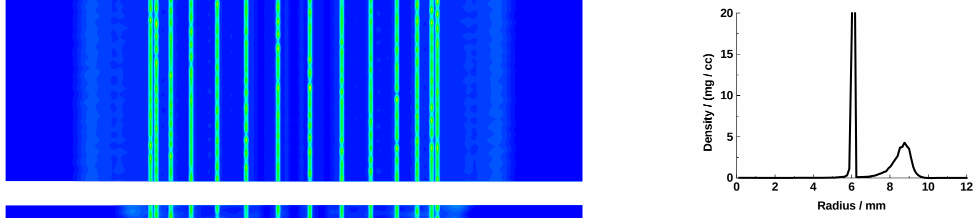
2531 ns

2.42 on 2.5 mg nested array

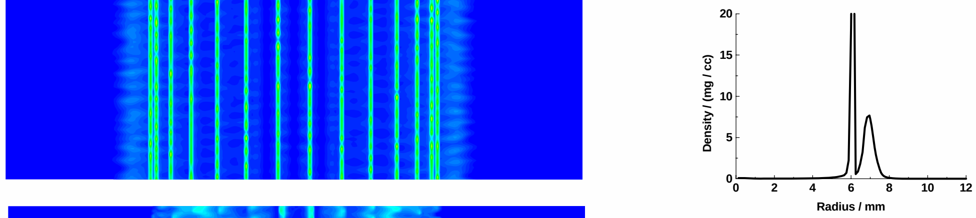
2500 ns



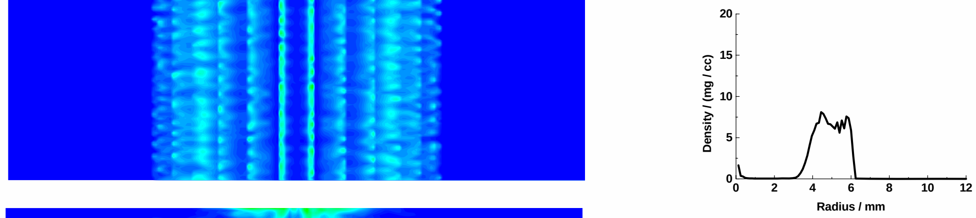
2510 ns



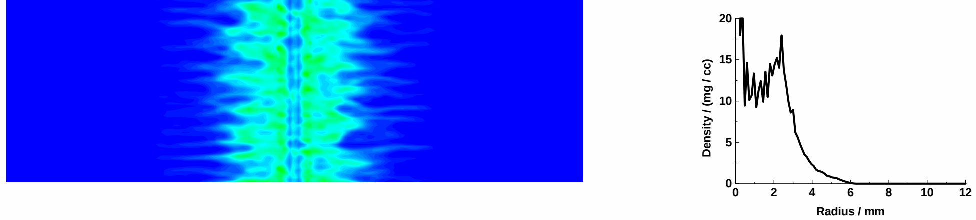
2520 ns



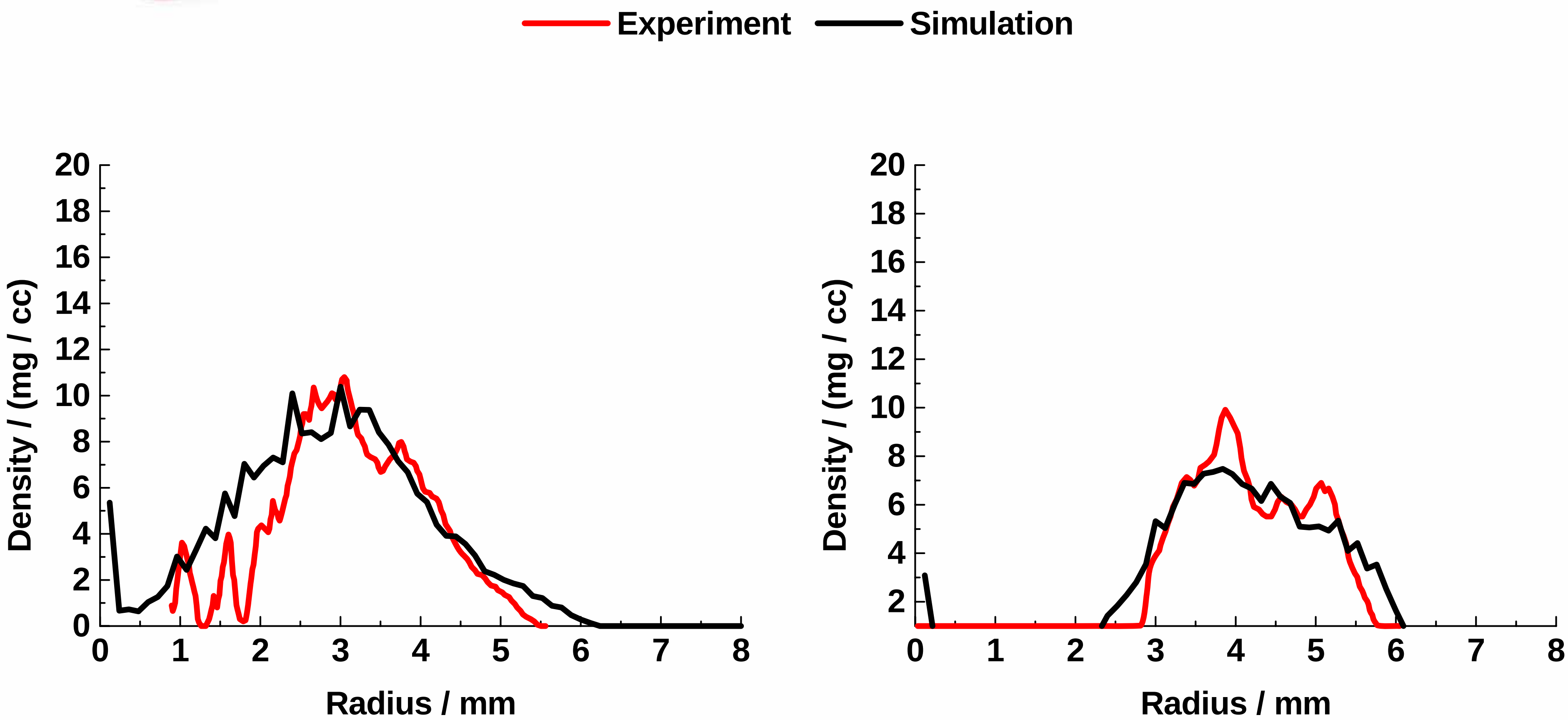
2530 ns



2540 ns



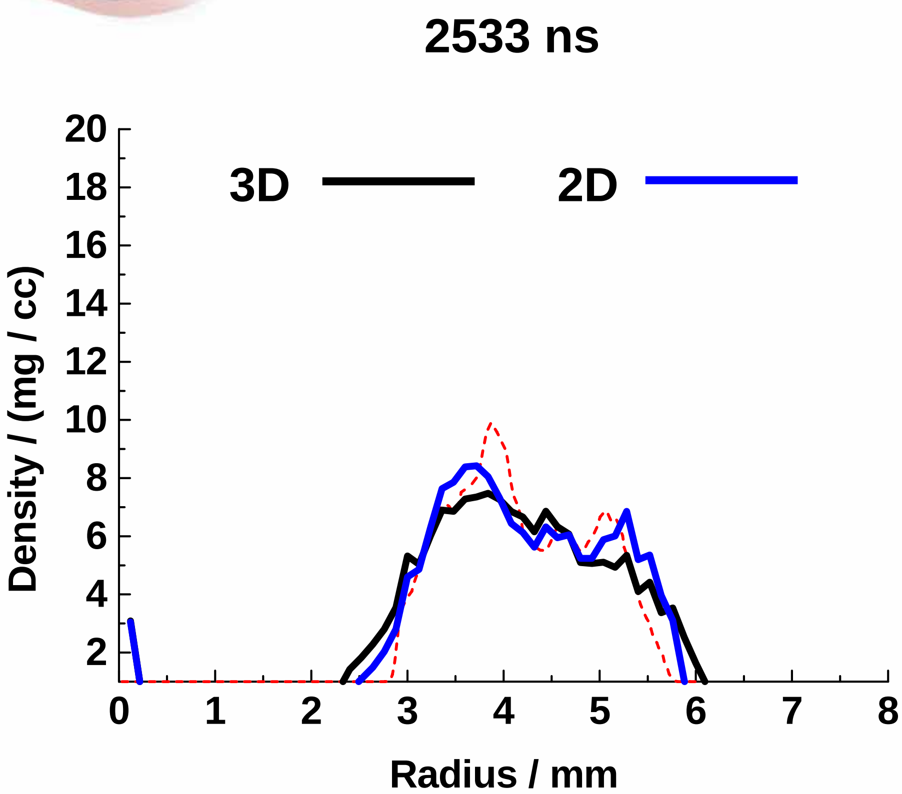
Good match to radiography measurement

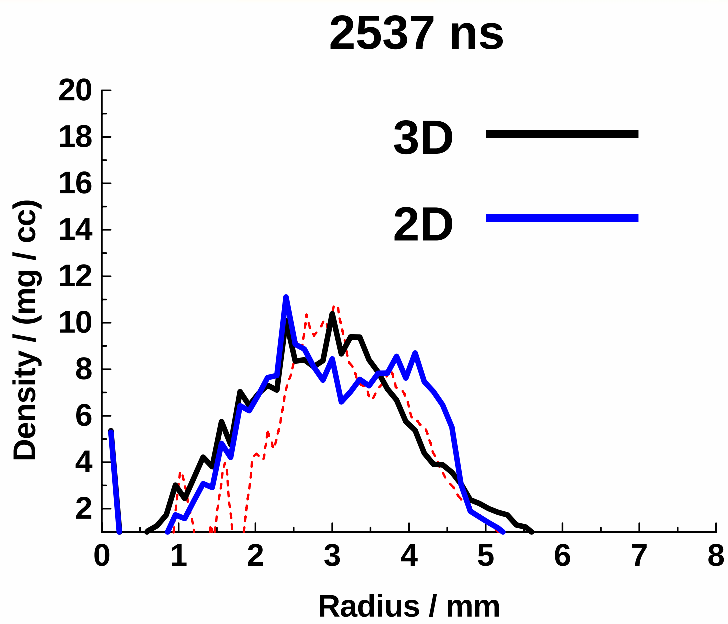


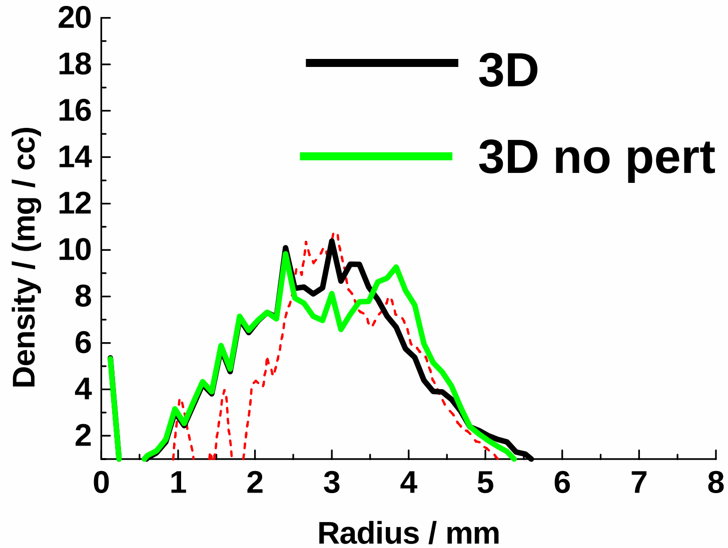
2537 ns

2533 ns

Mass distribution not a function of 3D perturbations, but later time evolution is







Large mass perturbation required on inner array to reproduce mass distribution

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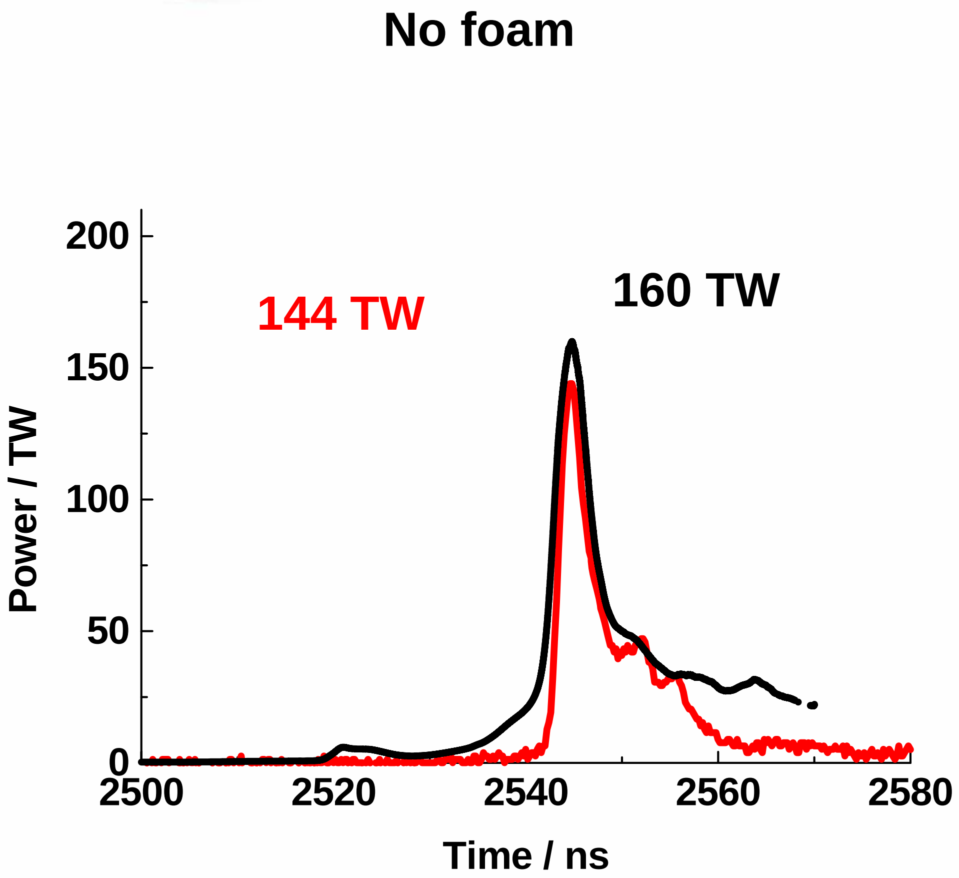
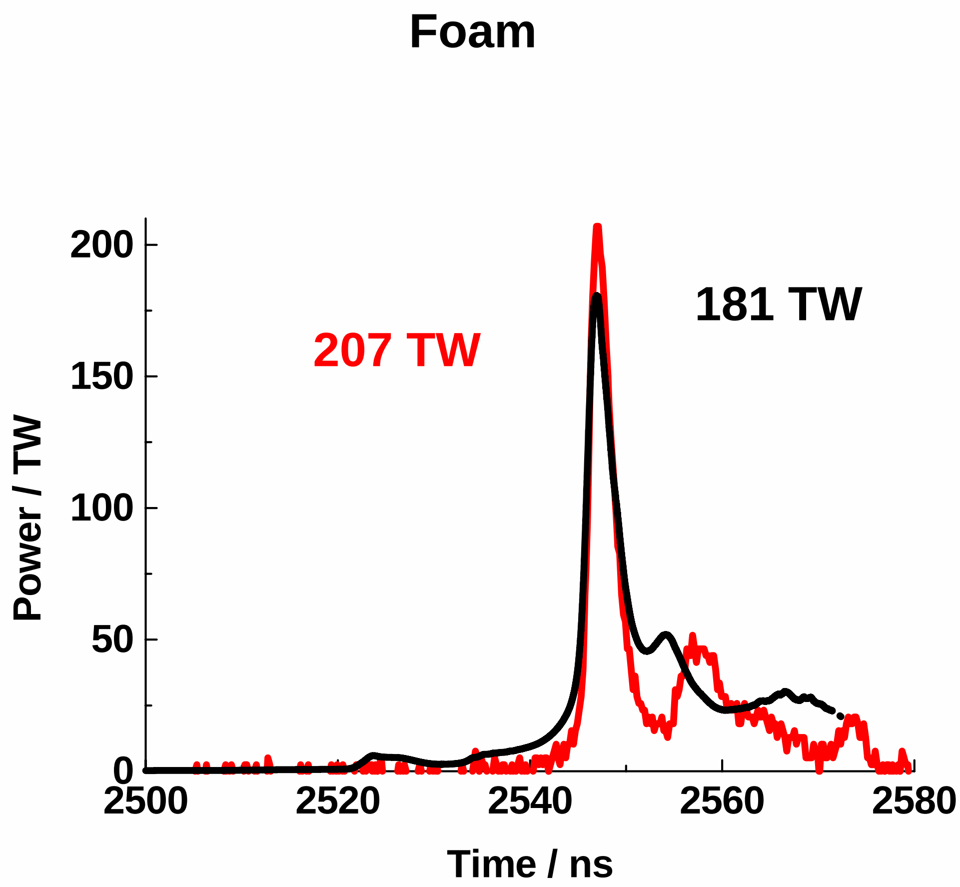
Good match to measure x-ray power with and without foam

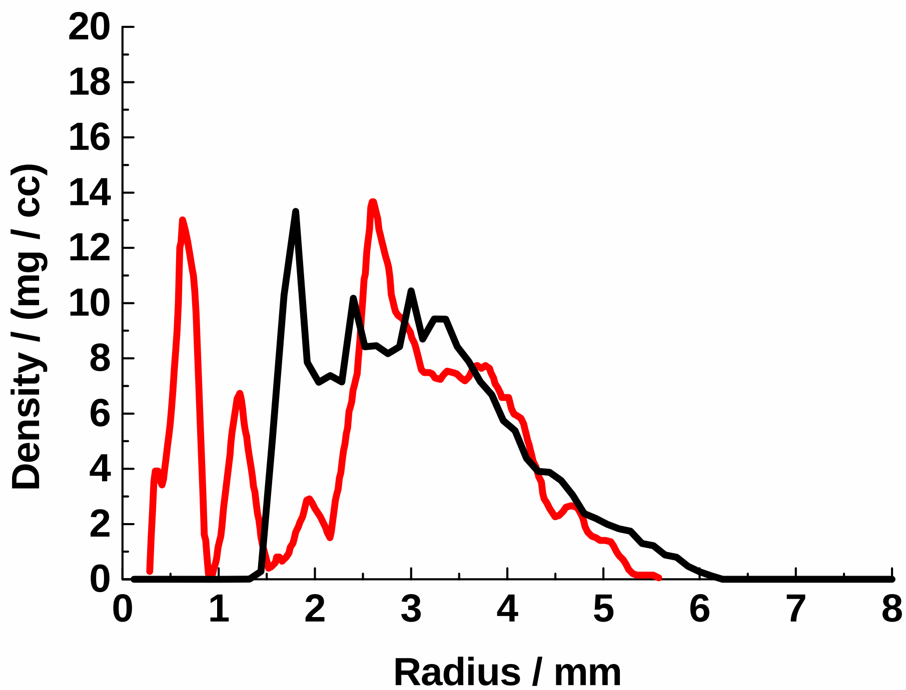


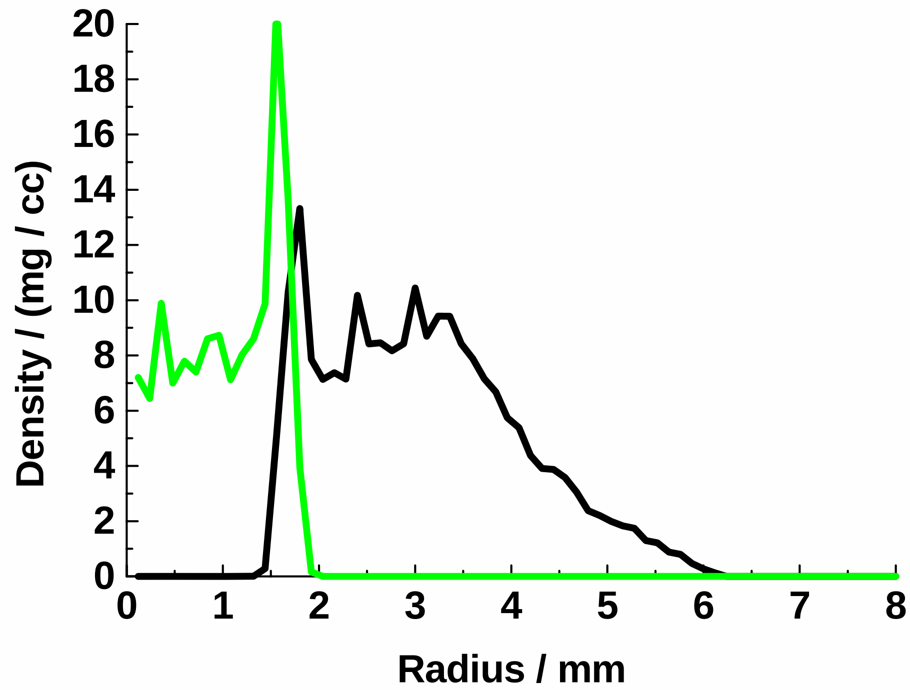


Experiment – foam raises power ~ 40 %

Simulation - foam raises power ~ 13 %

Foam acts to sharpen mass distribution. Not modeling radiation may be a problem



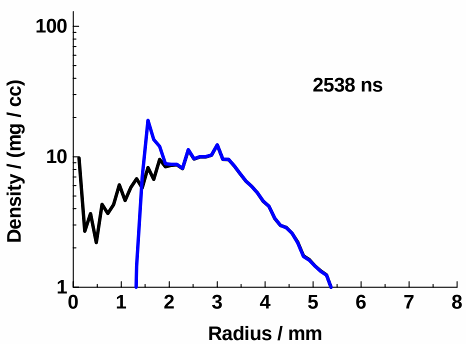


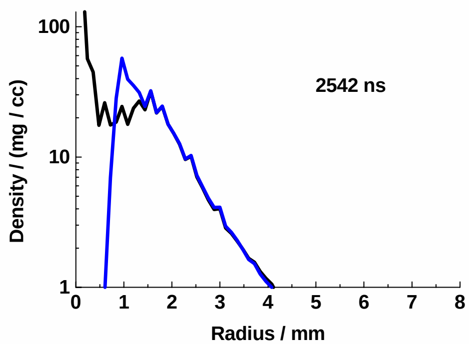
Mass profile has correct shape, but impact with foam appears to be at smaller radius than observed. Do we need to account for foam expansion ?

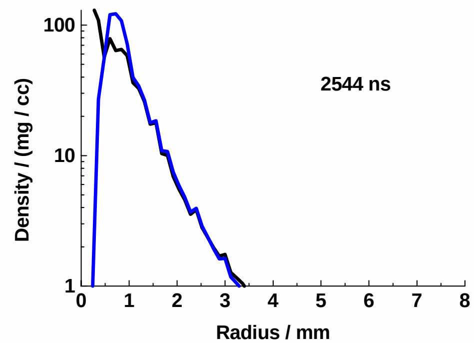
2537 ns

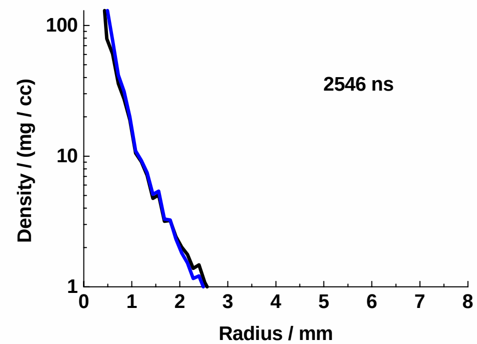
Narrower mass distribution results in sharper x-ray power rise and higher peak power

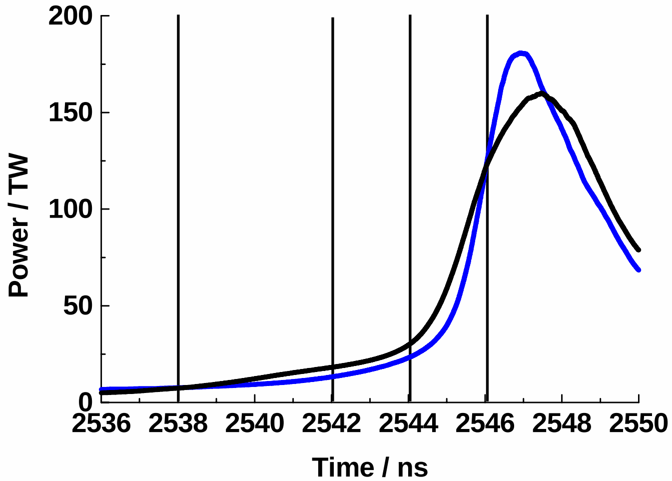
Comparison of simulated mass distribution with and without foam – mass profile steepens

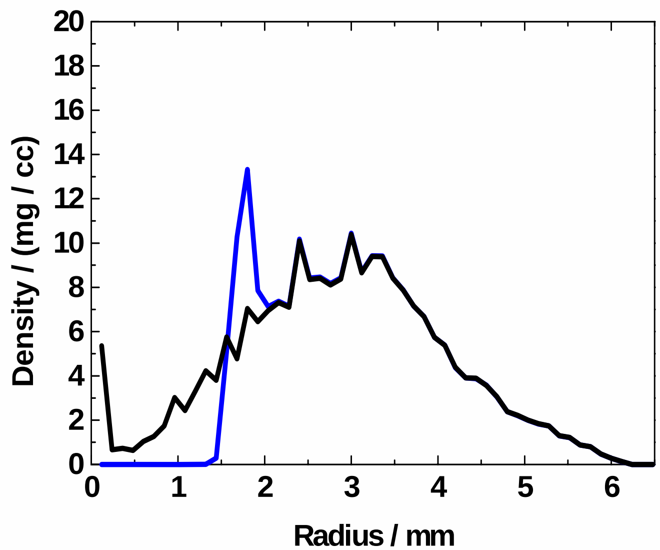


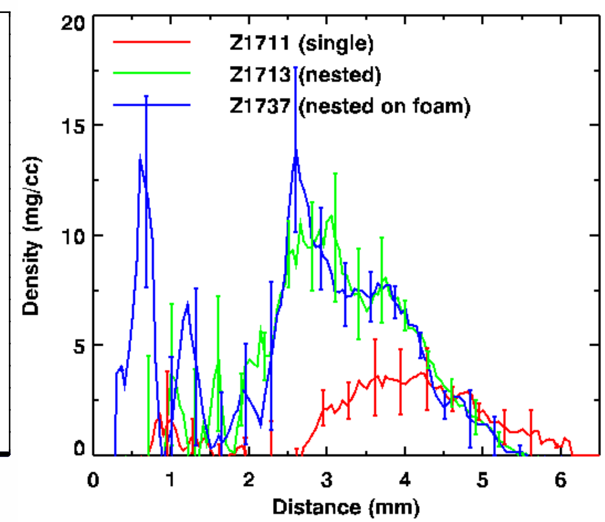












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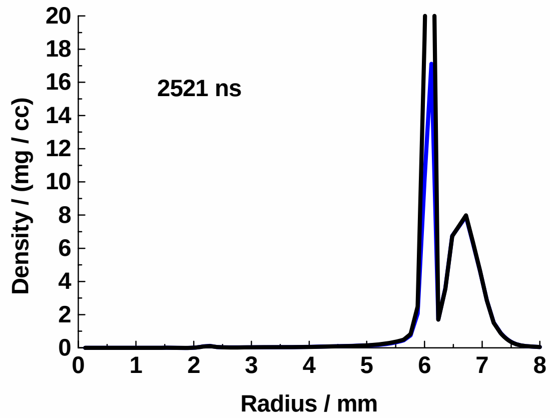
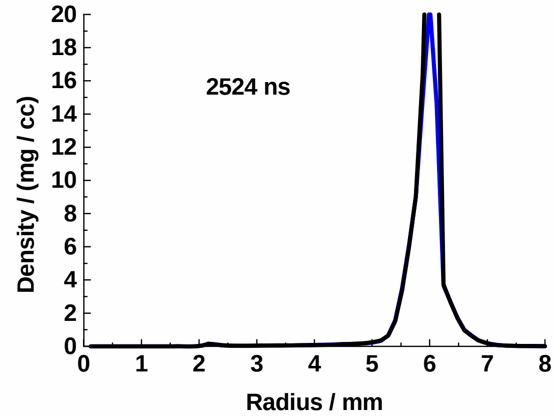
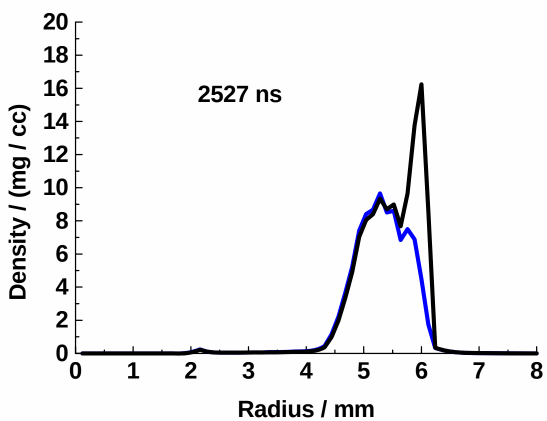
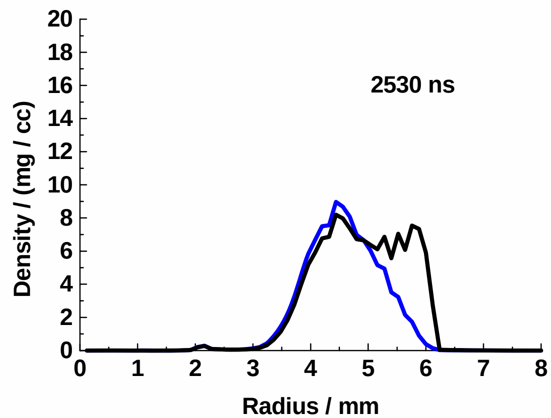
Lighter inner array creates narrower mass distribution at nested interaction point

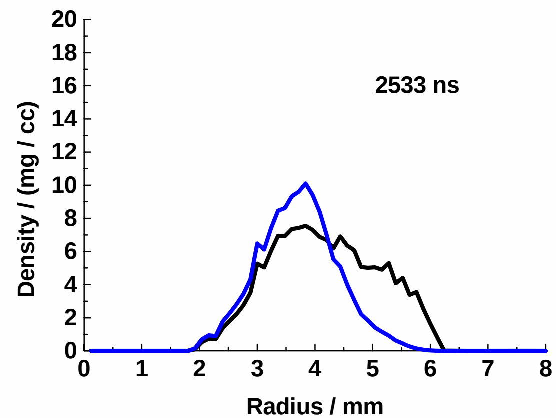
Comparison of foam runs for different inner masses – mass profile steepens at nested interaction point



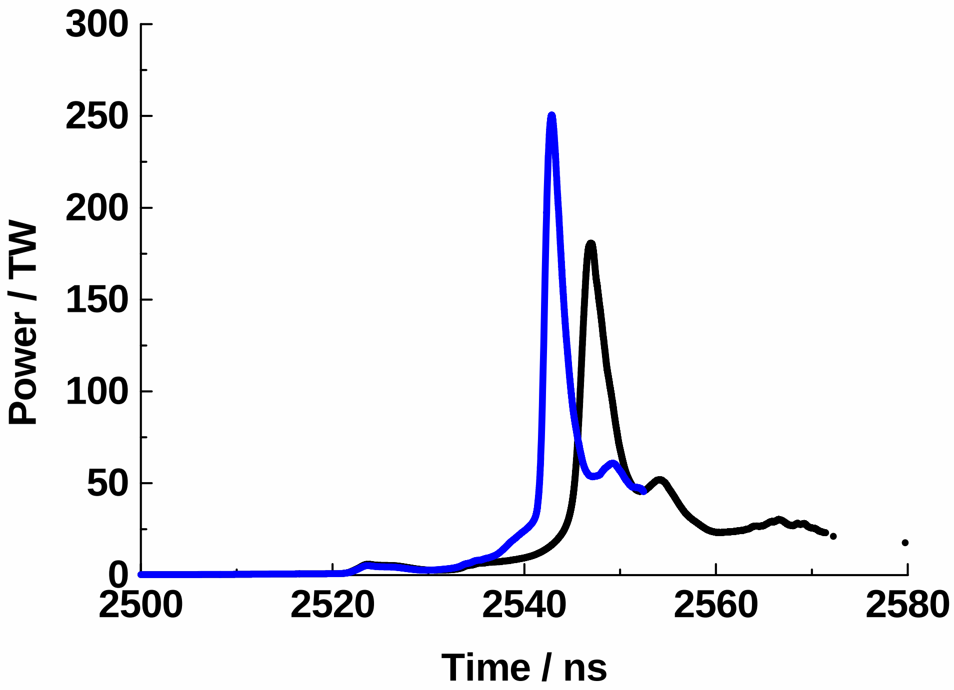


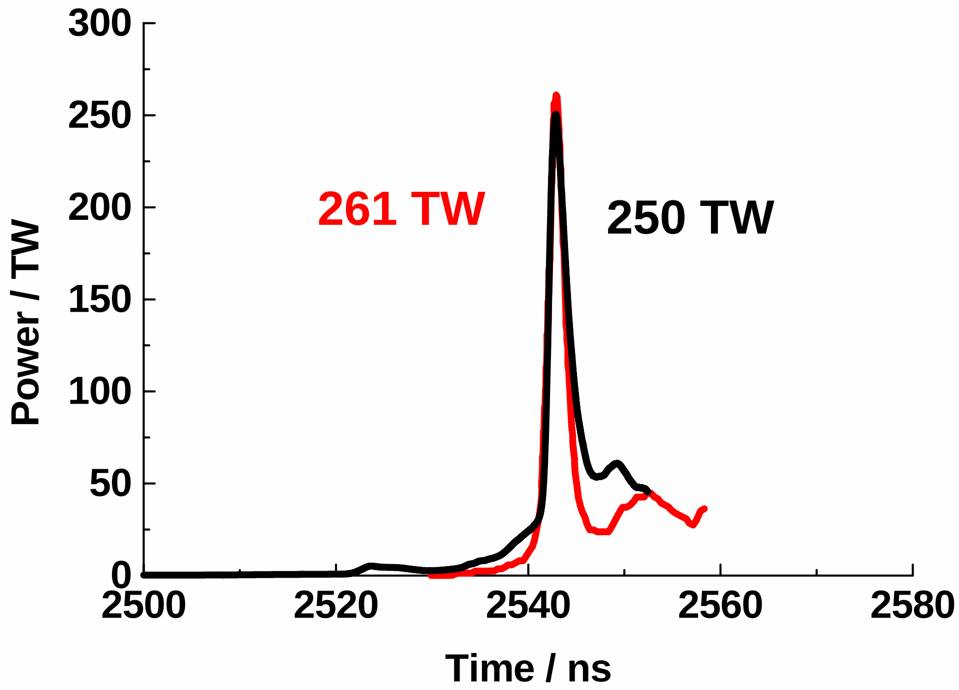






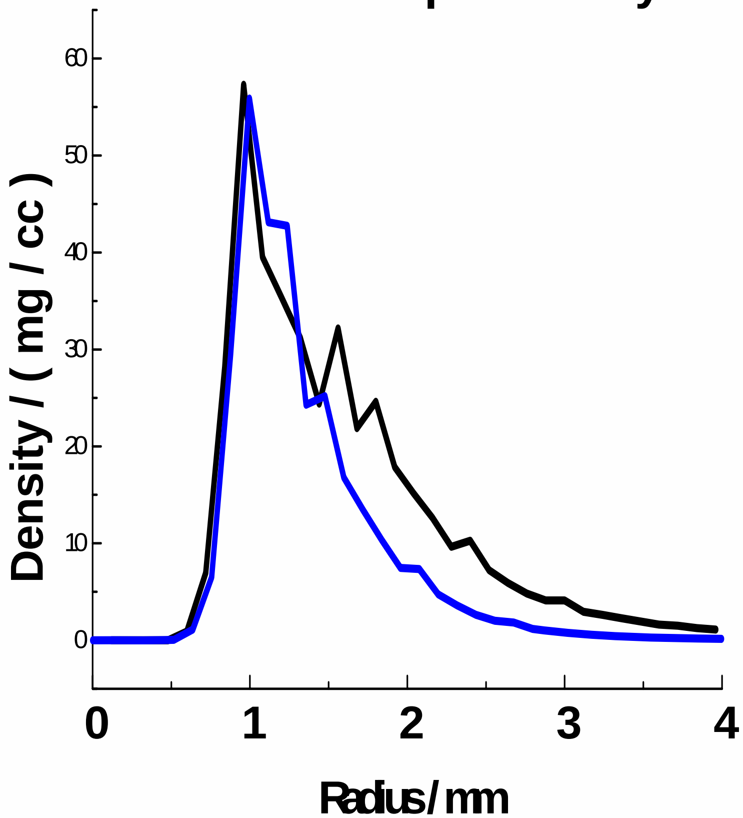
Better improvement can be obtained with lighter inner array mass (1.3 mg inner array)





Narrower mass distribution results in higher peak power

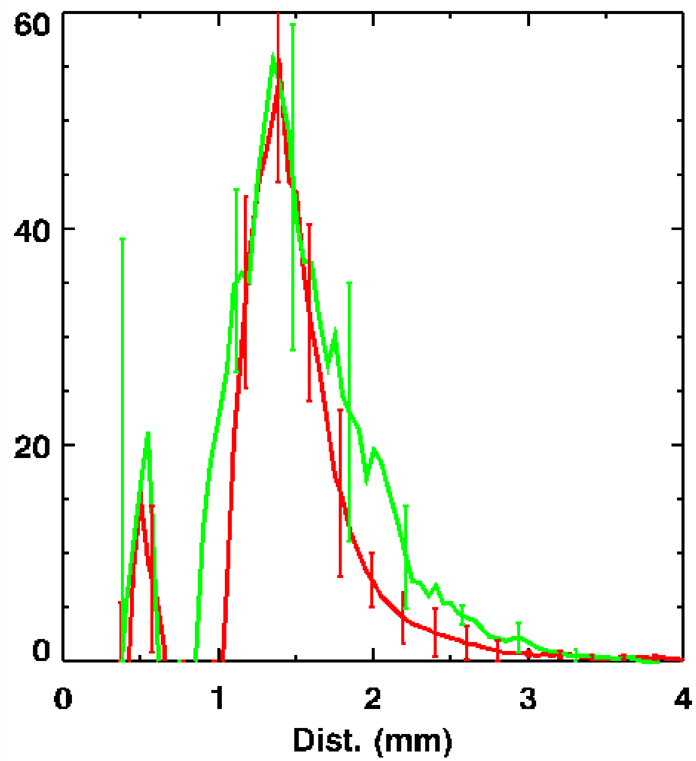
Density distribution from code ~ 4ns before peak x-ray



2.5 inner

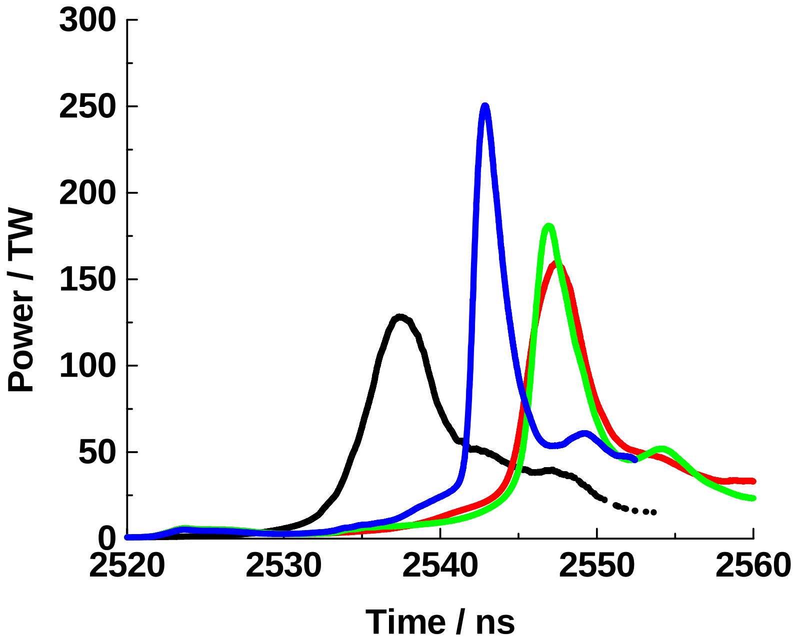
1.3 inner (translated 0.5mm)

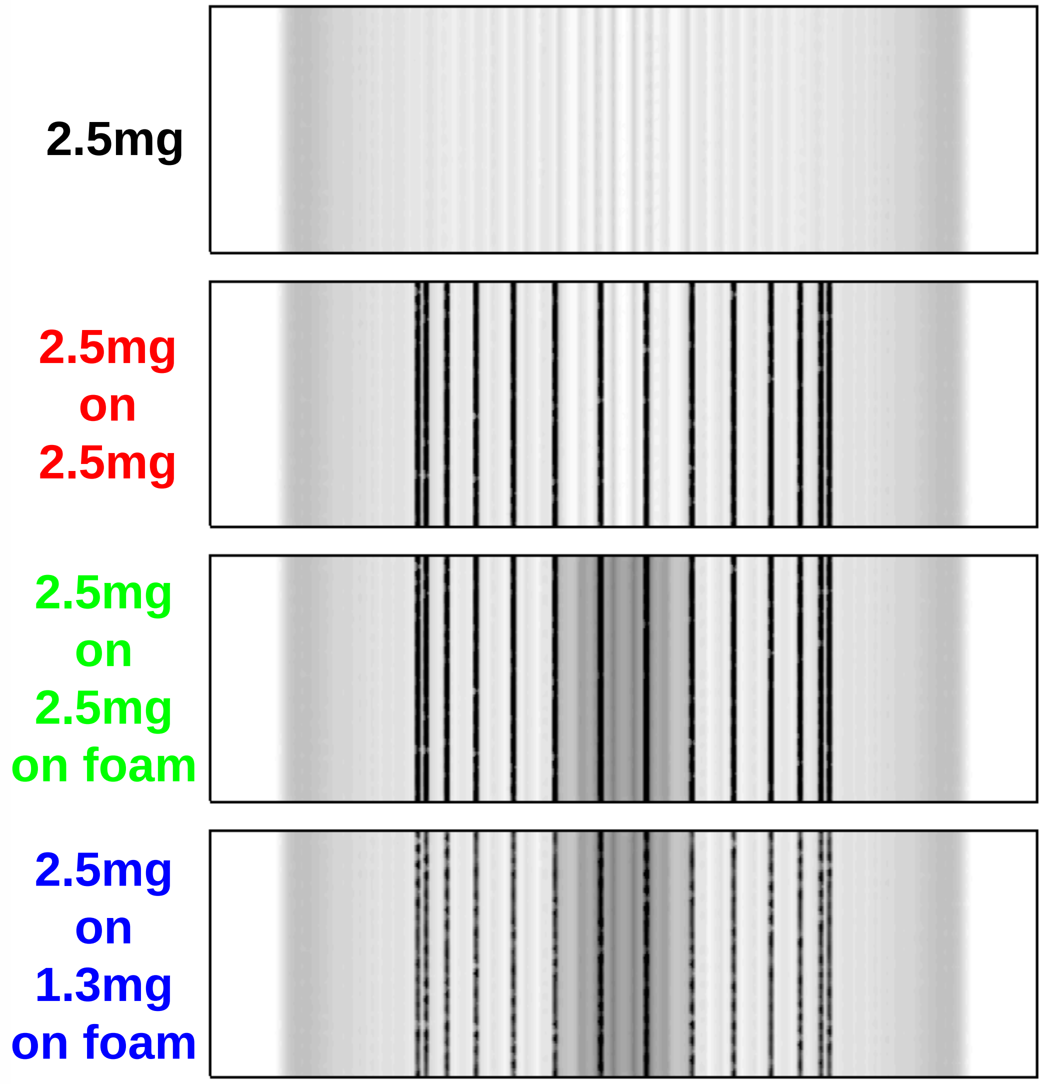
Experimental Density distributions



Experimental Radiography

Simulation Results





Summary

- Using the same model we are able to consistently get good agreement between simulation and experiment for single arrays and nested arrays on Z
- Simulations starting to give good quantitative agreement. We are able to reasonably and simultaneously match circuit behavior, x-ray pulse and mass distributions. With more benchmarking against ZR could be used as a useful design tool.
- More complete circuit model is now being used, but it contains free parameters that need to be better justified or calculated from first principles
- Possible gap closure issues for small AK gaps that need to be kept in mind, although more testing / data mining needed to be certain.