SAND2009-3327C

Current Losses in Wire Array Z-Pinches on the Z Generator

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Acknowledgements / Outline

Acknowledgements

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Outline

- **Demonstrate successful modeling of wire array implosions**
- **Describe circuit model applied**
- **Describe convolute loss**
- **Use MHD + circuit model to describe current losses in the feed**

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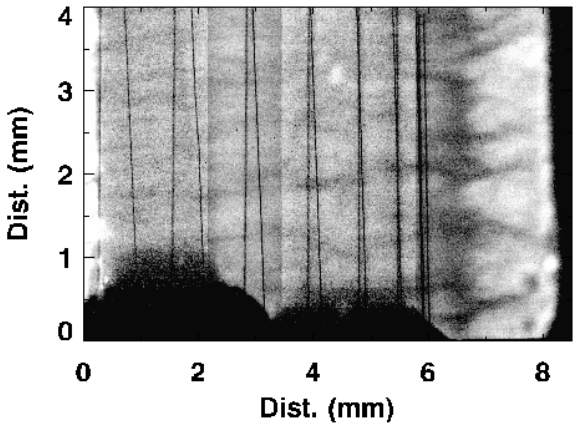
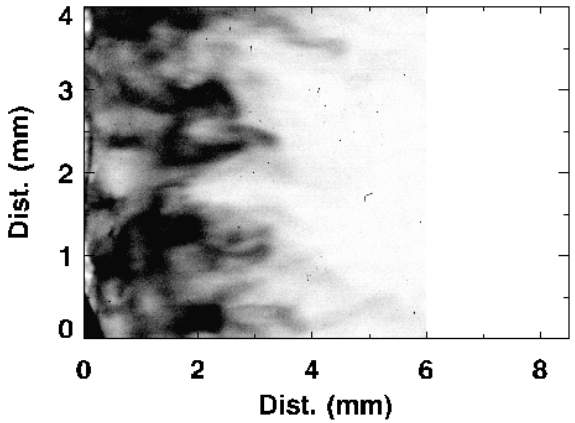
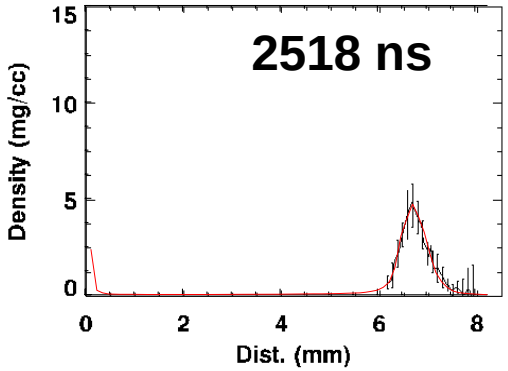
Radial Density distribution for 2.5mg array implosion (Z1735). Code results agree with radiography and x-ray pulse

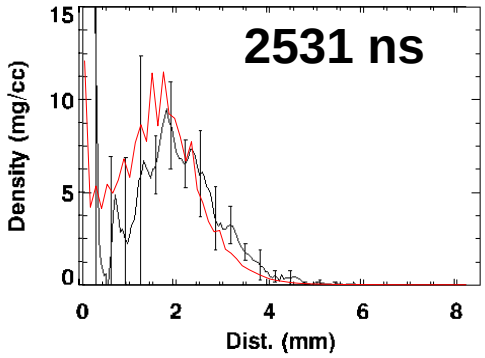
Radiographs



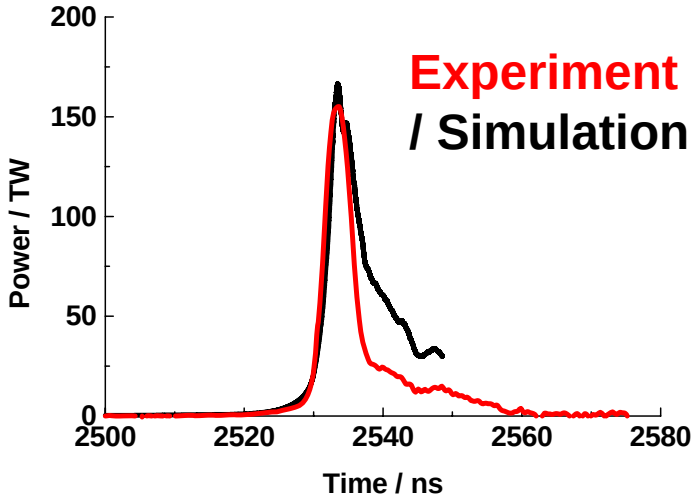


Abel inverted density vs. simulated density

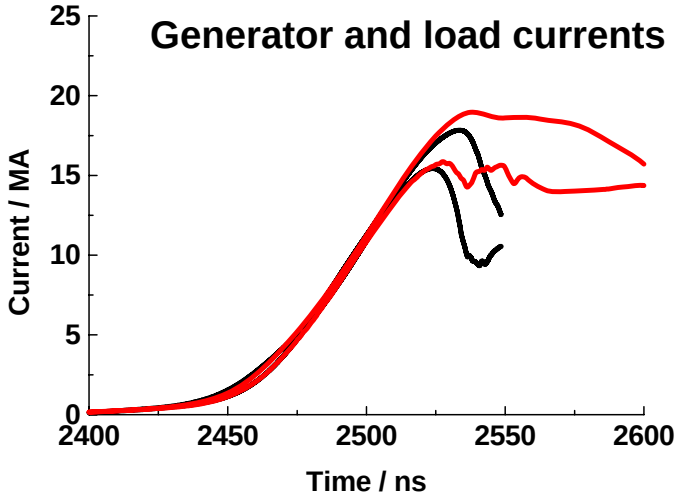




X-ray Power



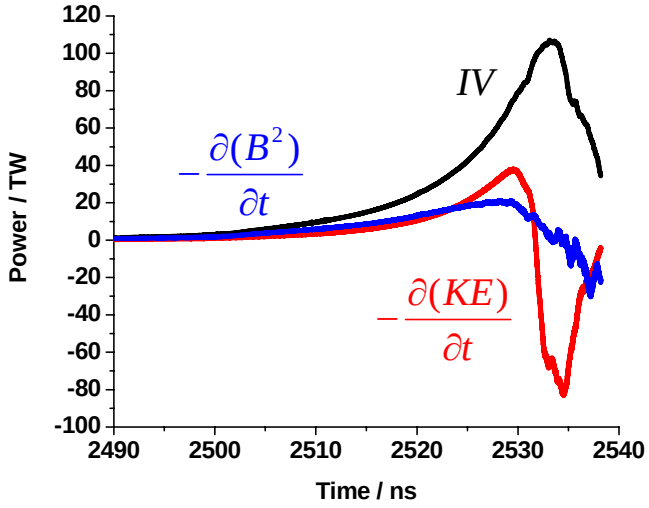
Generator and load currents

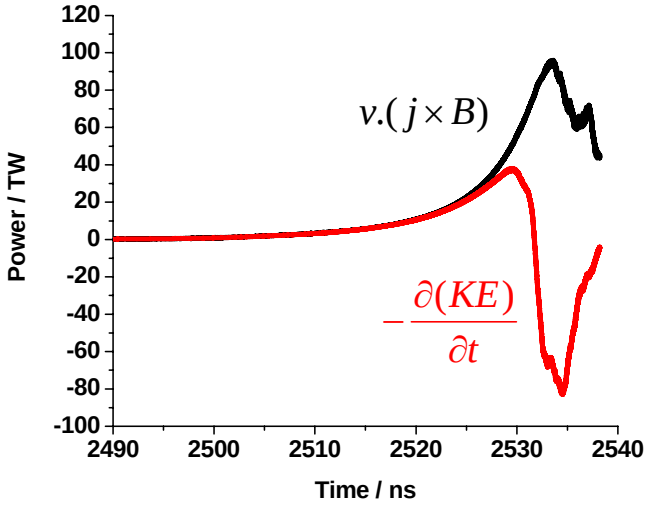


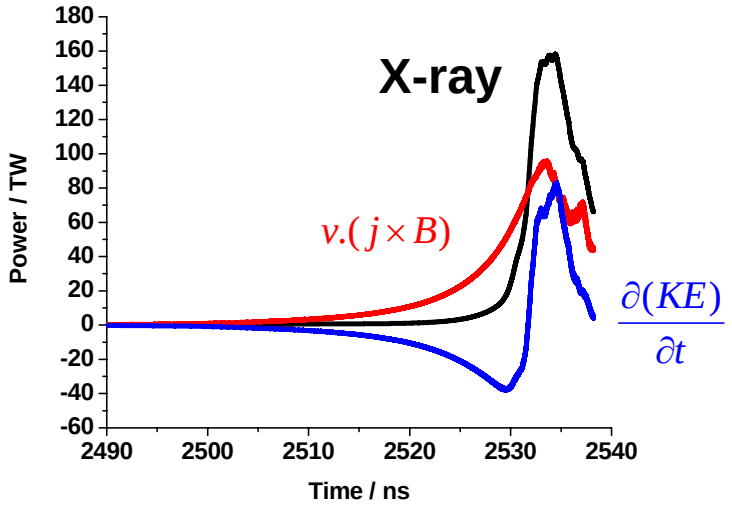
Simulations are 3D, full array height 100 micron resolution using a reduced wire number (120) and imposing a 10% mass perturbation

Obtaining the correct x-ray pulse requires obtaining the correct IV power delivered

Generator continually supplies Kinetic Energy as it is thermalized







IV power delivered by the generator predominantly goes into magnetic field or kinetic energy

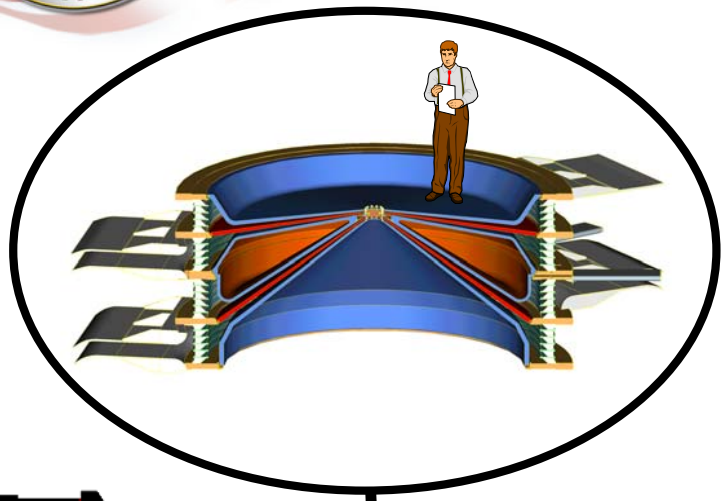
Work done on plasma initially builds up kinetic energy, but remains high throughout stagnation

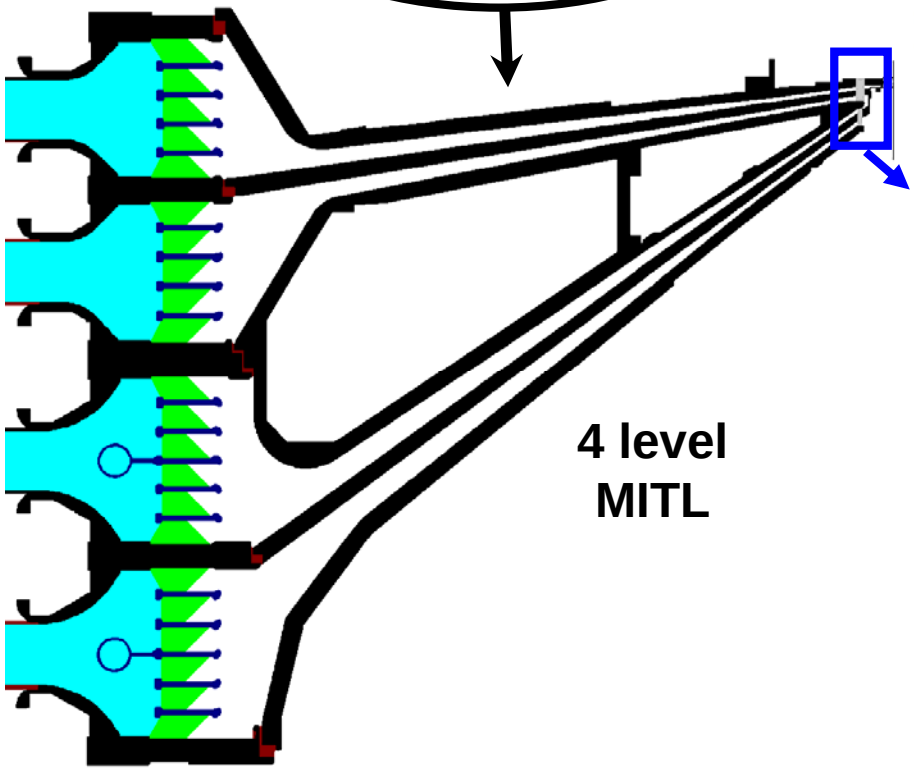
At stagnation IV power supplied is mainly seen as work done on plasma

IV ~ v.(jxB)

IV generator power ~v.(jxB) continues to contribute ~100TW throughout x-ray pulse. Correct x-ray power requires correct IV power delivered throughout stagnation

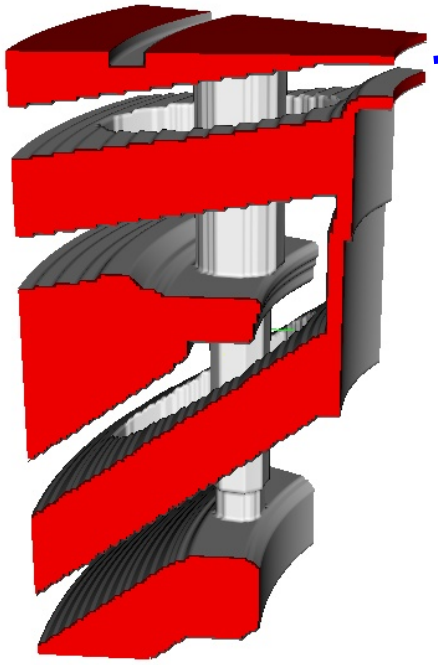
Hardware to include in the model



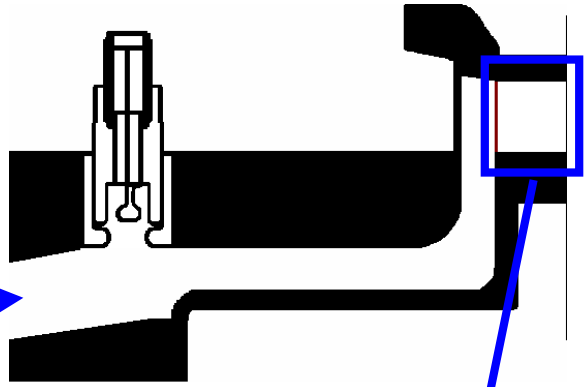


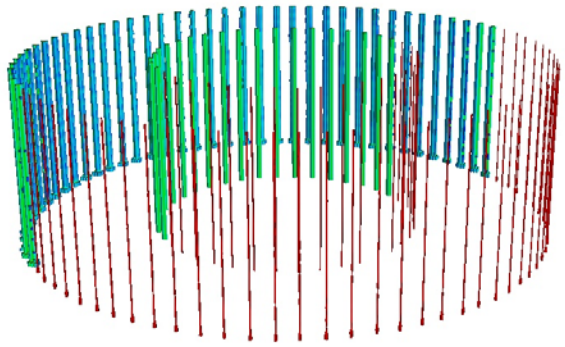
4 level
MITL

Double post
hole
convolute



Feed to load

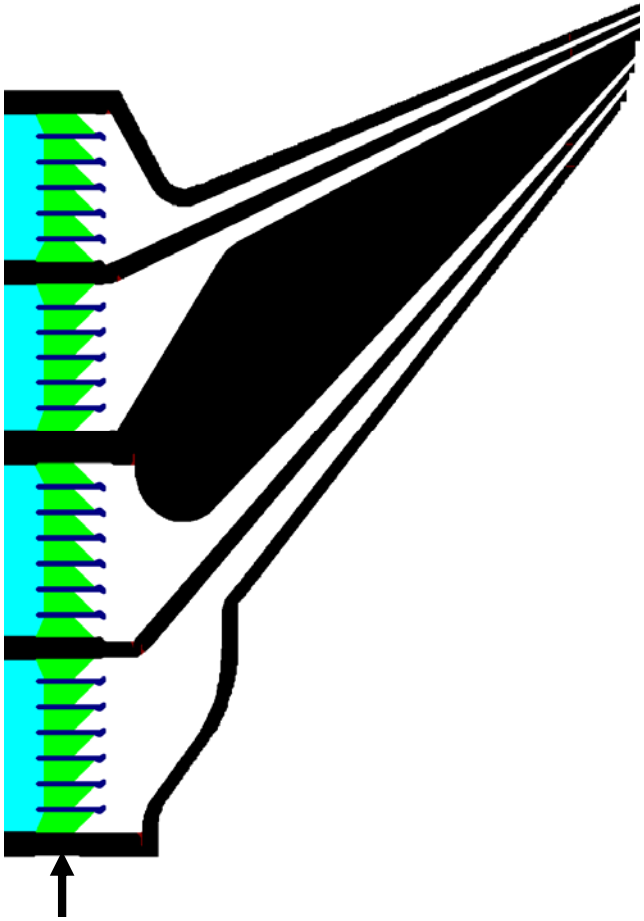




Wire Array Z-pinch

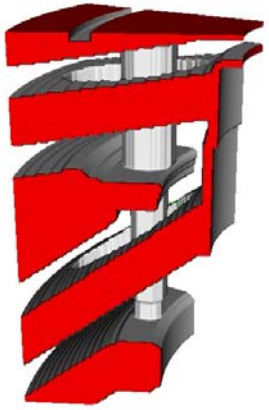
A significant current loss is known to occur at the convolute

4 level MITL

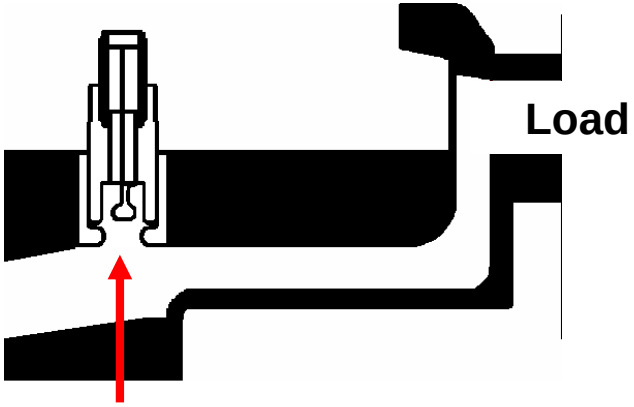


Stack Current

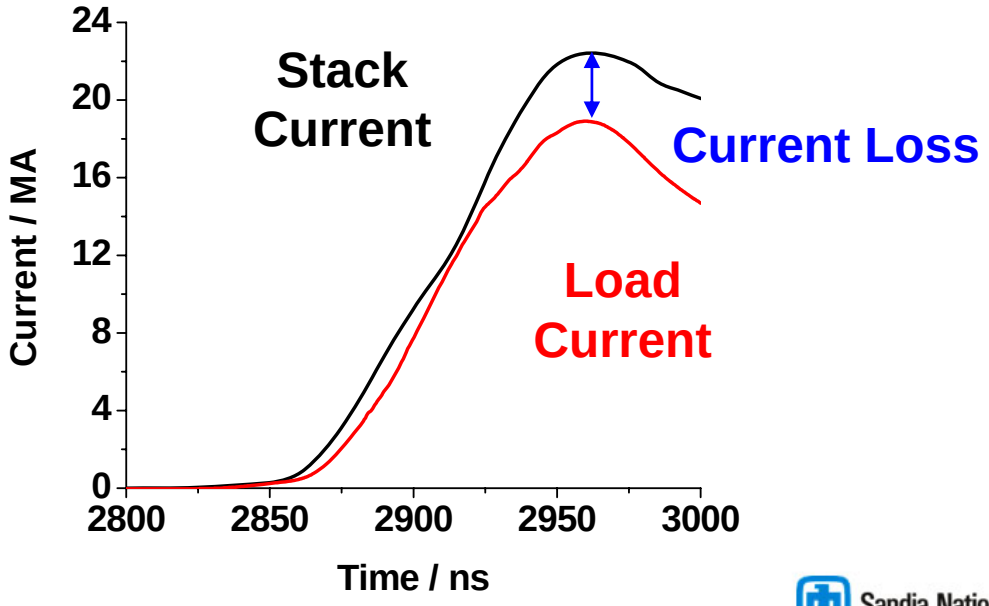
Double post hole convolute



Feed to load

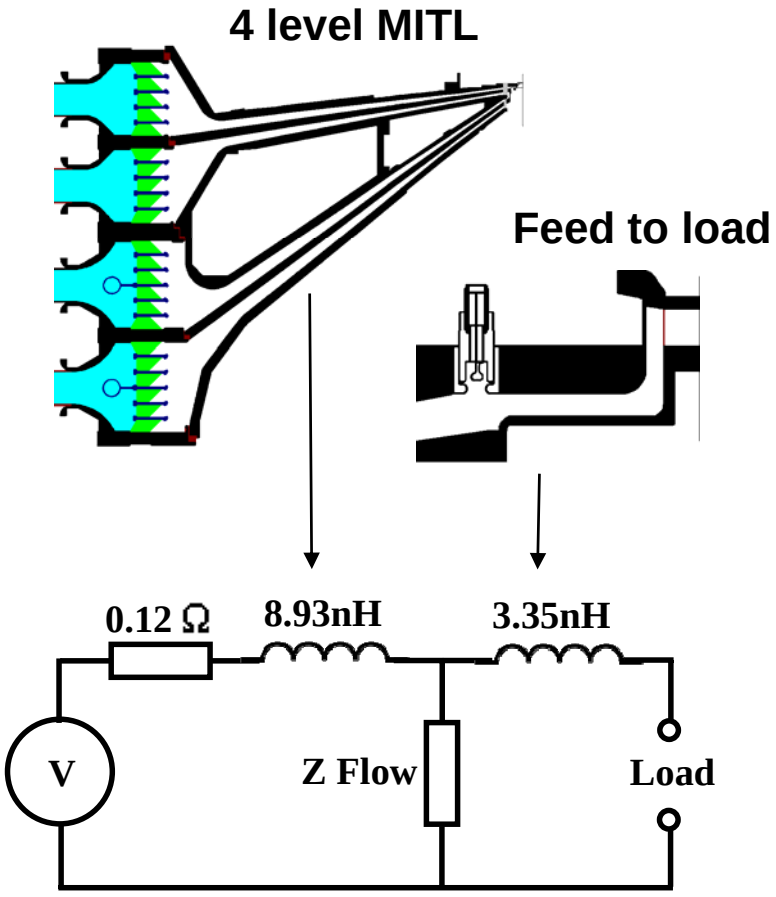


Load Current



For Z-pinch simulations the generator is typically reduced to a simple circuit equivalent

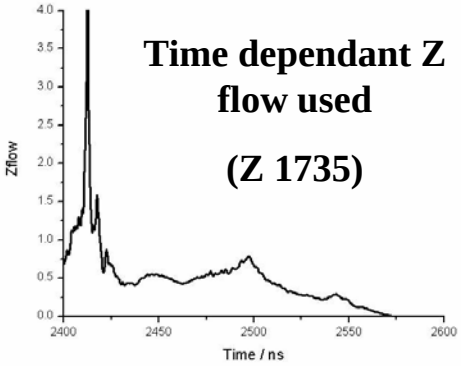
Simple circuit representation of Z



Electron flow current assumed to be lost where magnetic insulation breaks down in the convolute

$$Z_f = \frac{V}{\sqrt{I_A^2 - I_C^2}}$$

$$Z_f = 0.2 \rightarrow 0.5$$



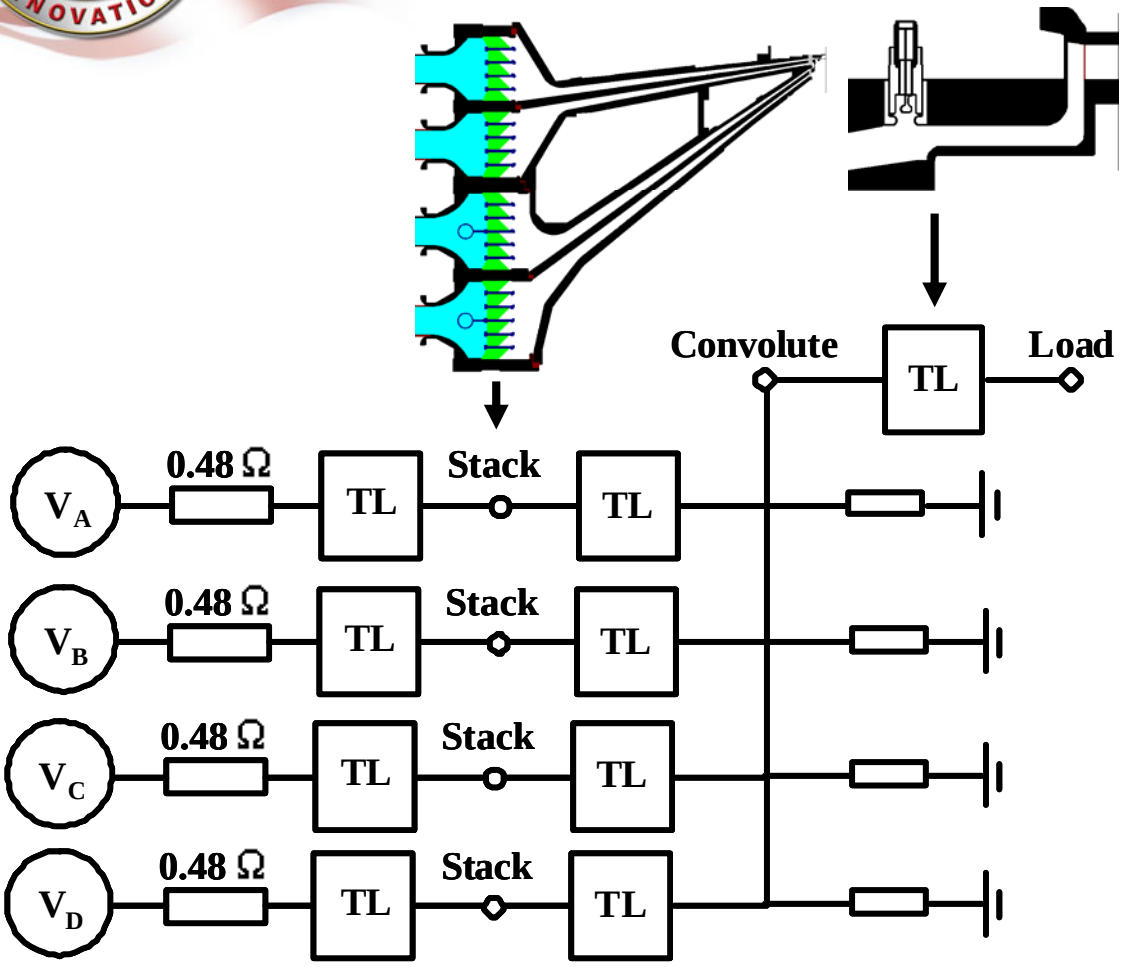
Time dependant Z flow used

(Z 1735)

Loss has been calculated assuming a constant flow impedance set to produce correct peak current loss

Better agreement has been obtained from a time dependant flow loss calculated for each specific shot

Simple circuit replaced by 4 transmission line equivalent



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

Flow loss calculated from vacuum impedance of the transmission lines

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

P. Ottinger, Phys Plas 13, 063189

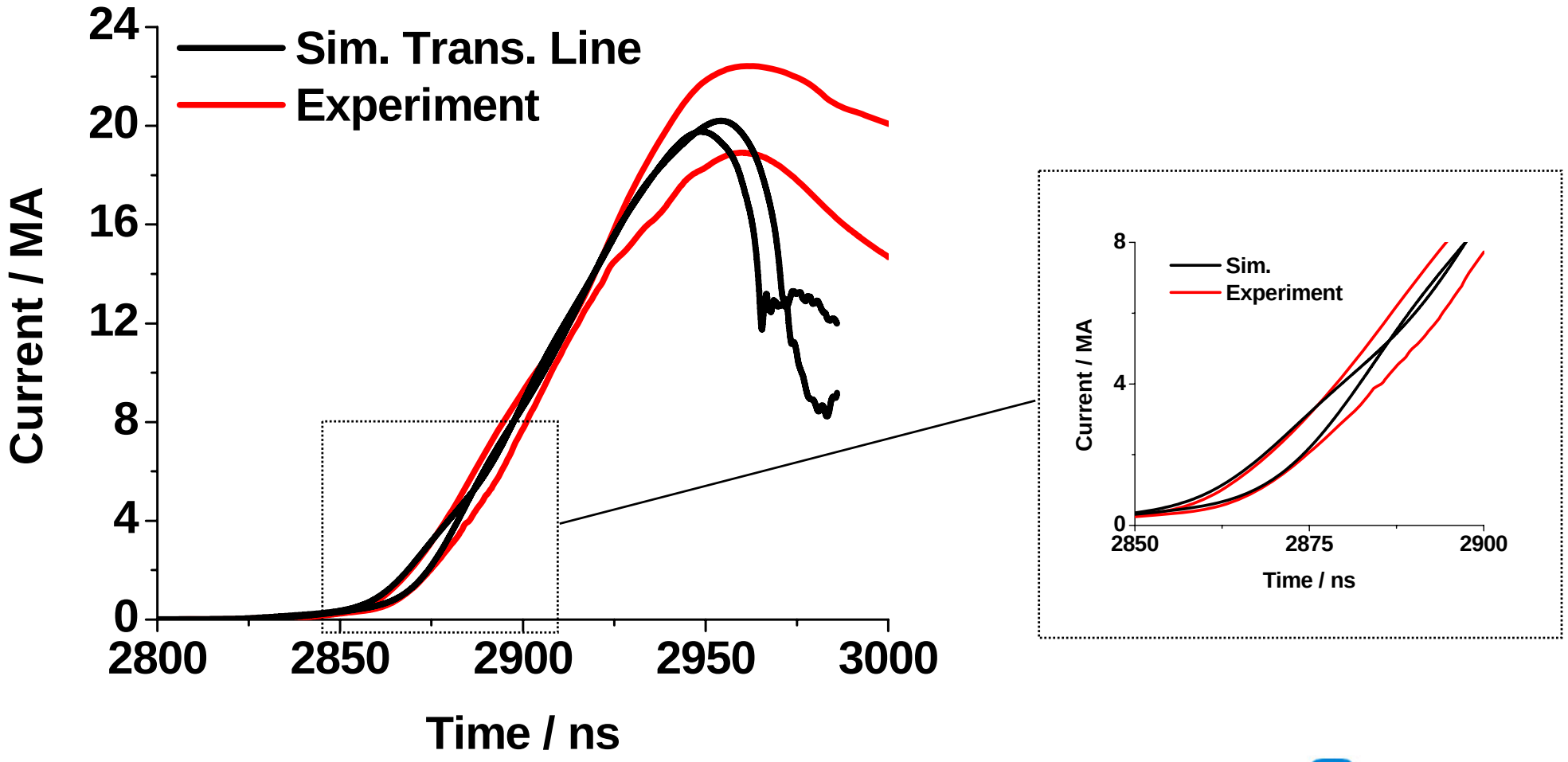
$$Z_v = Z_0\left(1 - \frac{vt}{g}\right)$$

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

Initial separation of currents due to different transmission line lengths feeding convolute

Transmission line circuit model without current loss

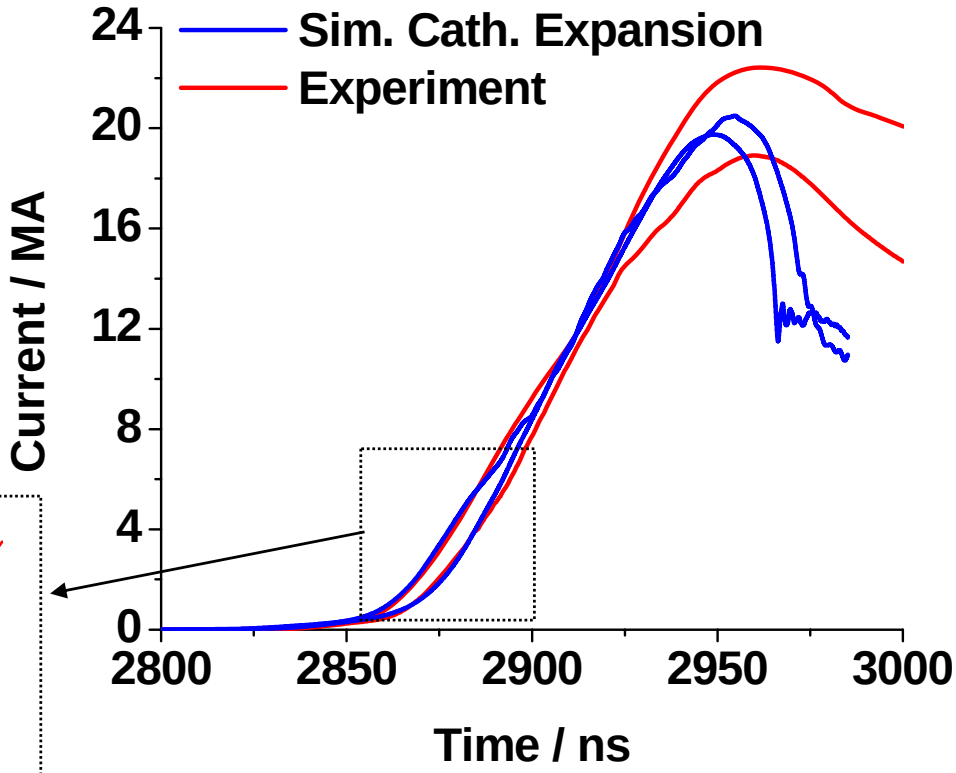
4 lines of feed are different lengths resulting in small separation of summed currents at the start of the current rise – not to be confused with a current loss



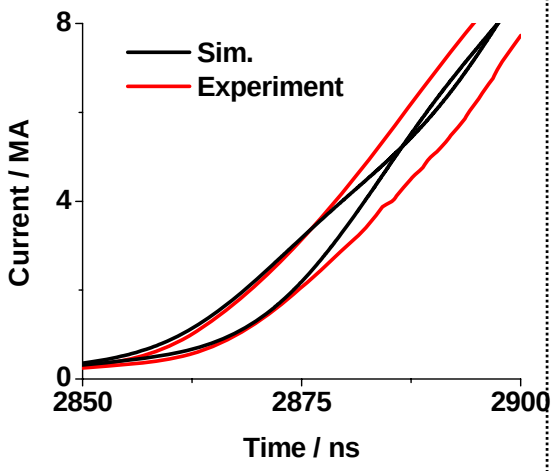
Flow loss too small at late times to account for measured loss

Including electron flow loss provides current loss at start of current rise, but loss is negligible at peak current

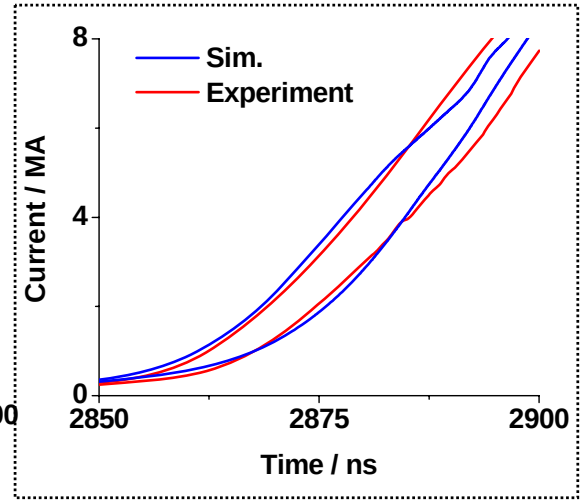
Flow loss with 2.5 cm/μs cathode expansion



Transmission line (no loss)

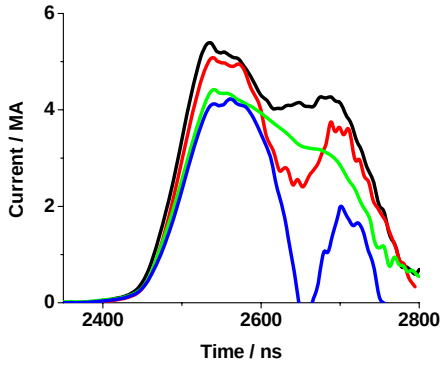


Transmission line (flow loss)

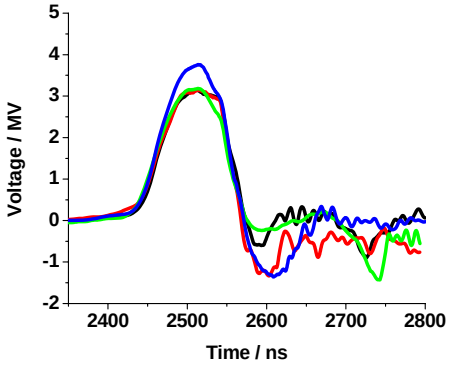


Voltage and Current into convolute inferred from Stack Measurements

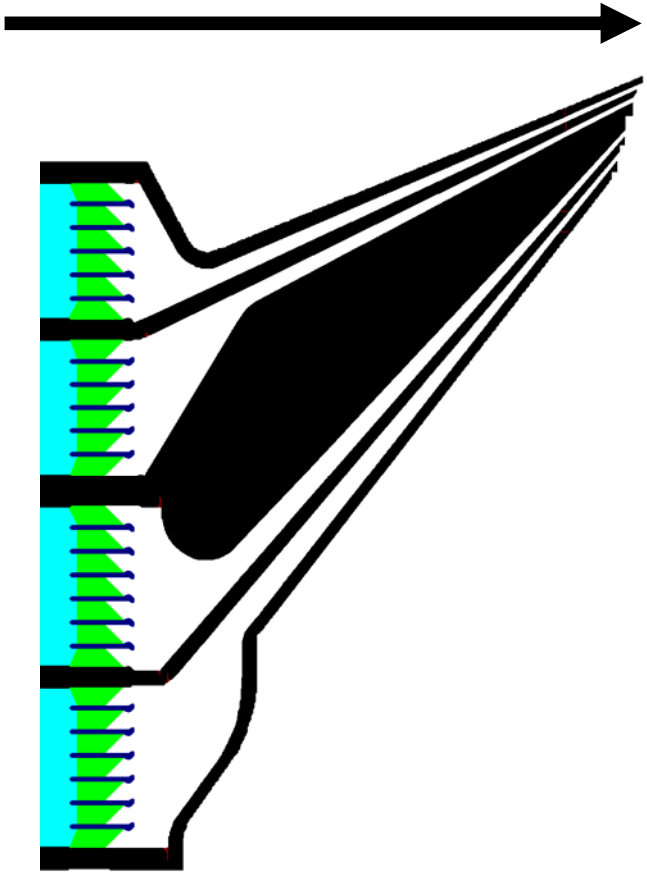
Translate stack voltage and current measurements through known transmission lines to obtain the total current and average voltage at the convolute

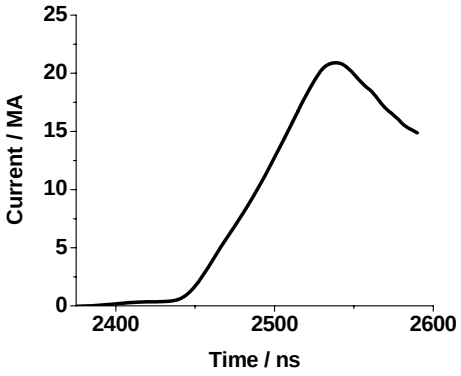


Stack Currents

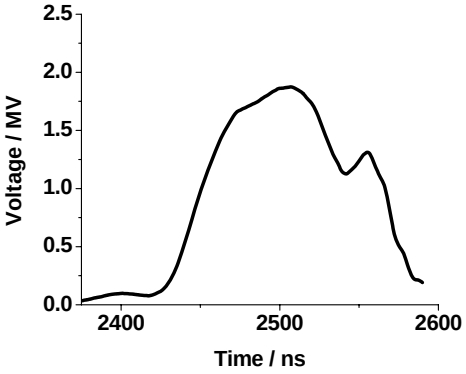


Stack Voltages





Total Current into Convolute



Average Voltage at Convolute

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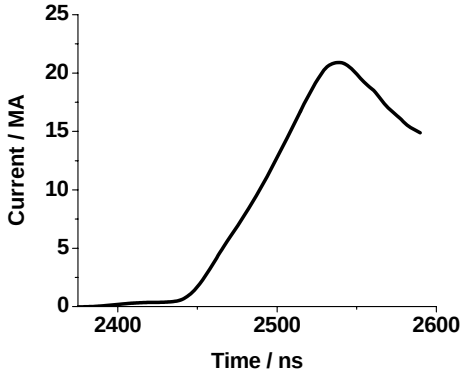
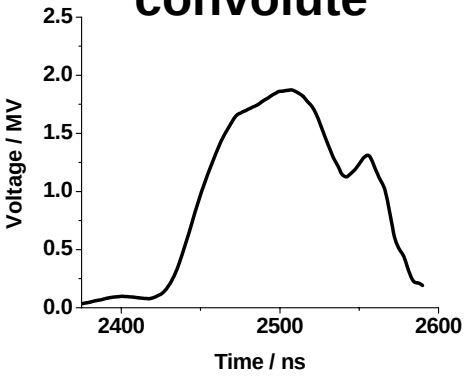
From stack measurements and load B-dot can calculate impedance of convolute loss

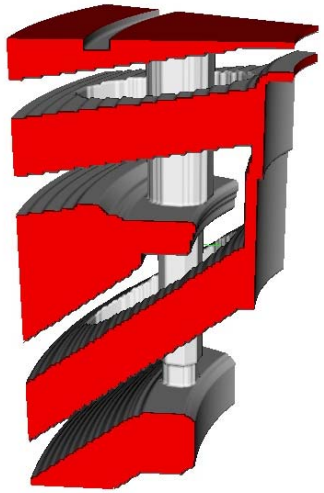
Current In
(Translated Stack Measurements)



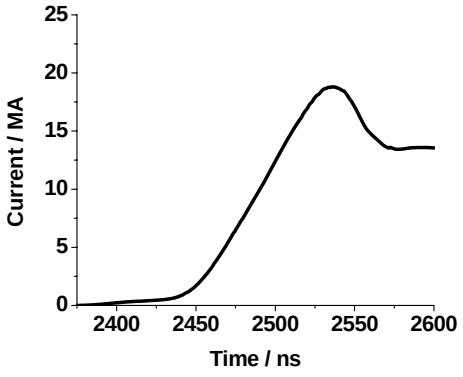
Voltage at convolute



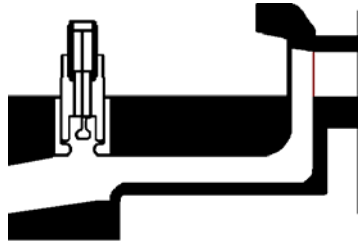
Double Post Hole Convolute



Current Out
(Load B-dot)



Load B-dot

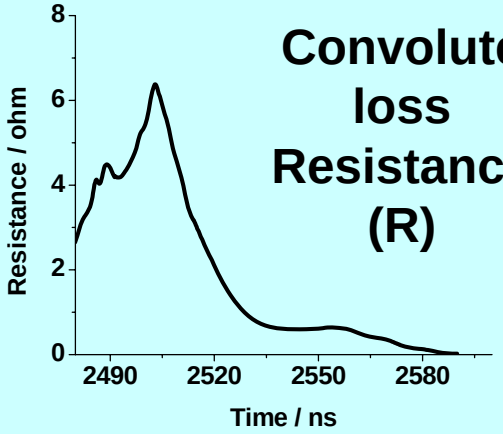


Load B-dot just measures current out of convolute – not necessarily the current into the load

We know the voltage and the current lost, so we know the loss resistance

$$V = (I_{in} - I_{out})R$$

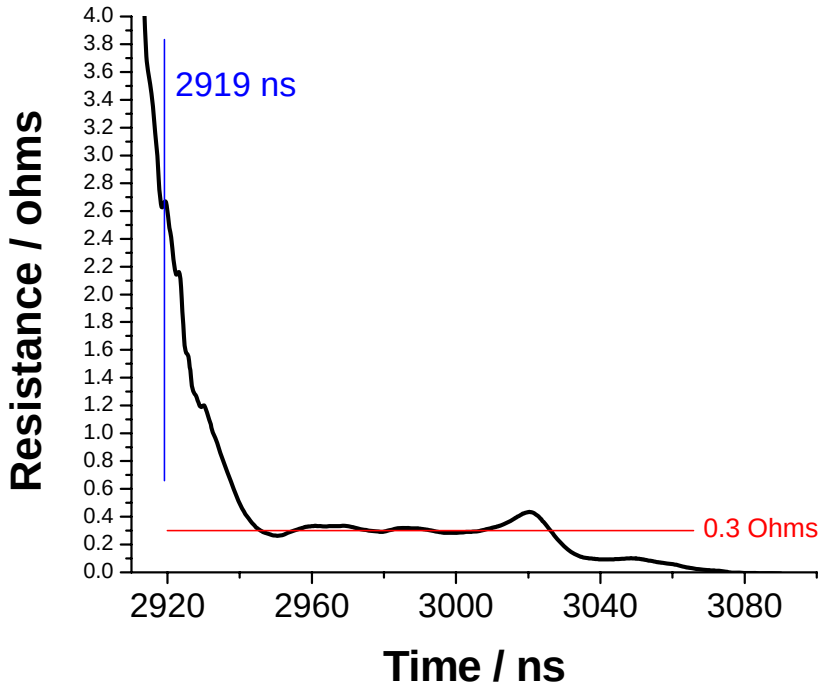
Convolute loss Resistance (R)



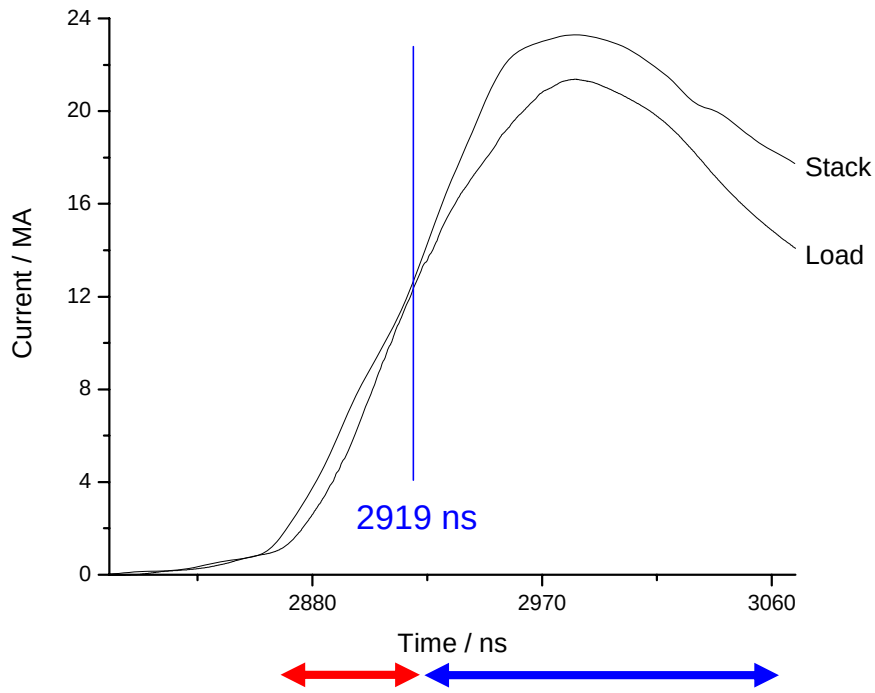
Convolute impedance suddenly collapses half way up the current rise consistent with short forming

Z 1787 - 19.5mg, 20 mm diameter Compact Array

Loss resistance



Load and Stack Currents



Flow Loss + Transmission line effects

Resistive convolute loss

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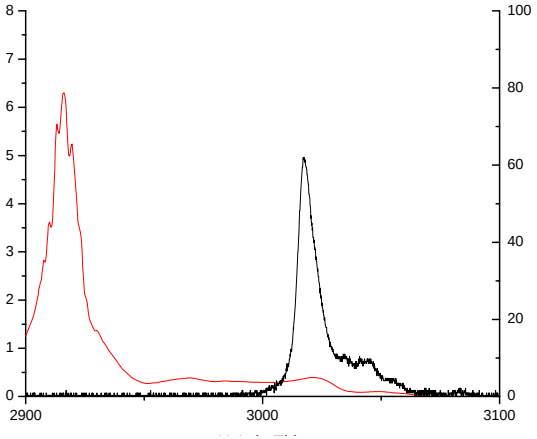
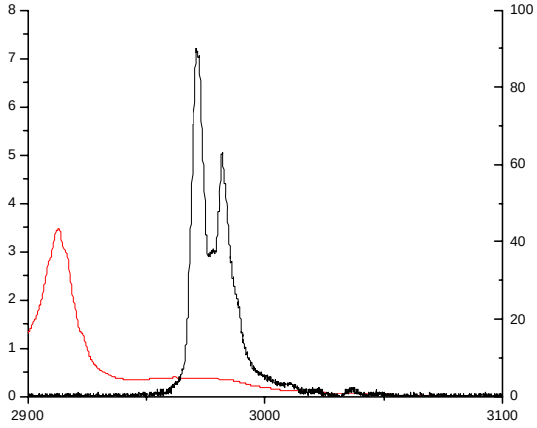
Convolute resistance remains roughly constant before further decaying after x-ray pulse

1787 (19.5 mg)



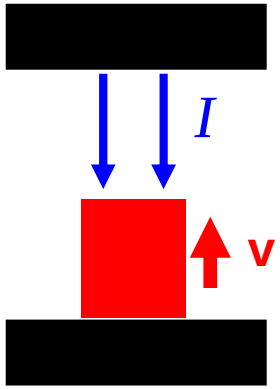
1786 (6 mg)



Convolute impedance collapses to roughly constant impedance for 1786 and 1787. Following x-ray pulse convolute impedance decays further

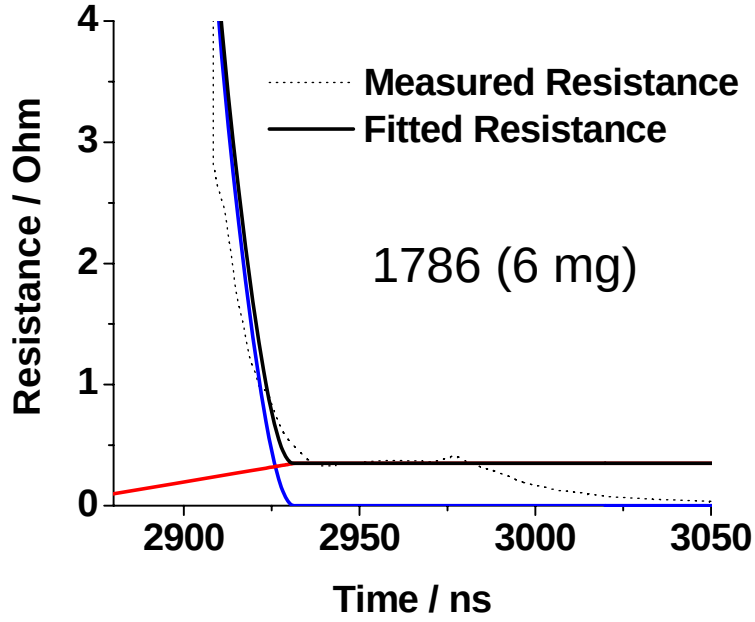
Convolute loss resistance can be fitted to resistive plasma gap closure

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



$\eta = 0.035$

v = 21 cm/ms



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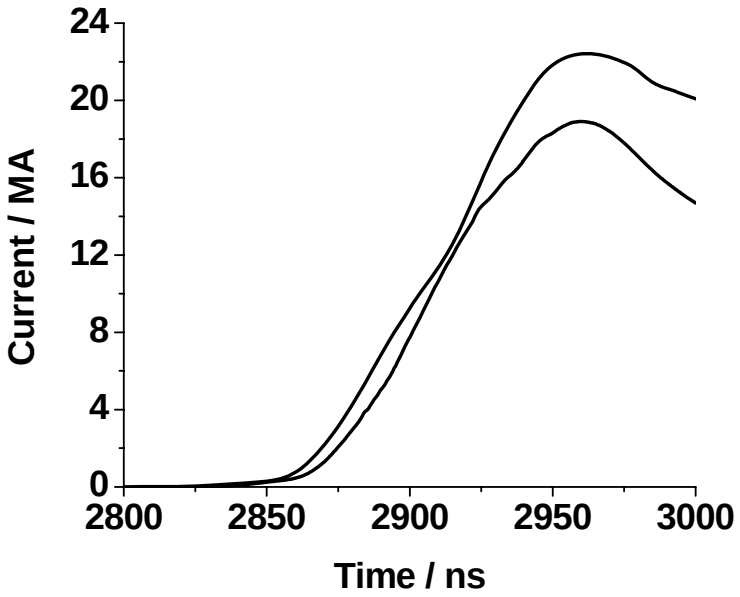
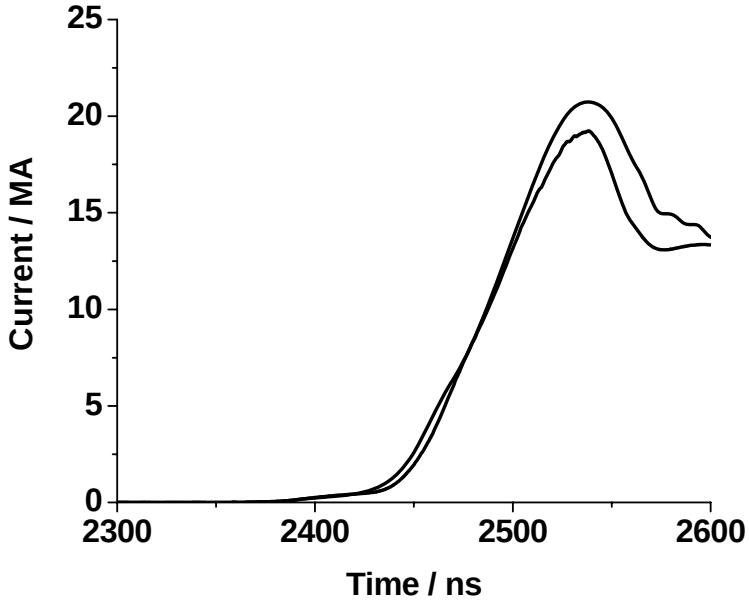
Behavior of currents qualitatively the same for ZR and Z so same mechanism could have been at work on Z

Z shot 1786 (6 mg ZR)



Z shot 1097 (6 mg Z)



Re-tune ZR shorting model for Z

ZR

Expansion velocity 20cm/μs

Effective area 15cm^2

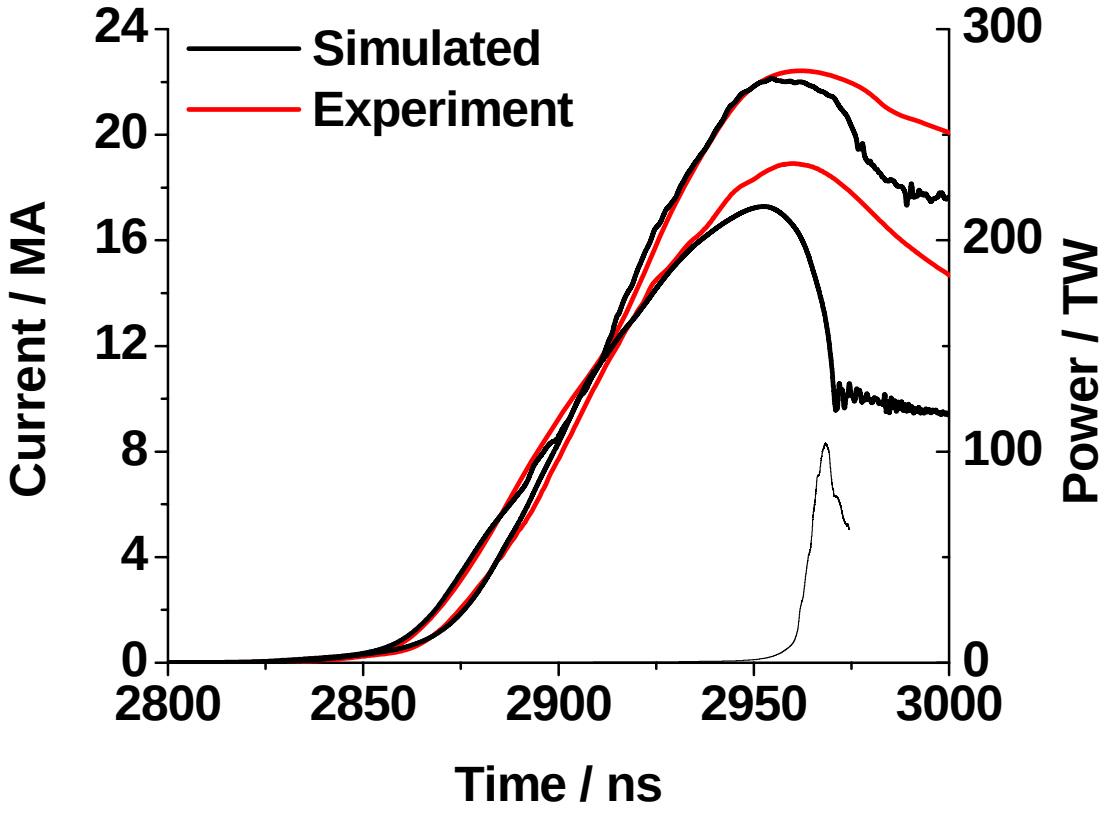
Z

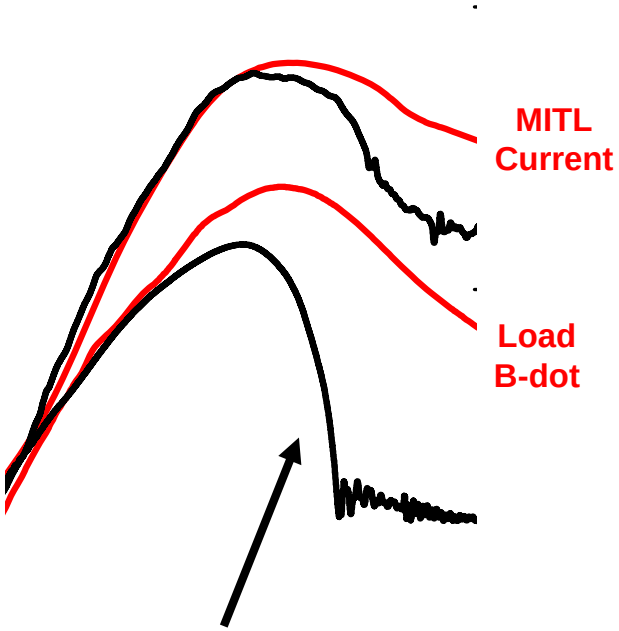
Expansion velocity 17cm/μs

Effective area 5cm^2

Put everything together for 6mg array implosion on ZR and get the wrong answer

- We know the forward going voltage for the generator (stack measurements)
- We know the flow loss and what all the transmission line hardware looks like
- We know what the time dependant convolute loss resistance is for a given shot
- We know how to do MHD (hopefully)

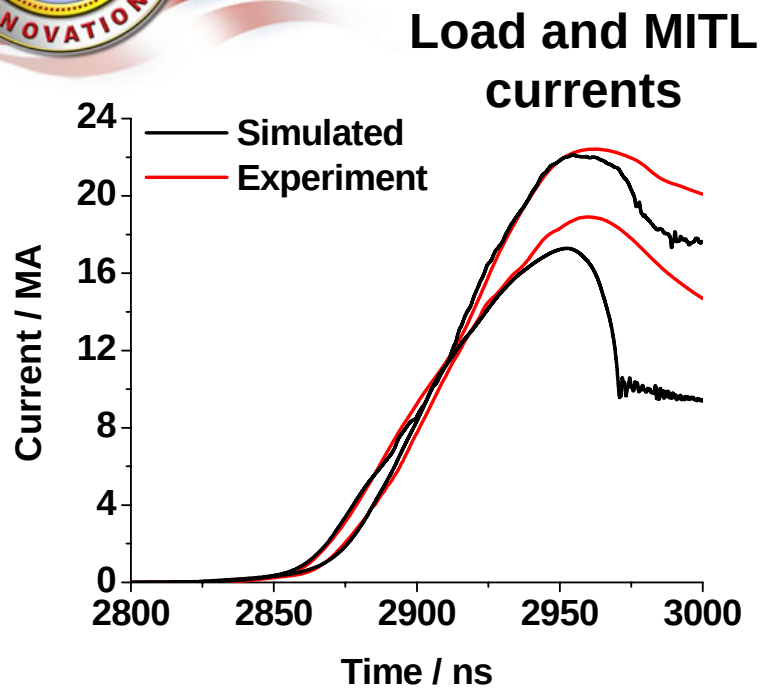


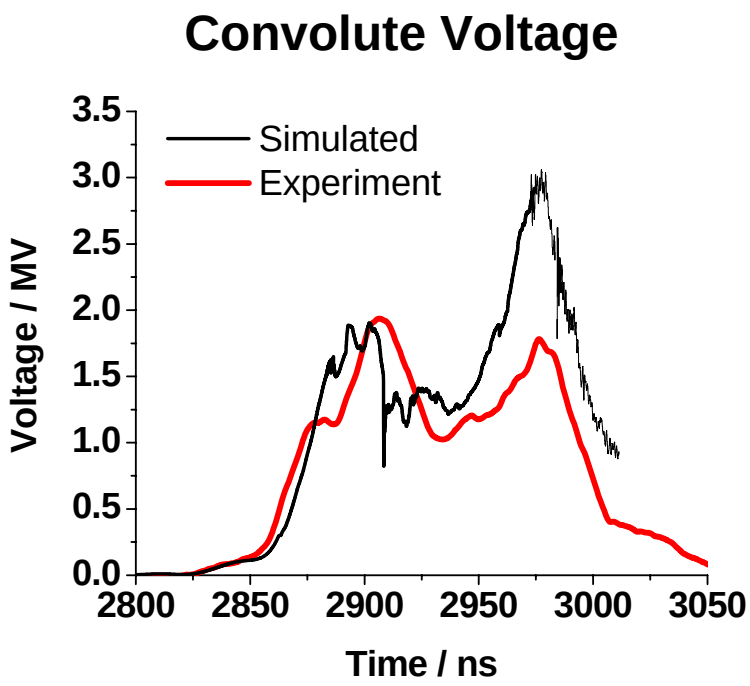


Simulated currents roll over too soon and drops too quickly compared to measurement. Current is continually dropping through power pulse.

Simulated currents don't agree with measured currents through x-ray pulse

What's going wrong ?





When driven with the correct forward going voltage wave, and using the correct convolute loss an imploding array is producing too high a voltage (as seen at the convolute) which is resulting in too great a drop in current

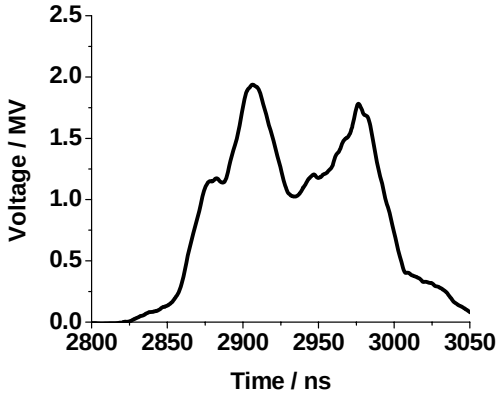
There is little reason to think that either the stack monitors or load b-dots are failing so we should be matching these measurements

We are recording neither the correct voltage or the correct current during the x-ray pulse, so our IV power delivered is questionable

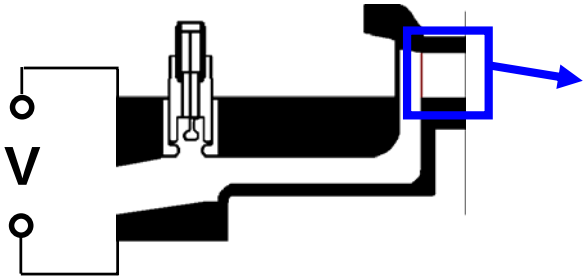
Is this a problem with the power feed, or a problem with the MHD ?

We know the convolute voltage – what current can that support in an imploding load ?

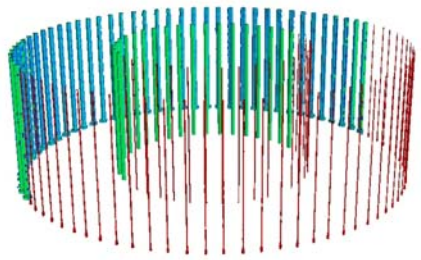
Convolute Voltage



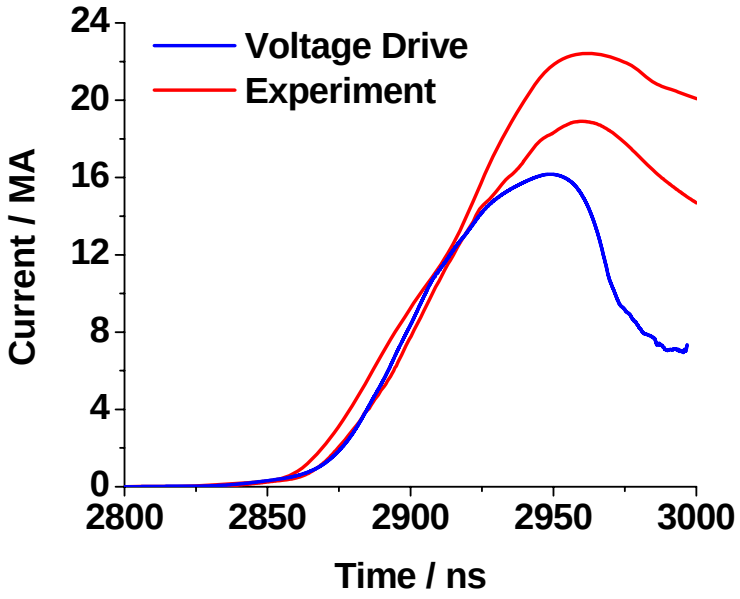
Load
B-dot



MHD



Known convolute voltage can be used to drive final feed line and the MHD calculation to see what current can actually be supported by an imploding load



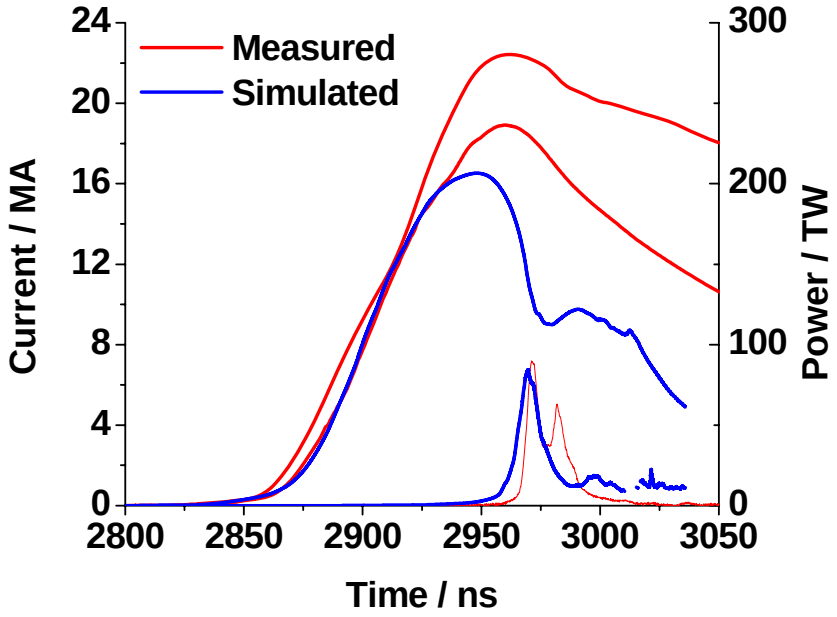
- Current supported by the convolute voltage is lower than the measured B-dot signal
- Convolute voltage **cannot** support measured load current for an imploding load
- Does the B-dot truly represent the load current ? Or is the MHD wrong ?

Good Agreement with X-ray powers so MHD is probably fine

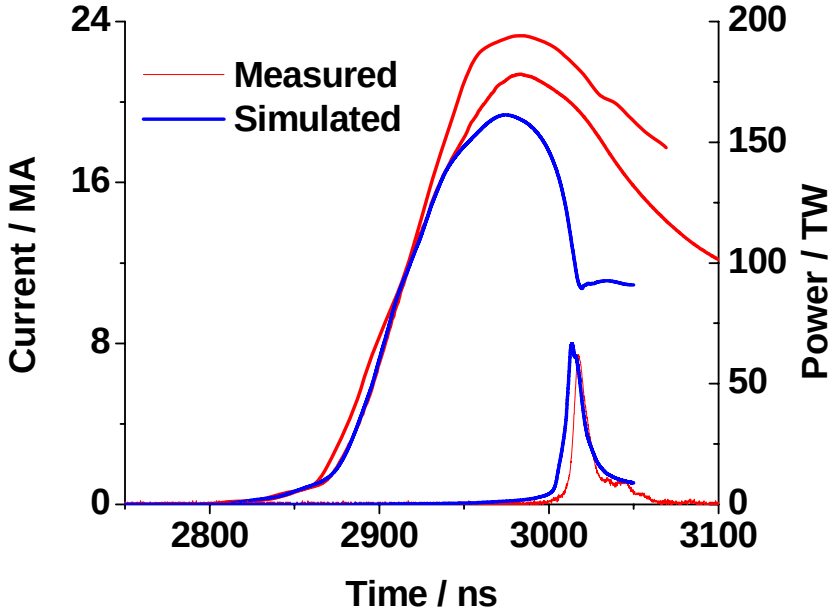
Despite significantly less load current than measured by the B-dot, the simulation is able to retain good agreement with x-ray powers.

As far as the simulation is concerned the power output is consistent with the lower current delivered to the load.

Highly probable there's current loss downstream of the B-dot, in parallel with the load



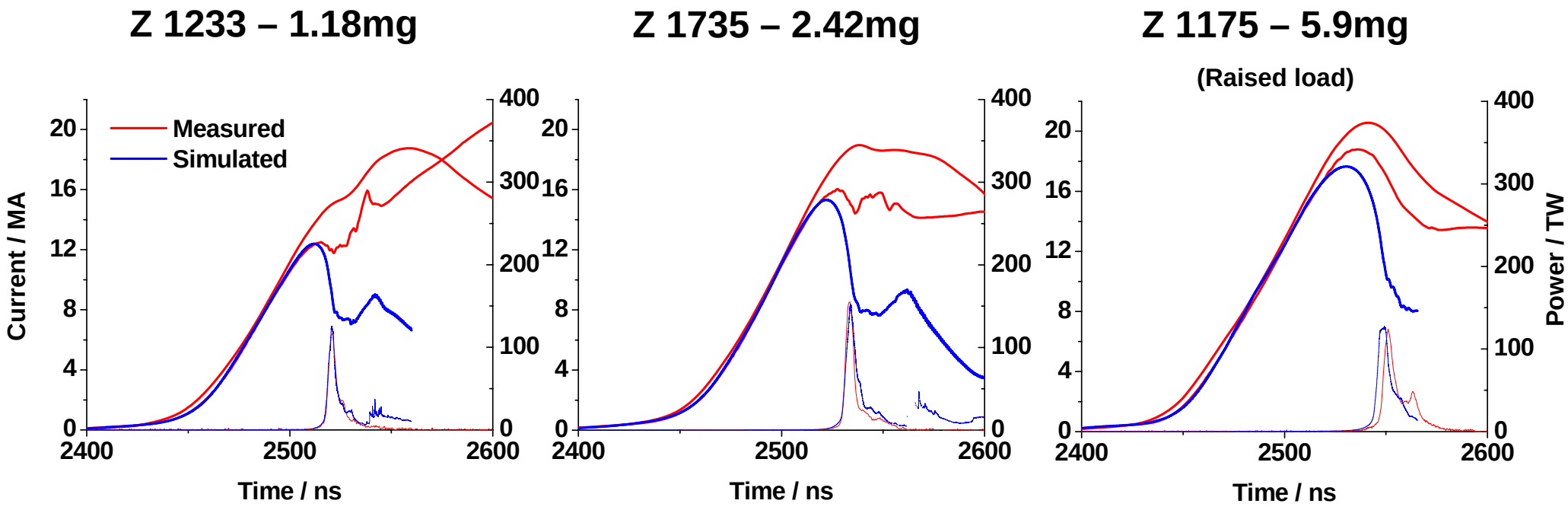
Z 1786 - 6mg Array



Z 1787 – 19.5mg Array

Both arrays are tungsten, 20mm in diameter, 10mm tall

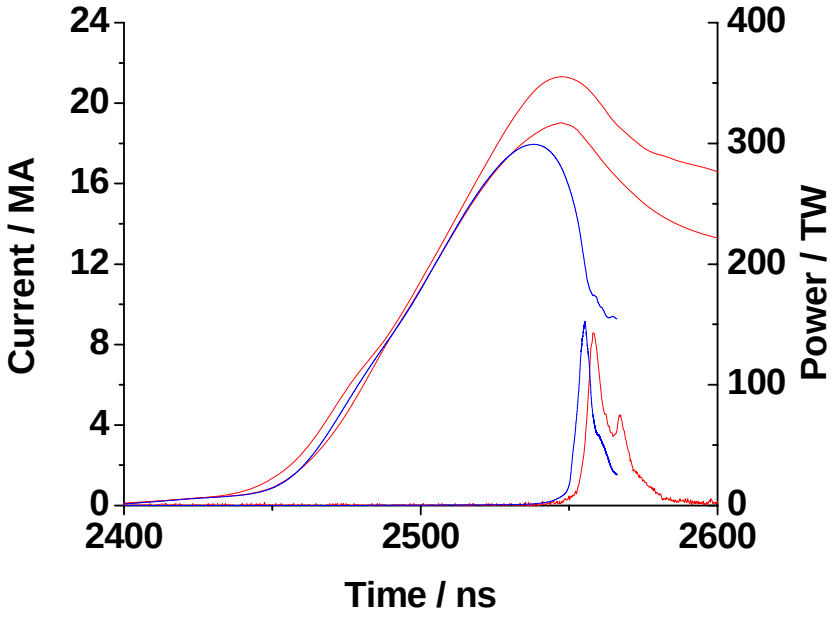
Mass scan shows current loss increasing for higher masses / longer implosion times



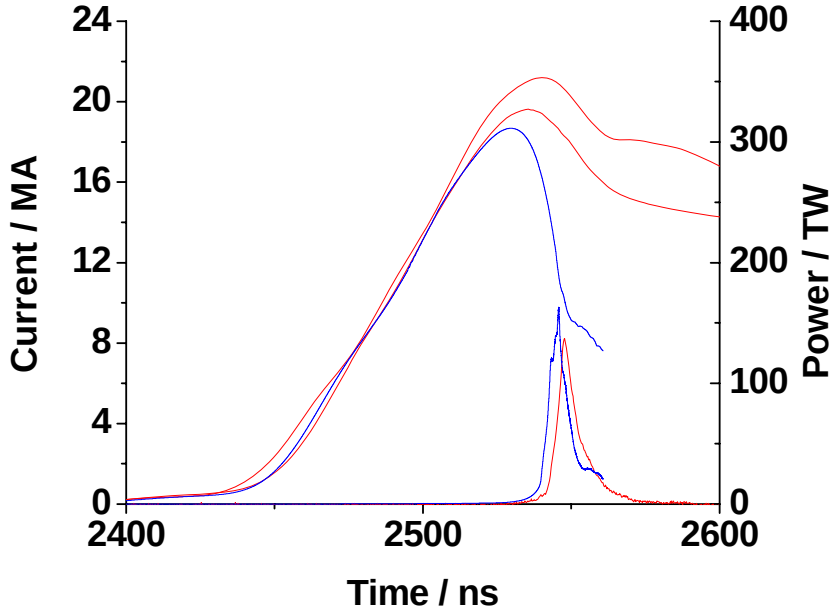
Current loss in the final feed is always significant at stagnation, and becomes increasingly significant at peak current as we progress to higher masses with longer implosion times

Current is lost for both 2mm and 4mm AK gap, yet x-ray power agrees (Stygar shots)

Z 818 – 6mg – 4mm AK gap

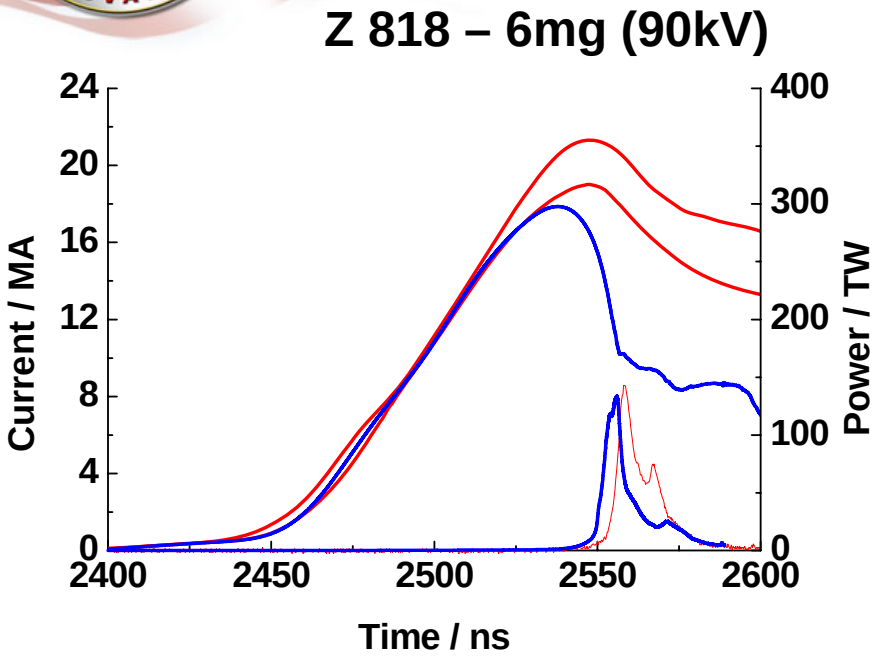


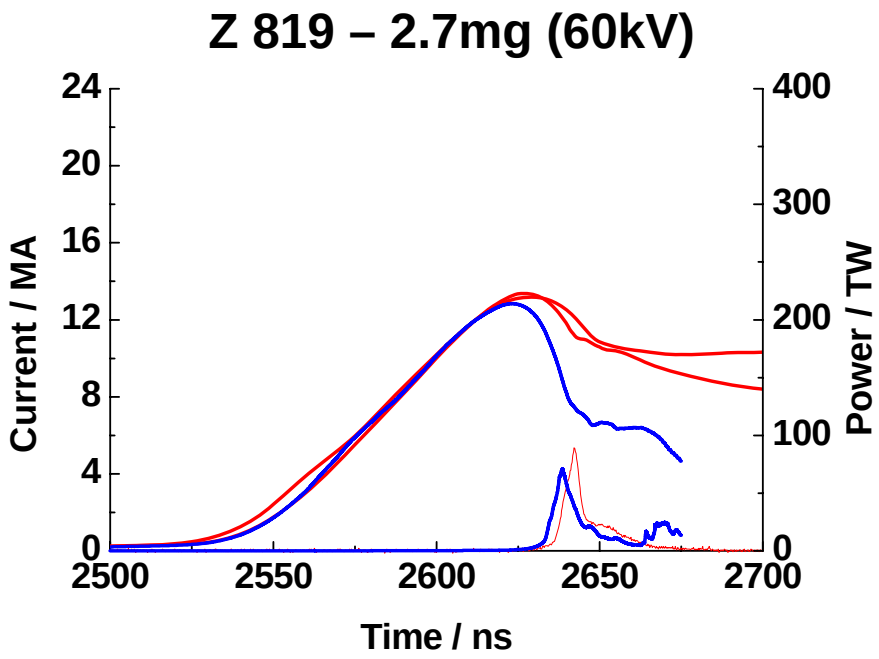
Z 597 – 6mg – 2mm AK gap



6mg later implosion time shots driven from voltage consistently give slightly early x-ray power. Current supported by the voltage is an upper limit of current available, since a loss in the vicinity of the load before the load inductance starts to rise will not influence the voltage. The voltage will be dictated just by the feed inductance before the loss, so actual current loss may be greater at earlier times, sufficiently delaying implosion.

Current scaling 'may' be changed by the difference between perceived and actual load current





Experiment $P \propto I^{1.32}$

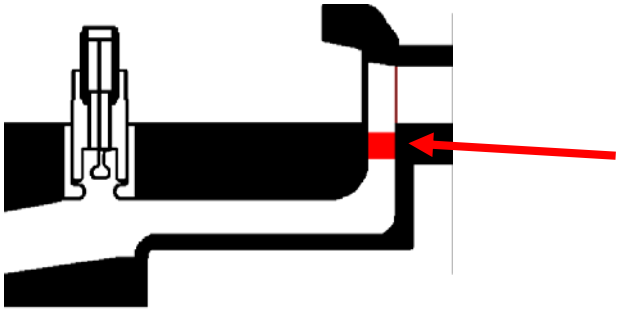
Simulation $P \propto I^{1.84}$

Very, very optimistic – just from these two shots - need to analyze a lot more data

Simulation gives higher current scaling partly because actual load current is lower than perceived by B-dot, and partly due to lower power for 60kV charge

Simulated power down for 60kV charge shot, but in agreement with 73TW of Z 725 – an identical shot.
What is error on that power ? Need to re-run using Z 725

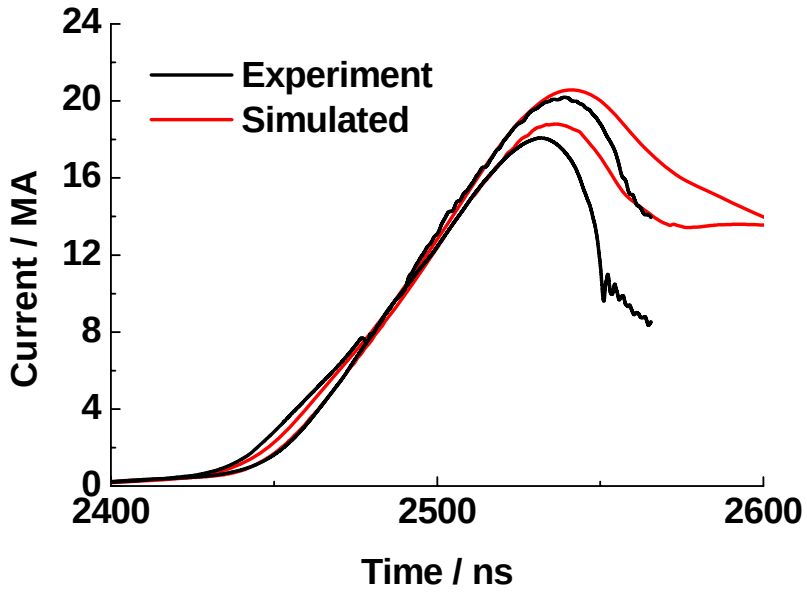
Circuit behaviors consistent with a loss in the feed



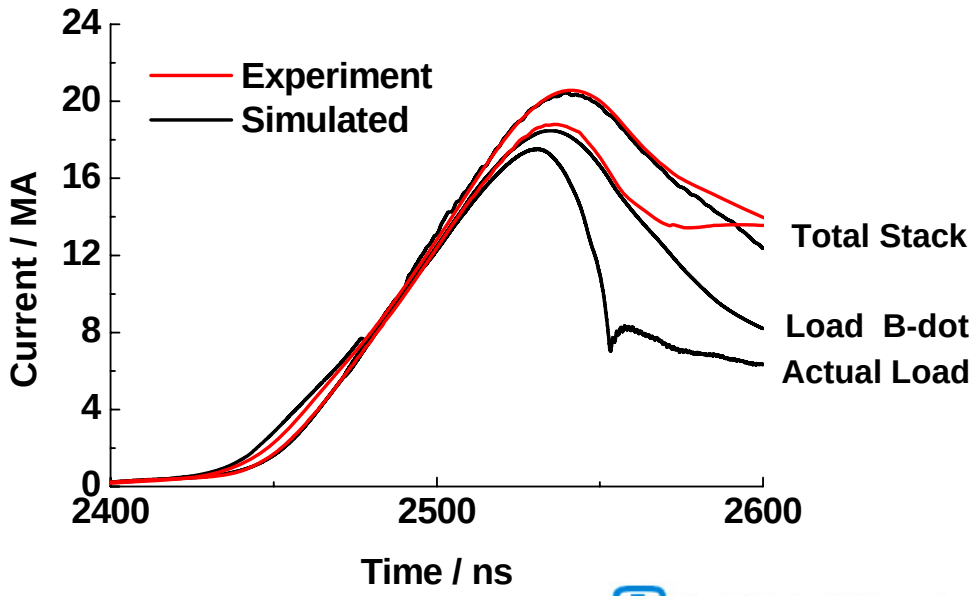
If we assume there is an electron flow loss present in the feed close to the load then we can describe current loss using a constant flow impedance, and recover good agreement with the measured load and MITL currents throughout the x-ray pulse

$$Z_f = 0.2 = \frac{V}{\sqrt{I^2_{upstream} - I^2_{downstream}}}$$

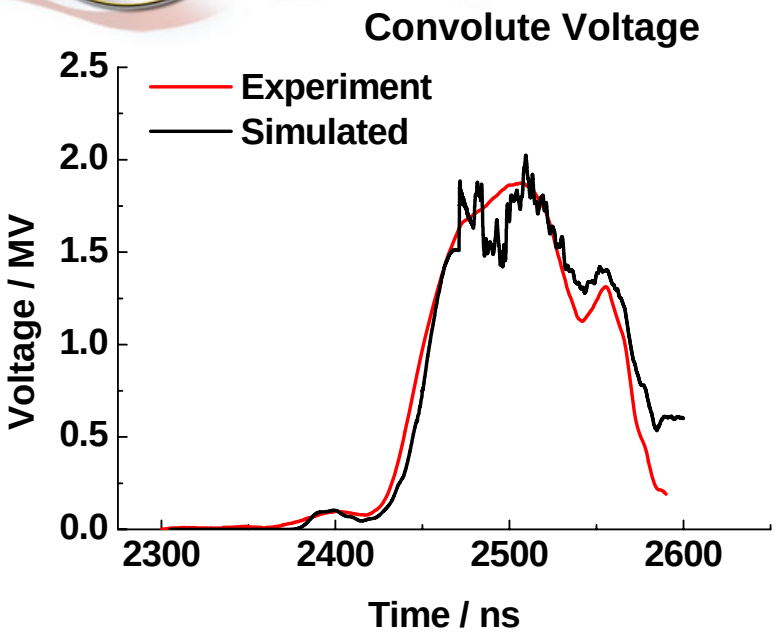
Without feed loss

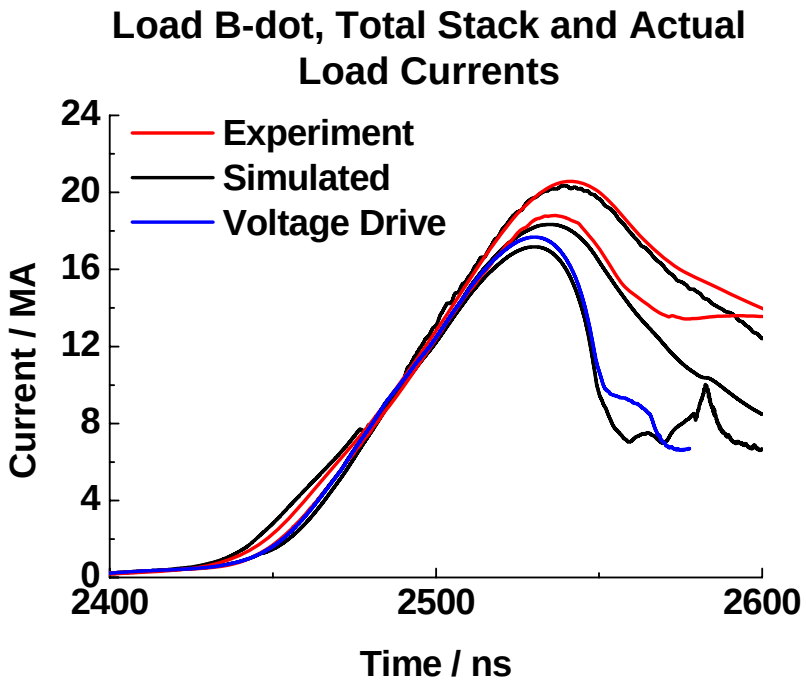


With feed loss



Electron flow feed loss produces correct convolute voltage





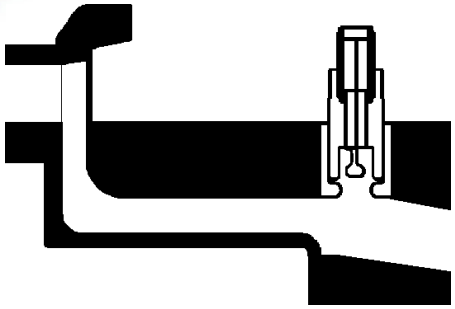
Using an electron flow feed loss produces:

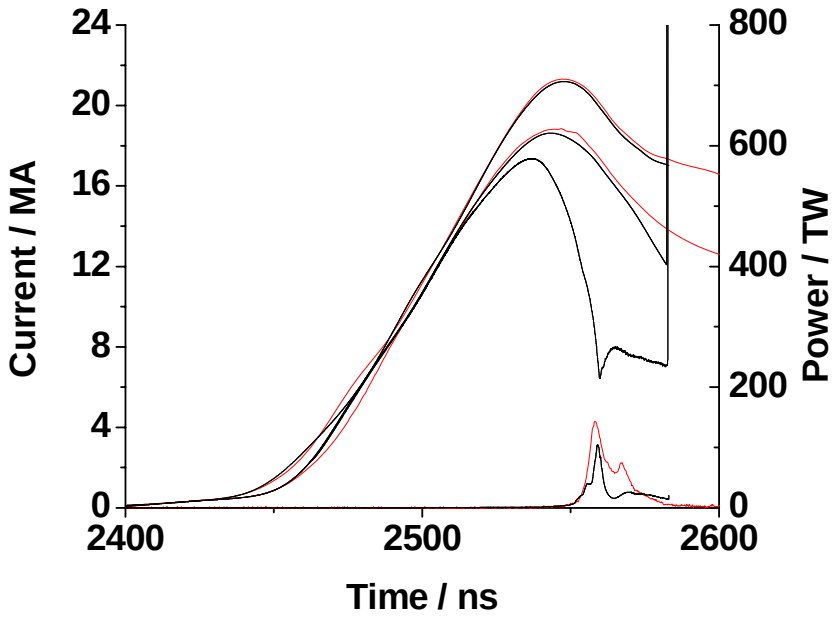
- **Correct convolute voltage**
- **Correct Load B-dot**
- **Actual load current (~same as volt. drive)**

Flow loss term not a function of AK gap. Doesn't change for Stygar AK gap scan (2D calcs.)

Z 818 – 6mg

4mm AK gap

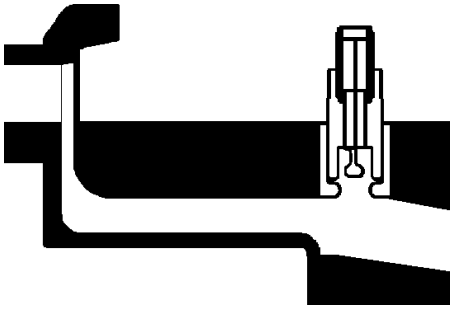


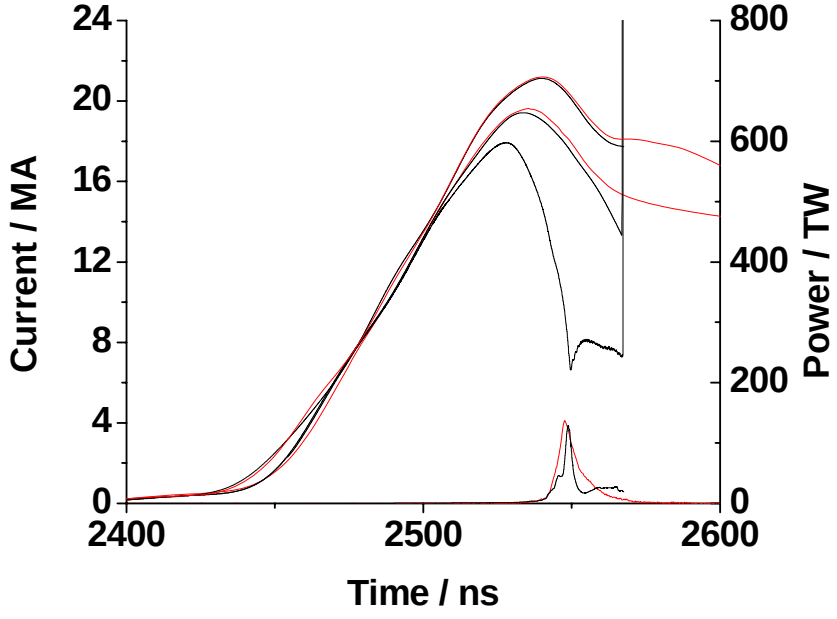


$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Z 597 – 6mg

2mm AK gap



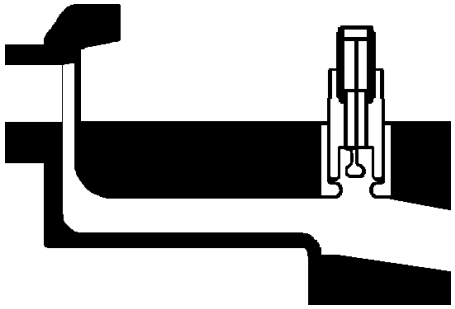


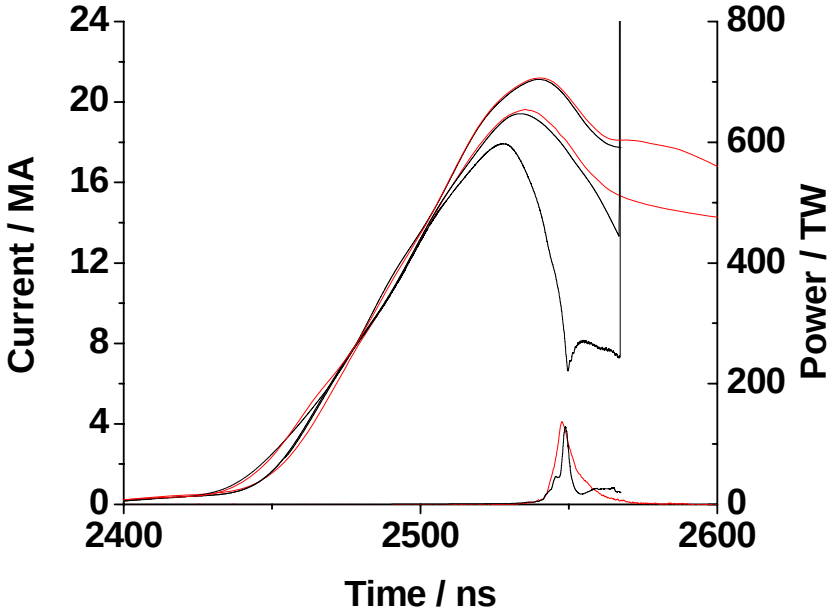
$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Loss term not a function ok AK gap area. Unchanged between standard and raised loads. 2D

Z 597 – 6mg

2mm AK gap

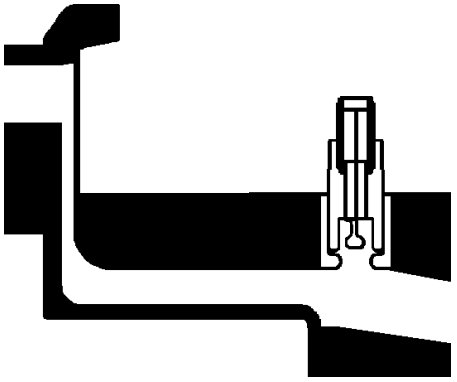


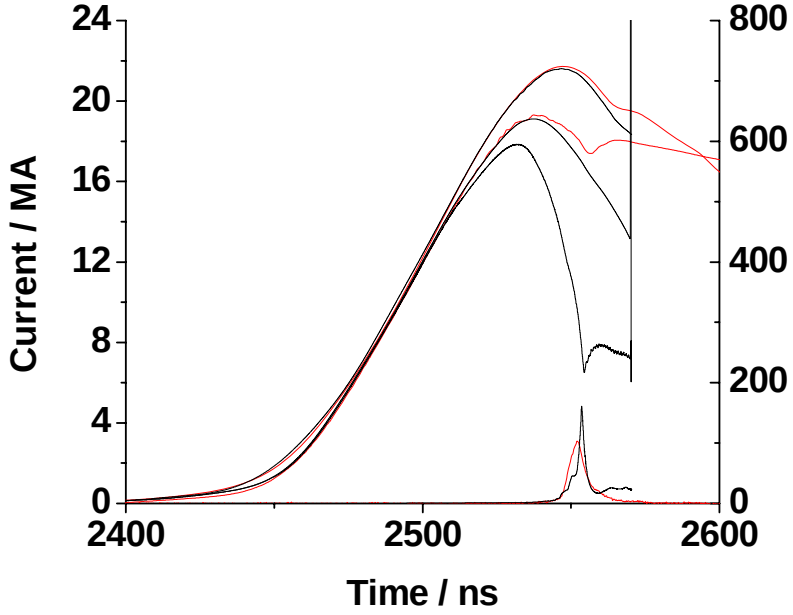


$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Z 1264 – 6mg

2mm AK gap (raised)



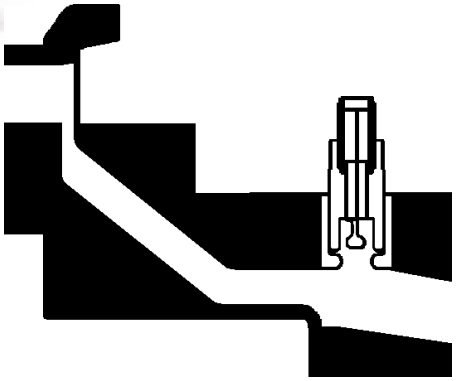


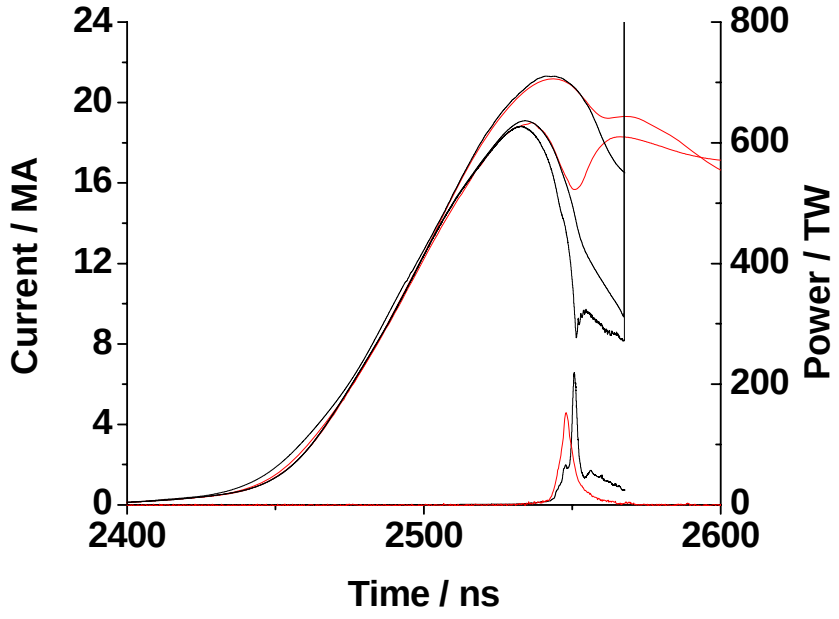
$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Conical feed significantly reduces feed loss from comparison of Bennett Rad-jet shots. (2D calcs)

Z 1332 – 6mg

2mm AK gap (conical)

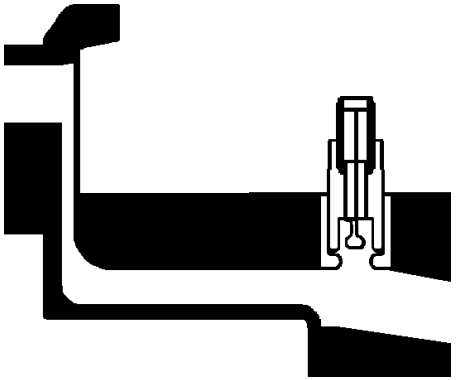


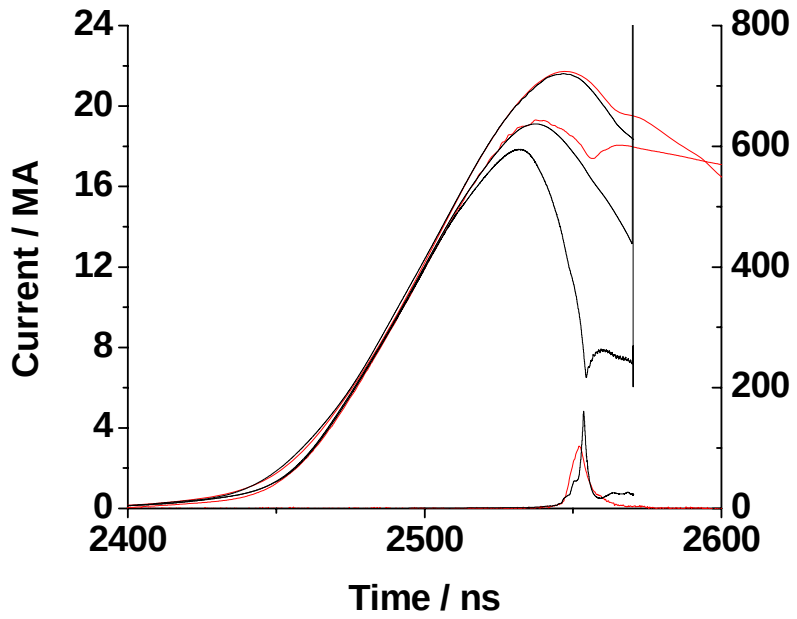


$$Z_f = 0.5 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Z 1264 – 6mg

2mm AK gap (raised)





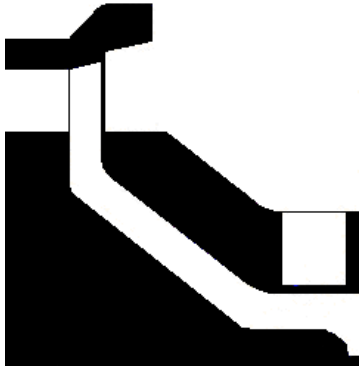
$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

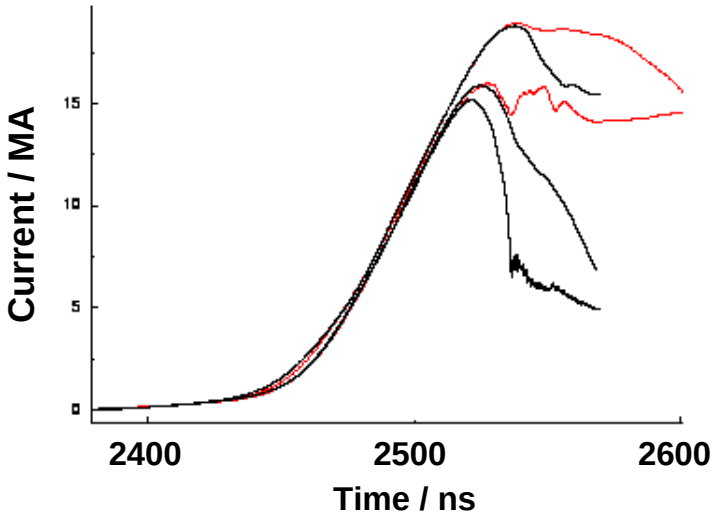
Conical feed for 2.5mg array also decreases current loss

Z 1735 – 2.5mg

5mm AK gap

(conical)



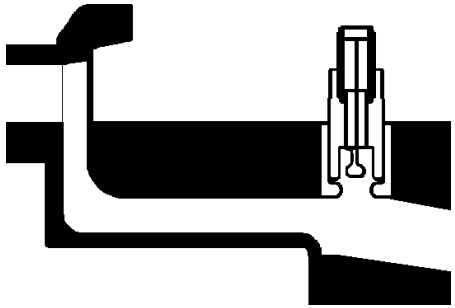


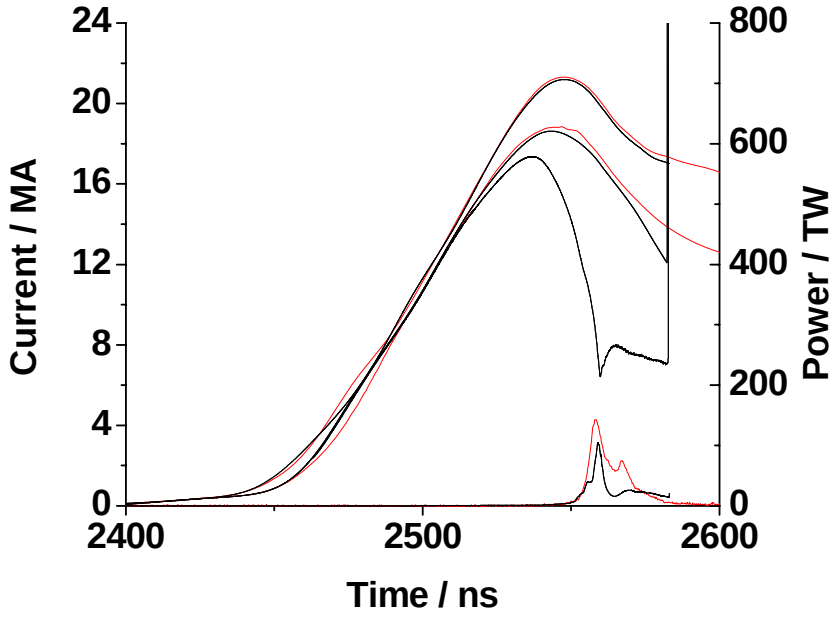
$$Z_f = 0.4 = \frac{V}{\sqrt{I^2_{upstream} - I^2_{downstream}}}$$

Z 818 – 6mg

4mm AK gap

6mm radial feed





$$Z_f = 0.18 = \frac{V}{\sqrt{I^2_{upstream} - I^2_{downstream}}}$$

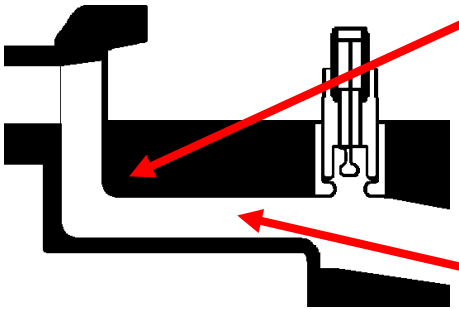
Feed loss seems slightly worse for ZR. Possibly radial feed gap change ? Or just within errors ?

Is tighter bend significant ?

ZR 1786 – 6mg

7mm AK gap

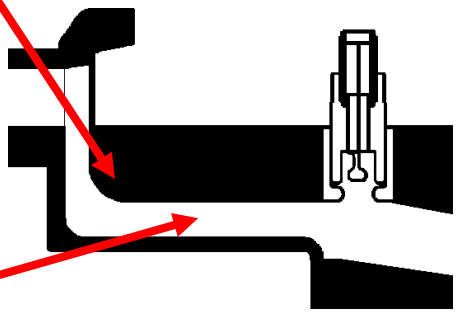
7mm radial feed



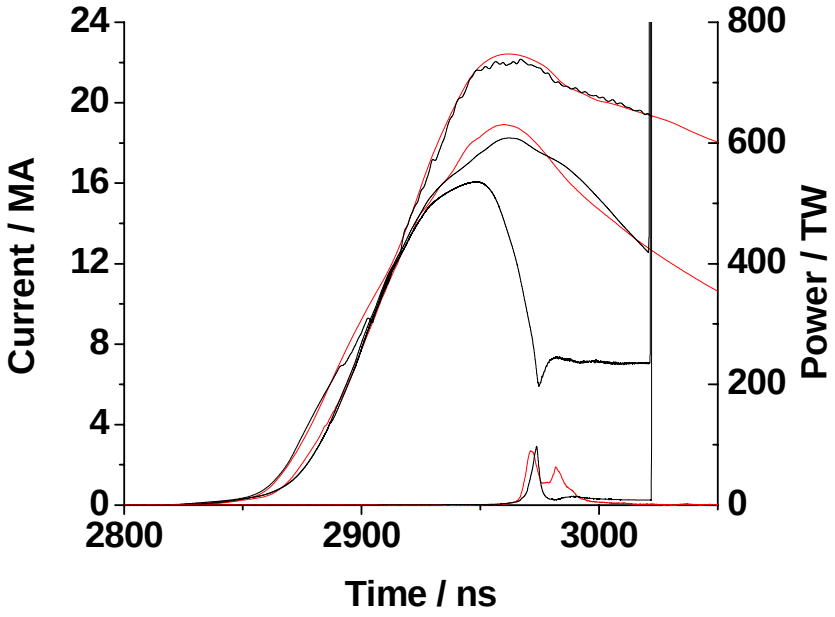
Z 818 – 6mg

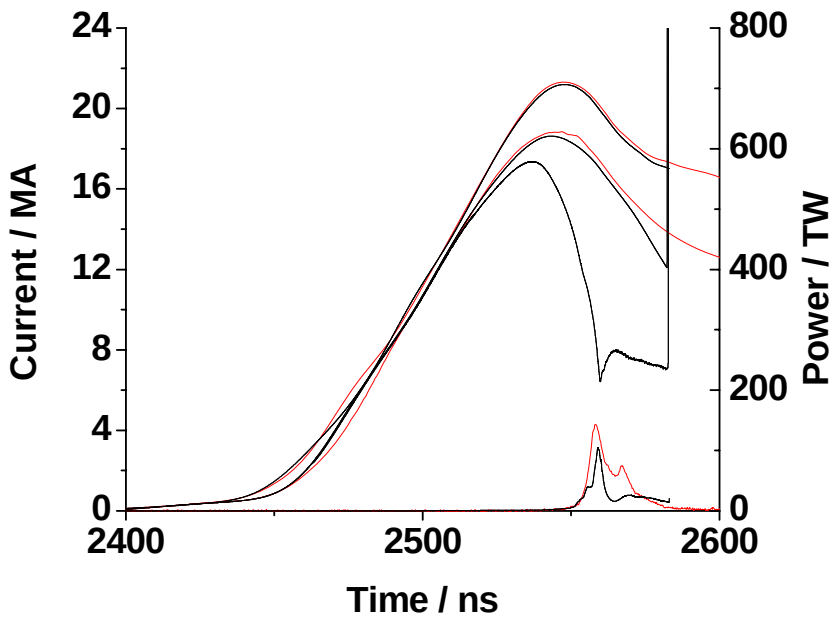
4mm AK gap

6mm radial feed



Larger gap for ZR





$$Z_f = 0.12 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

$$Z_f = 0.18 = \frac{V}{\sqrt{I_{upstream}^2 - I_{downstream}^2}}$$

Allow formation of cathode plasma in feed geometry

There is desorption of contaminant material from electrode surfaces

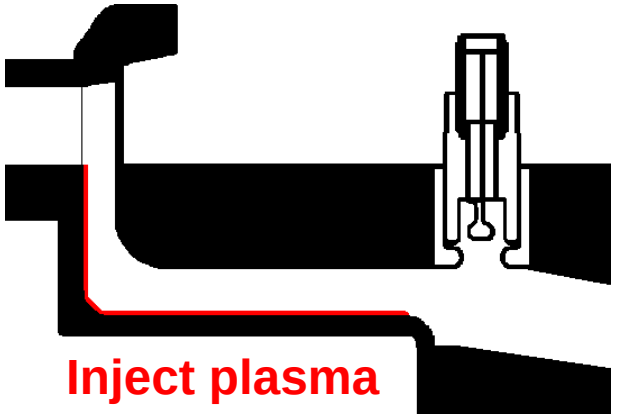
When voltage passes 250kV/cm a plasma forms along cathode surface

This plasma emits electrons which are magnetically confined constituting the flow current

In a 1D sense the plasma is confined and compressed against the electrode surface by jxB

However, with a shaped electrode geometry with the field gradients that introduces, is this plasma still effectively confined ?

Does the electrode geometry introduce a long wavelength perturbation the plasma can use to disrupt ?

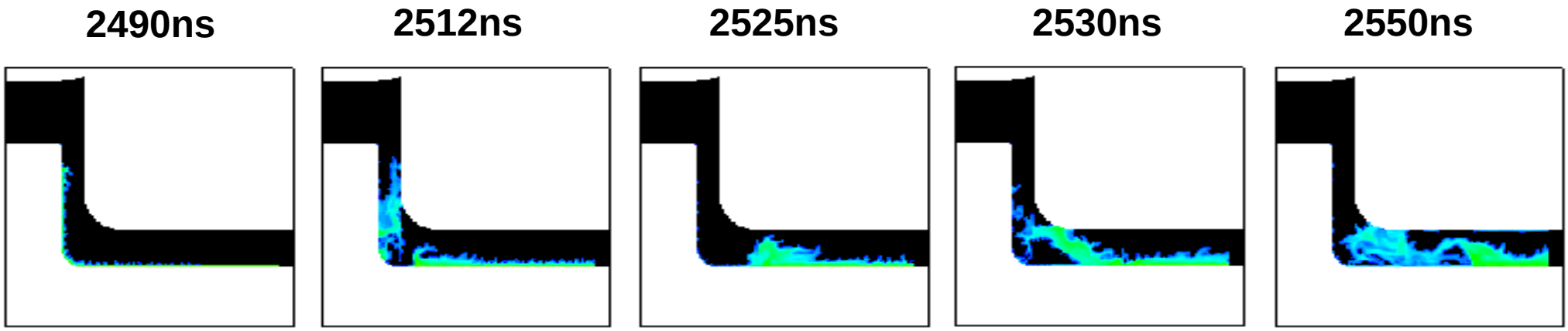


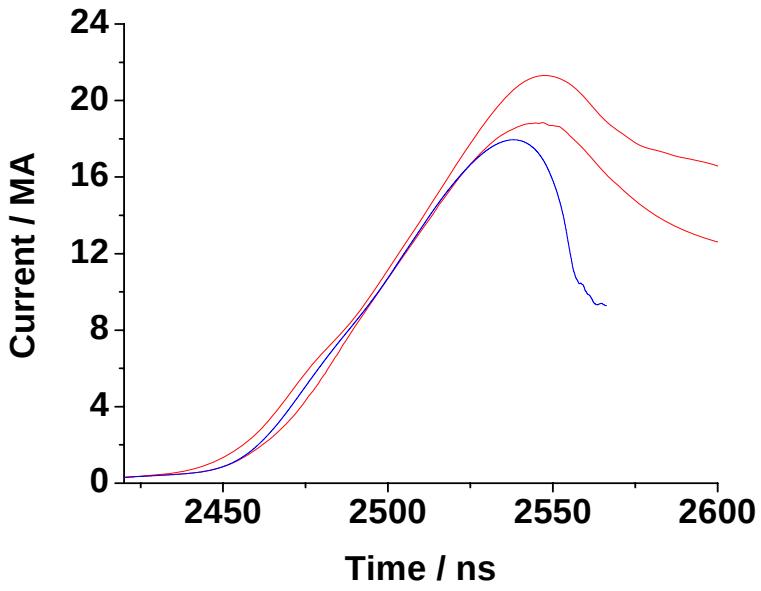
Set up 2D model of feed geometry

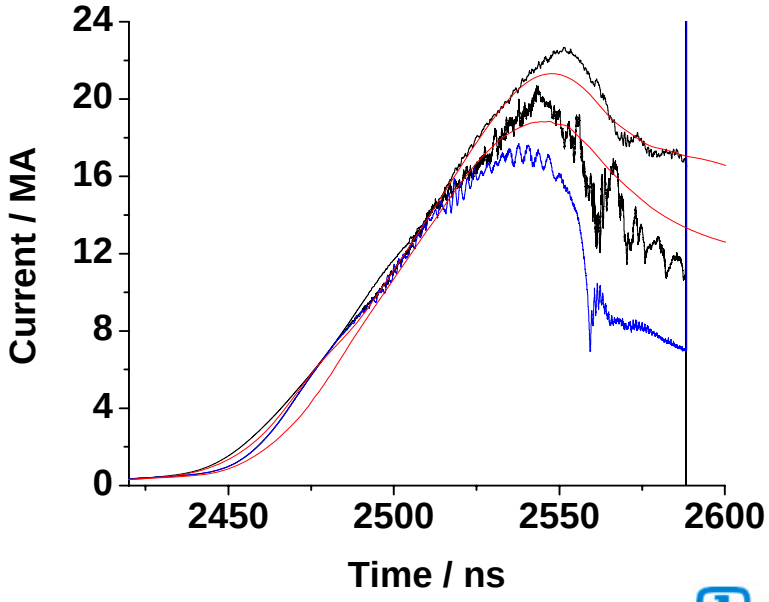
When feed passes 250kV/cm source plasma off of cathode

Carbon plasma injected at 0.1 ml/ns

Field gradient around bend compresses plasma and pushes it back up the feed line allowing shorting across gap







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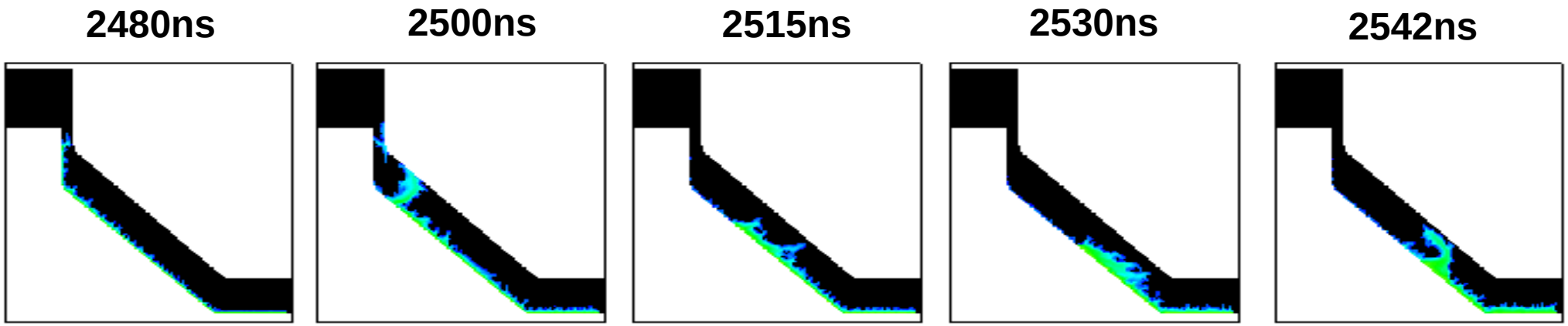
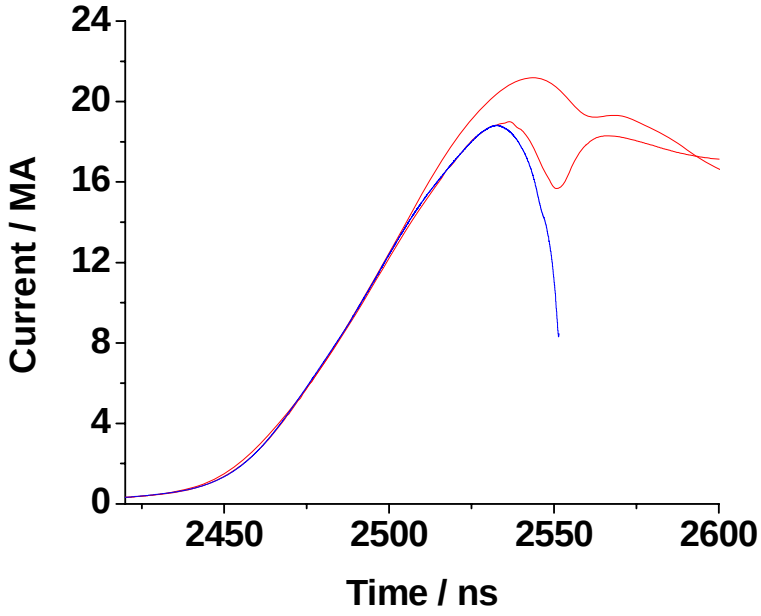
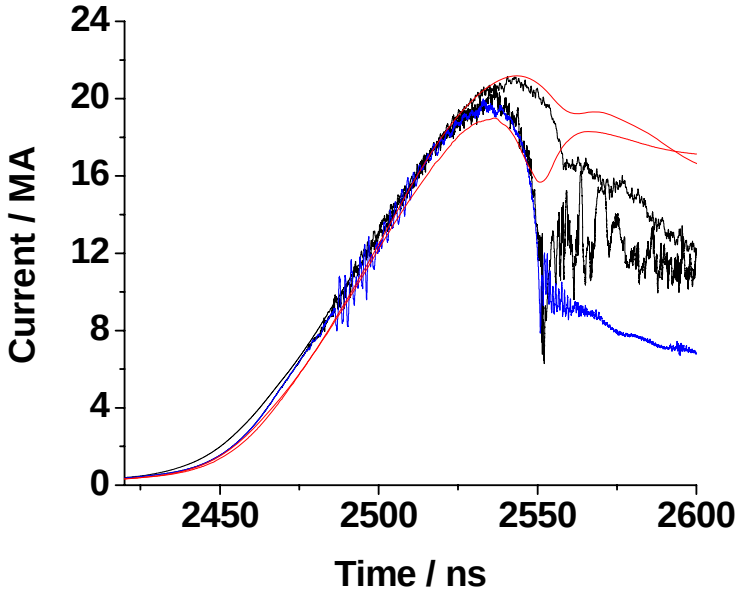
Conical feed is more effective at clamping plasma against electrode and preventing shorting







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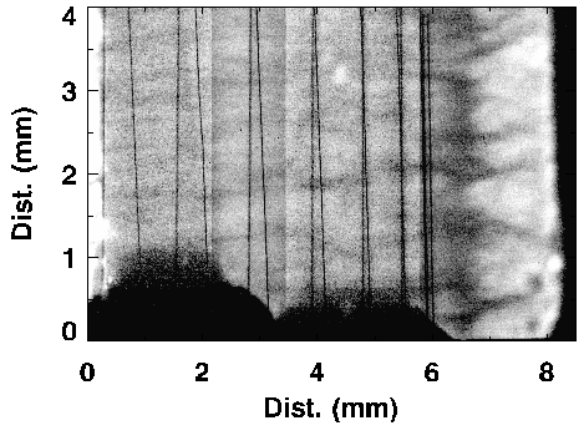
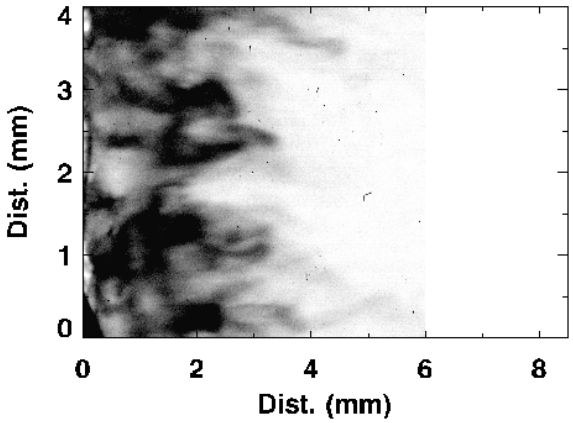
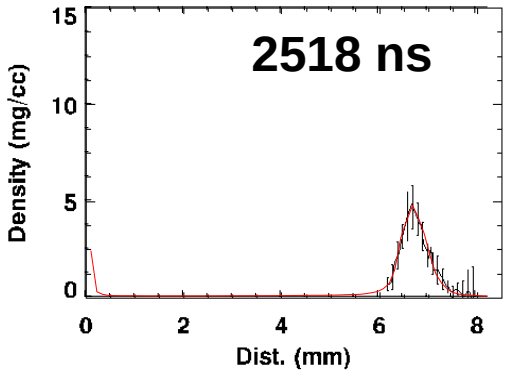
Radial Density distribution for 2.5mg array implosion (Z1735). Code results agree with radiography

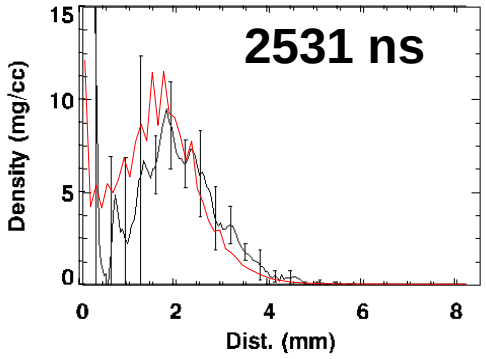
Radiographs



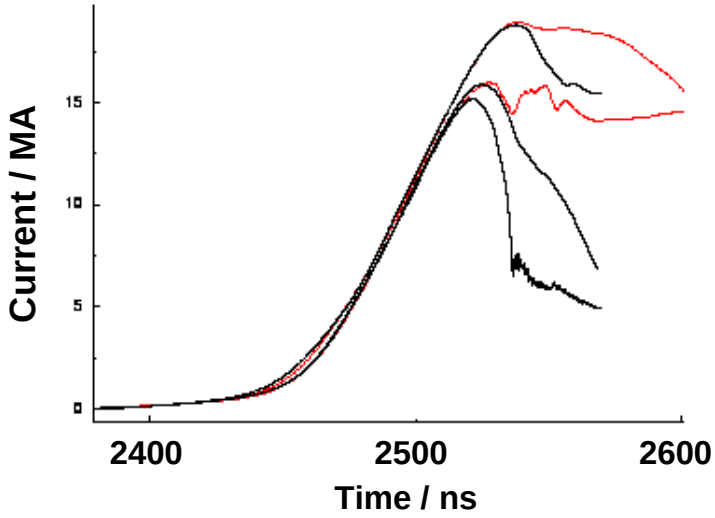


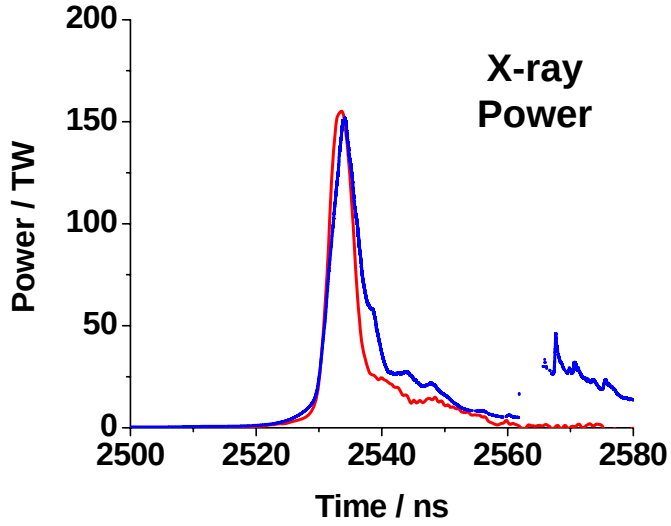
Abel inverted density vs. simulated density





Generator and load currents





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Conclusions

- Power pulse seems to include a large contribution of power delivered from the generator through stagnation – need to be getting correct currents and voltages in simulation to have confidence in their predictions
- Convolute loss better captured by resistive short rather than flow loss
- Electrical data is consistent with a current loss in parallel with the load, inside the load B-dot location
- Feed loss is dependant on feed geometry (conical feeds better)
- Possible to reproduce feed loss by assuming MHD instability development in cathode plasma
- The difference between the percieved and actual load current affects power scaling
- Since electrical power delivered is an important contribution to the power radiated, then higher powers may indeed be possible from a higher impedance generator. But any such gains are negated, and would likely not be observed while there is a current loss.