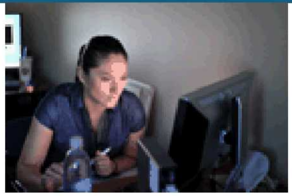
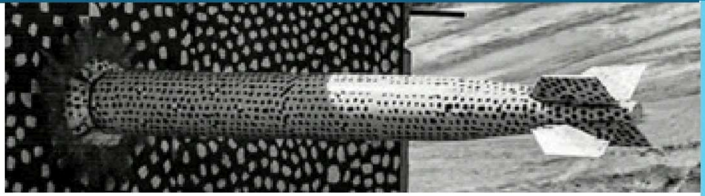
SAND2020-2174C

Toward predictive pulsed power loss estimates to ensure dynamic materials properties experiment success





PRESENTED BY

Andrew Porwitzky and Brian Hutsel

Sandia National Laboratories

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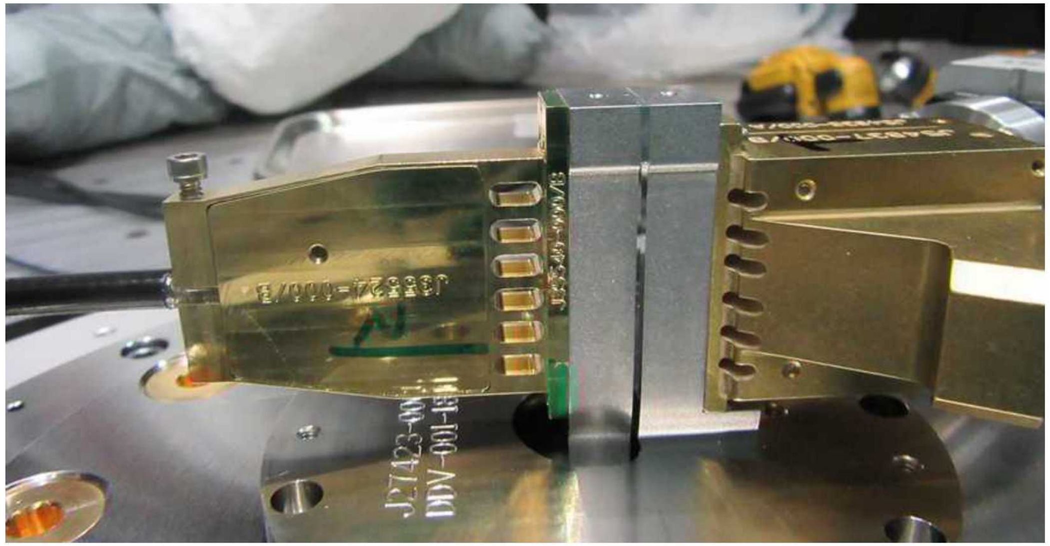
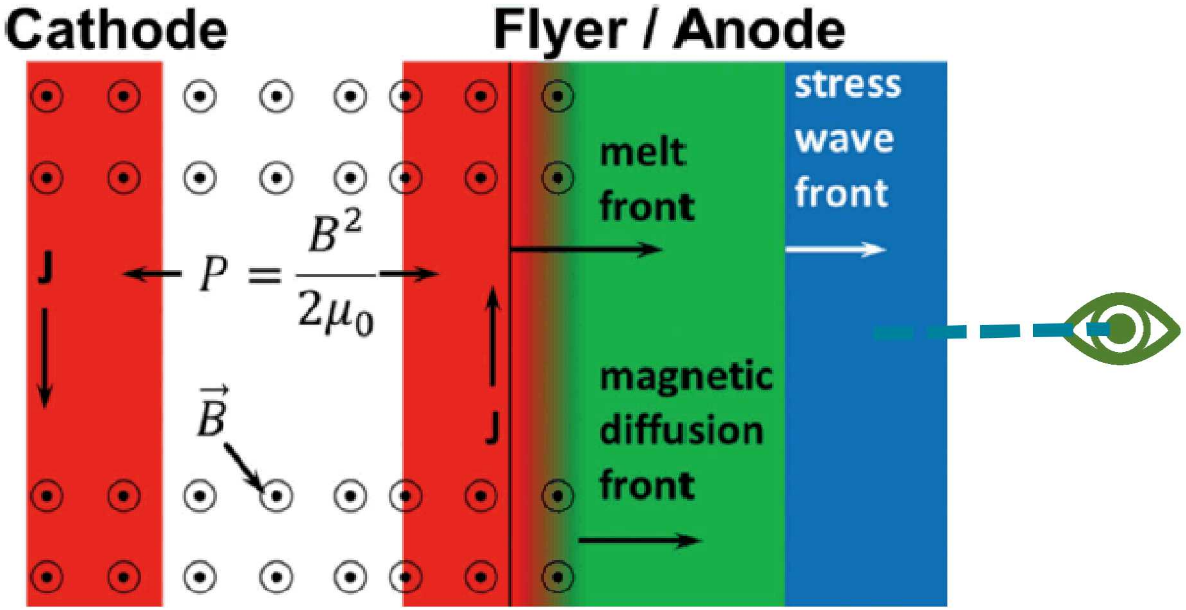
APS March Meeting 2020
Session S02: Dynamic Compression II: Experiments

Driving a Z Flyer

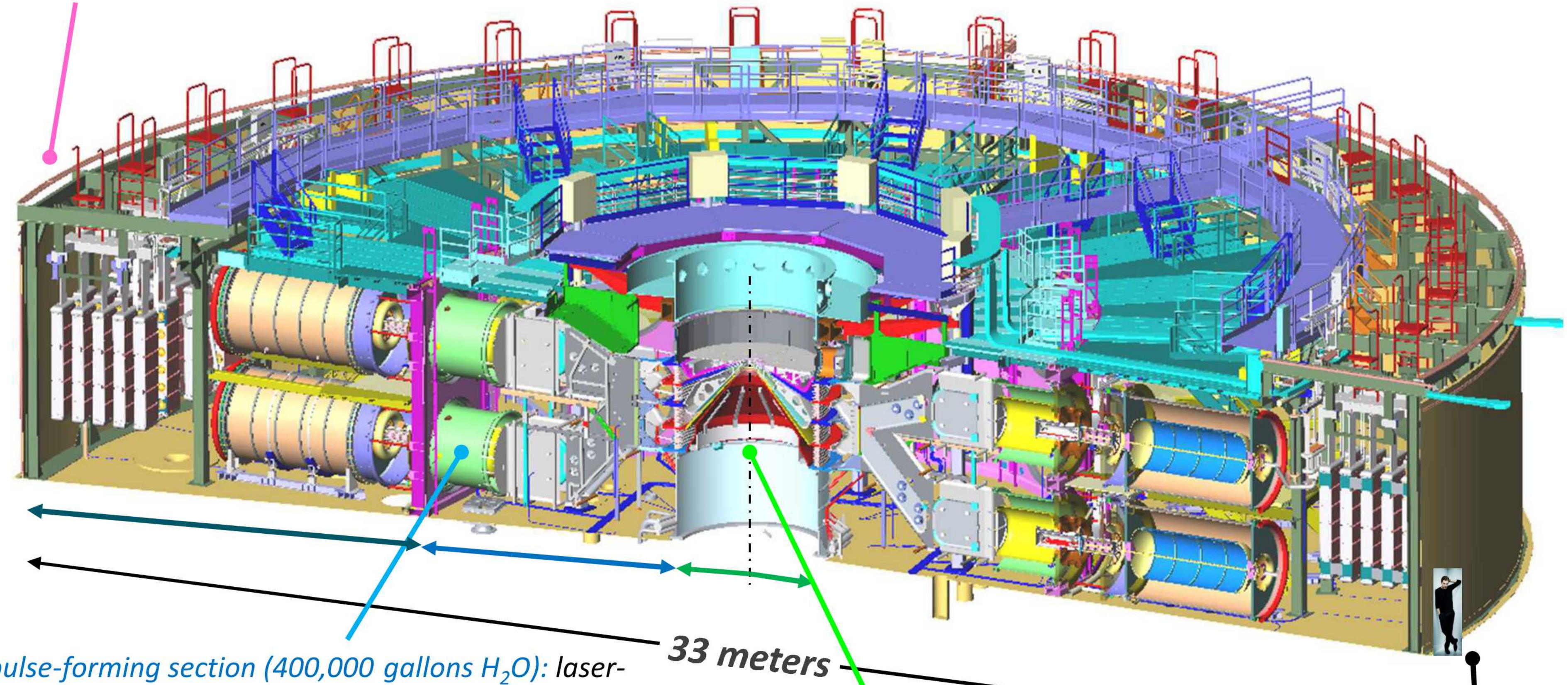
- Z delivers a multi-MA current to a magnetically accelerated flyer in a carefully controlled way.
- This current induces magnetic fields which propel the flyer to high velocities and/or high compression ratios.
- The magnetic diffusion front follows behind the stress wave front, thus the samples are compressed without magnetic field diffused into them.
- Unintended fluctuations in load current delivery (changes to dI/dt) alter the pressure history (dP/dt) and can cause unintended shocks to form in an isentropic compression experiment.
- **Accurate prediction of load current is exactly equivalent to accurate prediction of loading history.**





Z Machine at Sandia

energy storage section (600,000 gallons oil): stores 23 MJ in 36 banks of 60 capacitors (each 2.3 μF), charged in parallel (90 kV), discharged in series (5.4 MV)

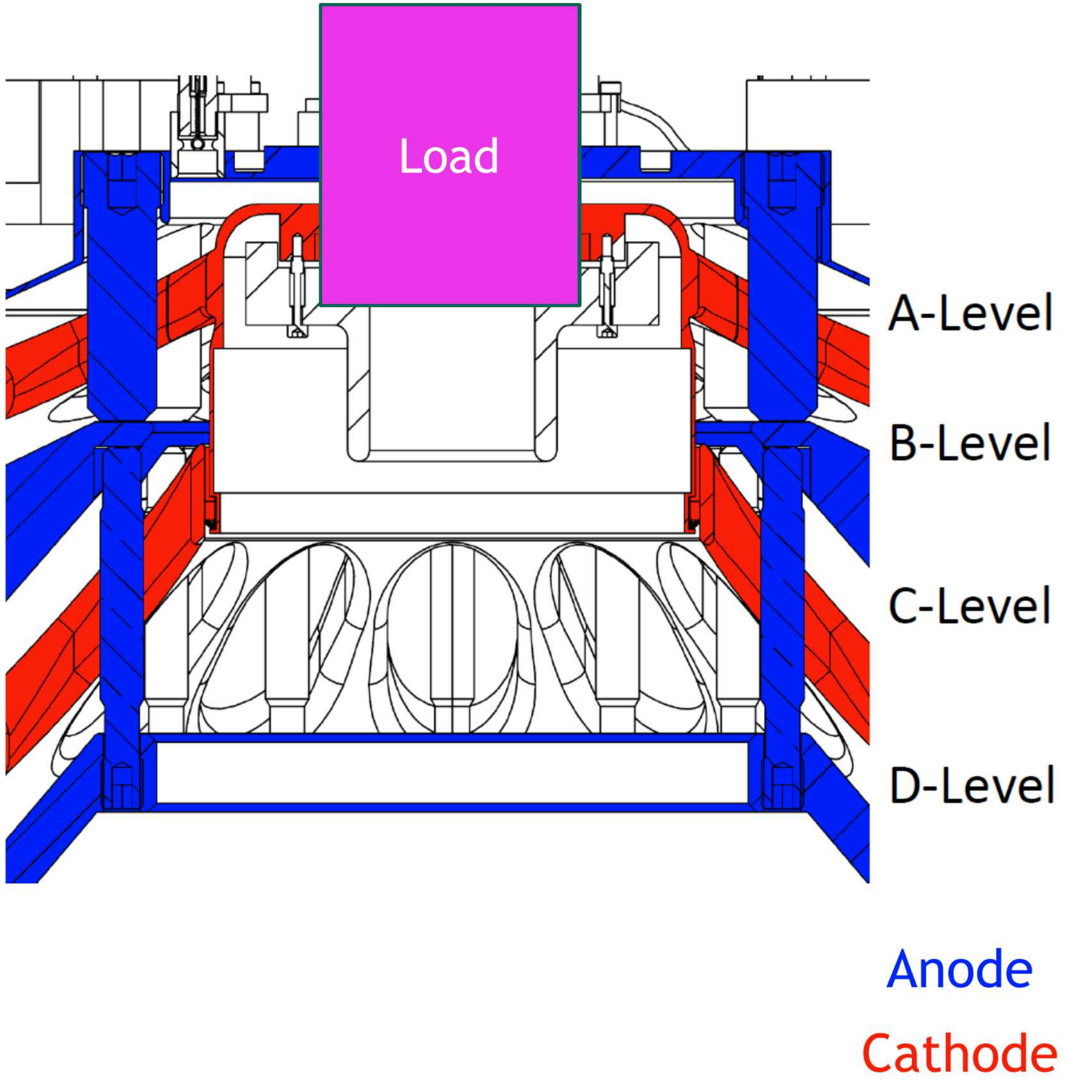


pulse-forming section (400,000 gallons H_2O): laser-triggered SF_6 gas switches & H_20 spark-gap switches compress pulse to 100-1500 ns rise time, tri-plates reduce 36 lines to 18, convolute reduces further to 4 radial feed gaps

center section (10^{-5} torr vacuum): ***magnetically insulated transmission lines (MITLs) deliver up to 26 MA pulse to load, convolute reduces 4 feed gaps to 1***

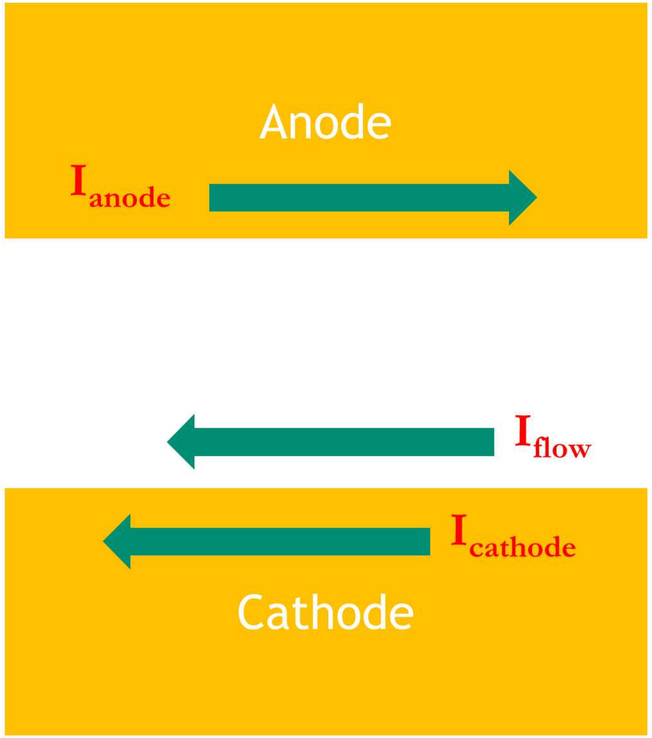
Convolute Power Flow

- Z convolute combines the four MITL levels into a single power flow gap.
- Magnetic nulls are formed around the convolute posts, potentially allowing charged particles to escape the magnetic insulation. This can result in measurable current loss.
- Convolute loss is – in principle – fairly well understood and can potentially be modeled with simple computational tools or analytical methods.
- Plasma gap closure – which can play a role in current loss on any multi-MA pulsed power driver – is much more difficult to predict due to the stochastic nature of plasma formation from material desorption and/or vaporization and free-gas expansion.
- Convolute loss is triggered if the load inductance is mismatched to the driver. Many of our DMP targets have load inductances that are significantly above what Z was designed to do.



Z Ion Loss Model

- An ion loss model, developed by Hutsel *et al.** as part of a larger Z circuit model, has long been applied to synchronous short pulses (100ns rise time) considered standard for Z ICF experiments. In that configuration, the model predicts loss onset based exclusively on time varying inductance inside the convolute.
- One of the main assumptions of the ion loss model is the existence of an **electron flow current** which carries a fraction of the cathode-side current in a plasma sheath.
- The magnitude of the flow current is dependent on the voltage across the power flow (AK) gap, which is a function of driving current and load inductance.
- Since this current is carried outside the conductor, it is a potential loss mechanism, though of small magnitude (order 10-100 kA).



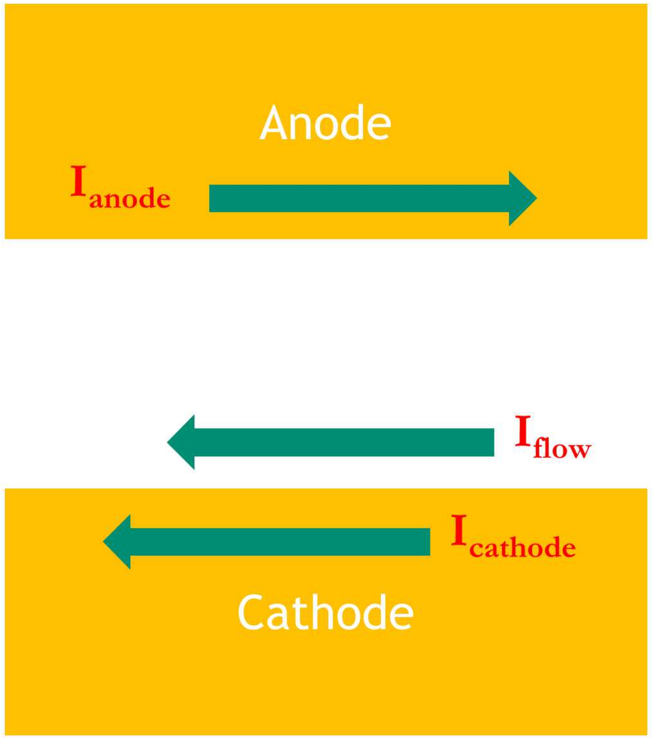
$$I_{anode} = I_{cathode} + I_{flow}$$

$$V = L\frac{dI}{dt} + I\frac{dL}{dt} \qquad I_{flow} = \frac{13}{16}\frac{V^2}{I_a Z^2}$$

* "Transmission-line-circuit model of an 85-TW, 25-MA pulsed-power accelerator," B.T. Hutsel *et al.*, Phys. Rev. Accel. Beams 21, 030401 (2018).

Z Ion Loss Model

- The presence of electrons in the AK gap modifies the space charge limited (SCL) emission, aiding in the removal of positive ions from the anode surfaces.
- These positive ions can contribute order-of-magnitude larger current loss than the electron flow current. The flow current is thus a trigger for major loss mechanisms.
- Since the model allows for the production of ion plasma from modified SCL emission, plasma gap closure is possible. A very crude closure model is included based on constant plasma drift velocity, with limiters included as tuning knobs.
- For ICF, these knobs were adjusted to match a half dozen experiments, and have since been applied to over 100 shots.* For DMP, three tuning parameters were identified that correspond to **threshold anode heating to produce plasma (loss onset time), minimum gap closure dimension (maximum current shorting), and electron flow current sheath collisionality (prevalence of electron plasma)**.



$$I_{anode} = I_{cathode} + I_{flow}$$

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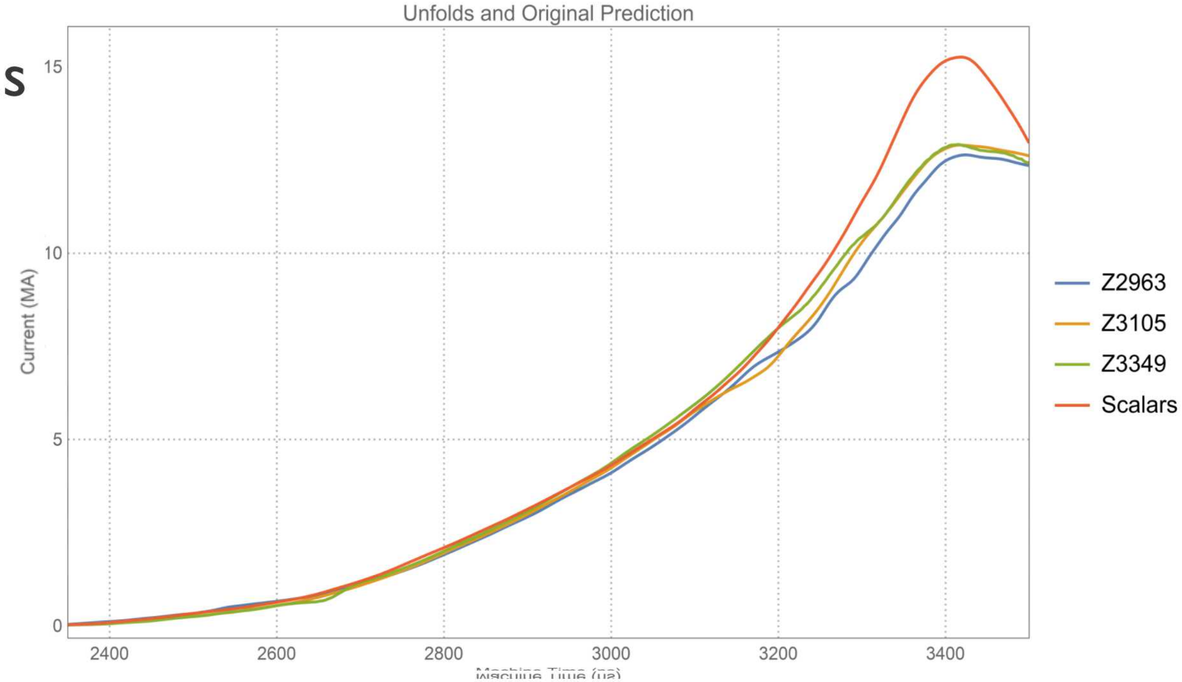
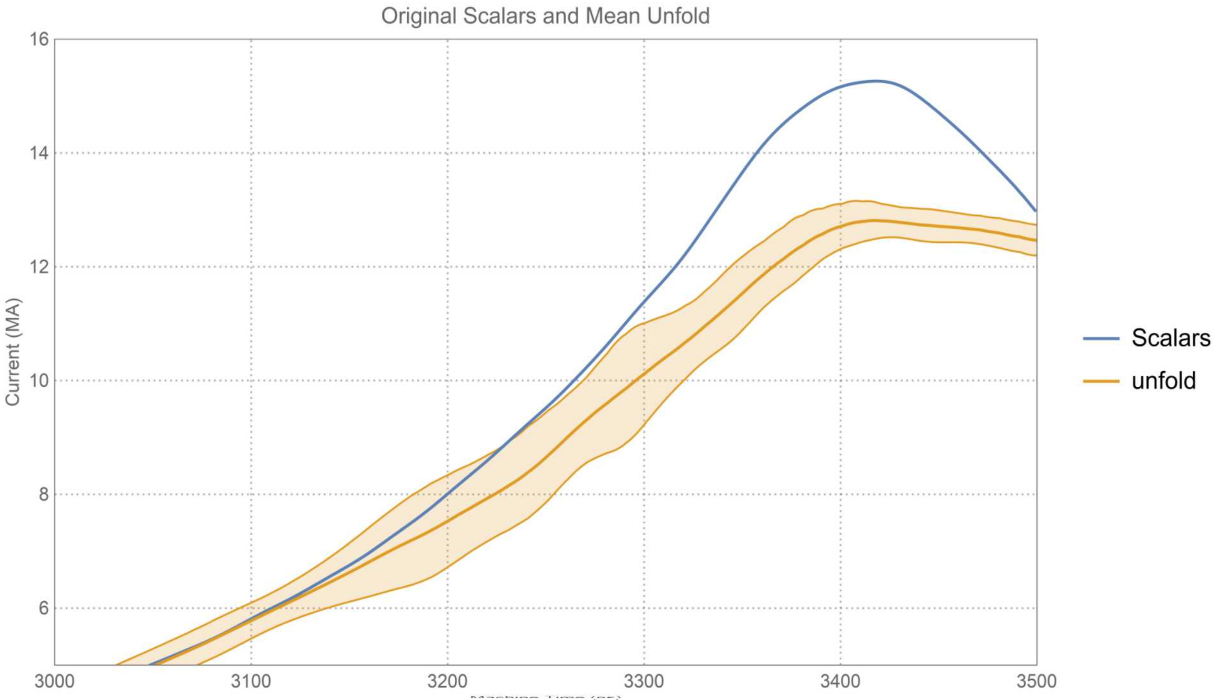
Tuning to Large Inductance Experiments

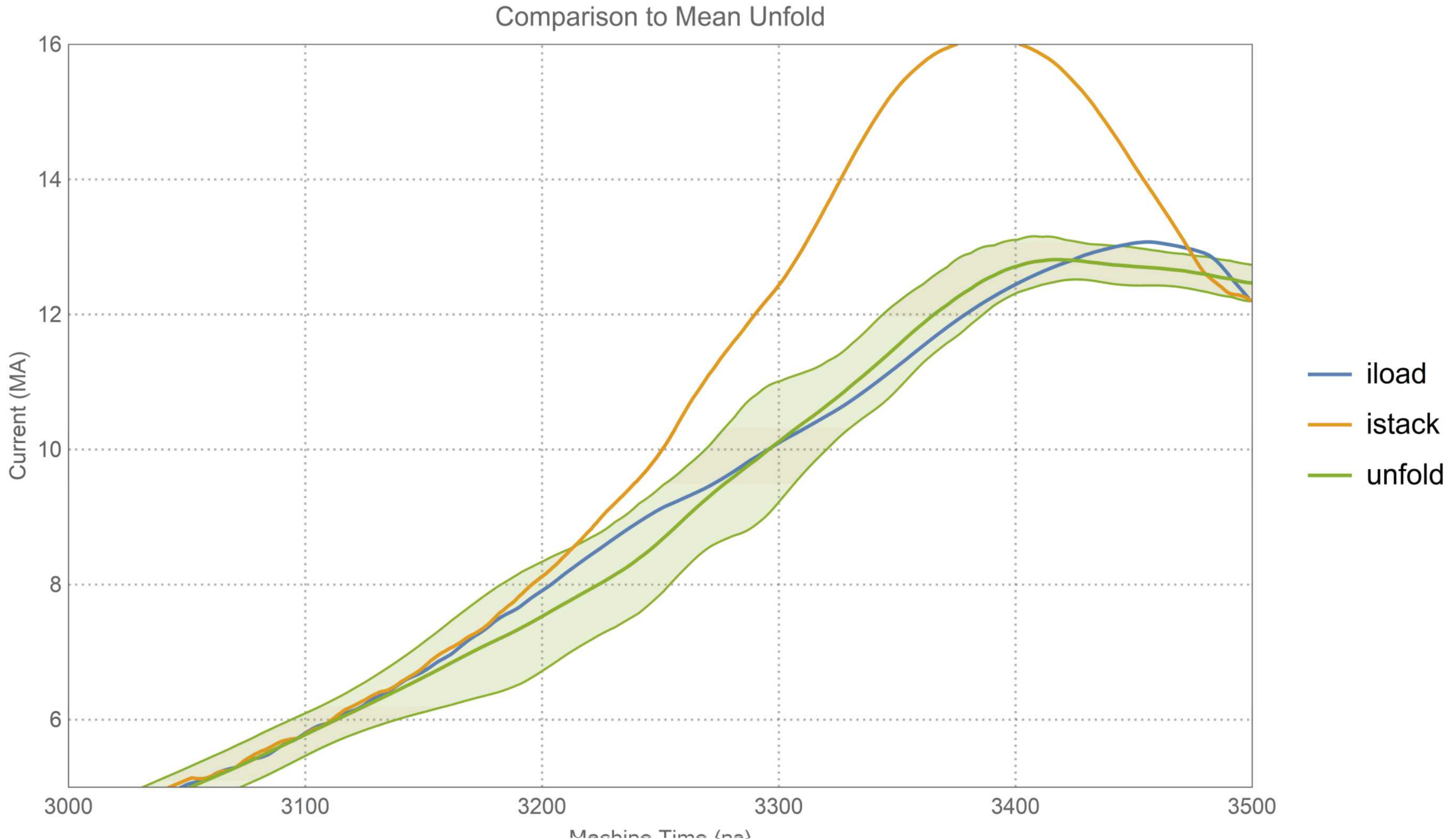
- Three experiments with >8 nH inside the convolute, and repeat pulse shapes and load hardware were used to tune the model. (Both current and inductance histories are identical between the three experiments.)
- Loss was observed to vary from shot-to-shot, which we believe is indicative of the stochastic nature of material desorption from electrode surfaces.
- Shot-to-shot variability was captured by simple 2σ method and used as a target for tuning. Increased "uncertainty" can be seen around the area of loss onset variability.
- Note that although loss onset time varies, peak load current is quite consistent between shots. In the ion loss model, this behavior is captured by the minimum gap size.



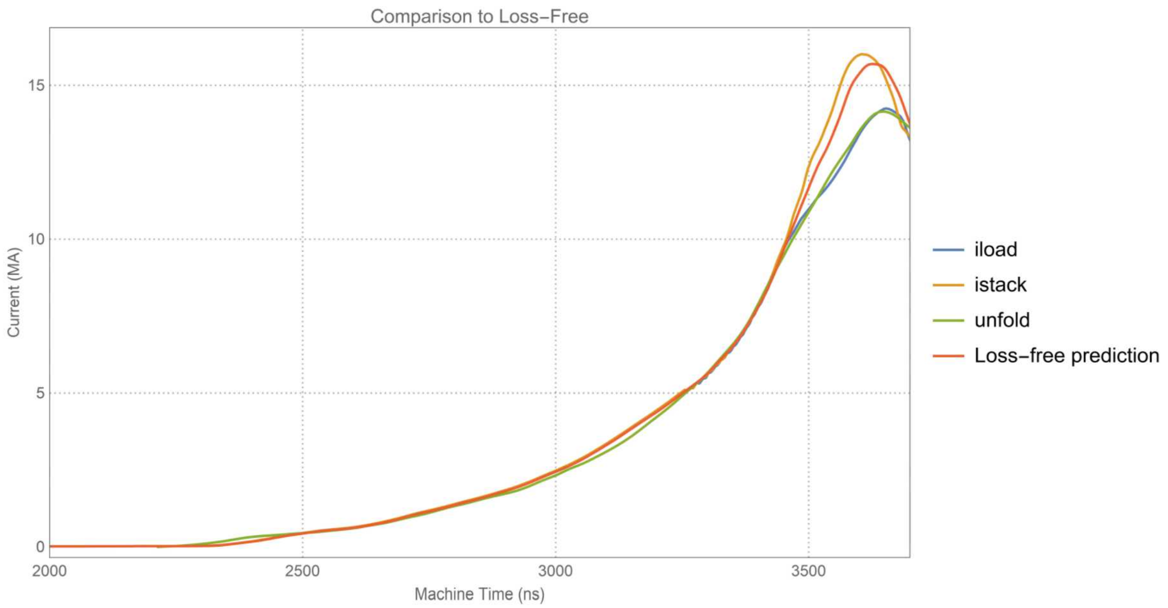


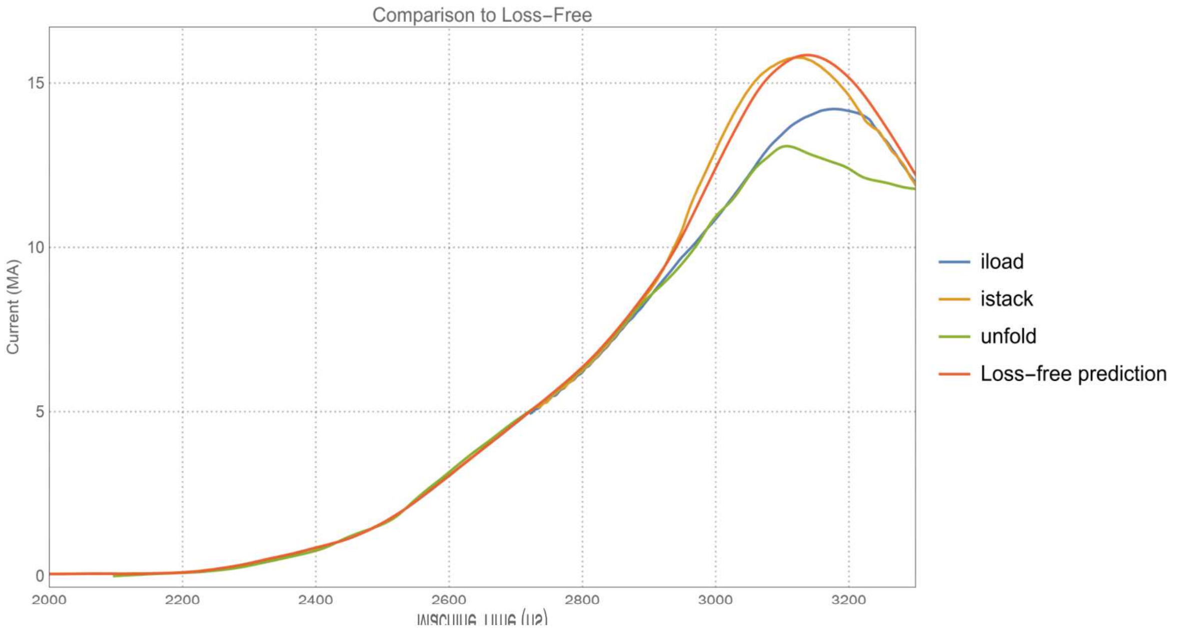
Tuning to Large Inductance Experiments

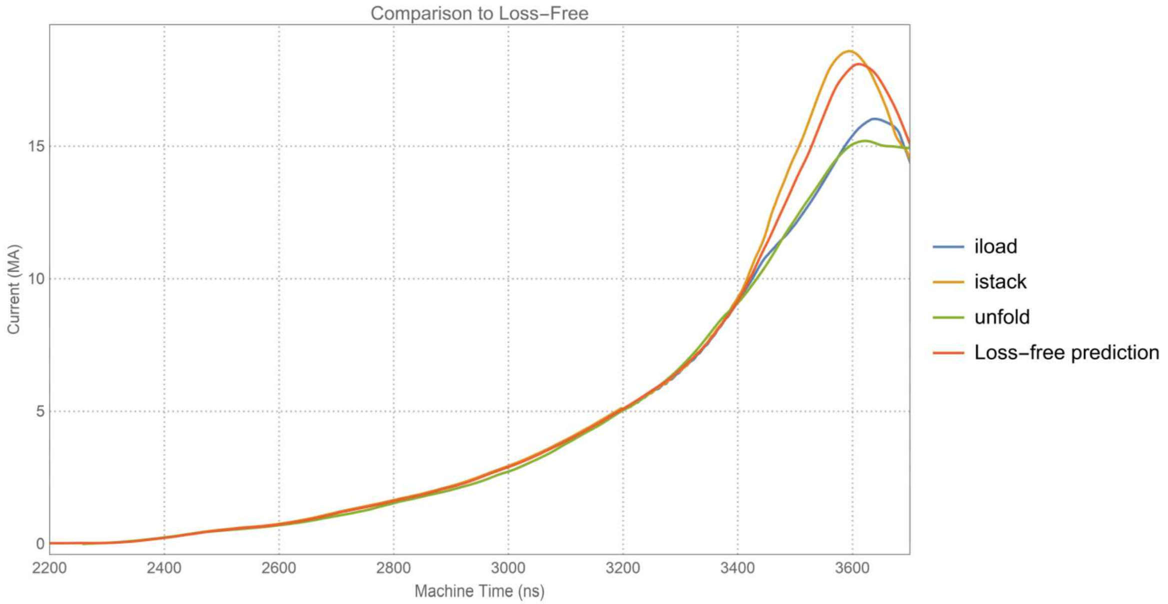
- The ion-loss model was tuned using only the three parameters discussed above and the "prediction" was found to reproduce the results to within the target window for physically reasonable parameter values.
- **No other experiments were used to tune the model.**

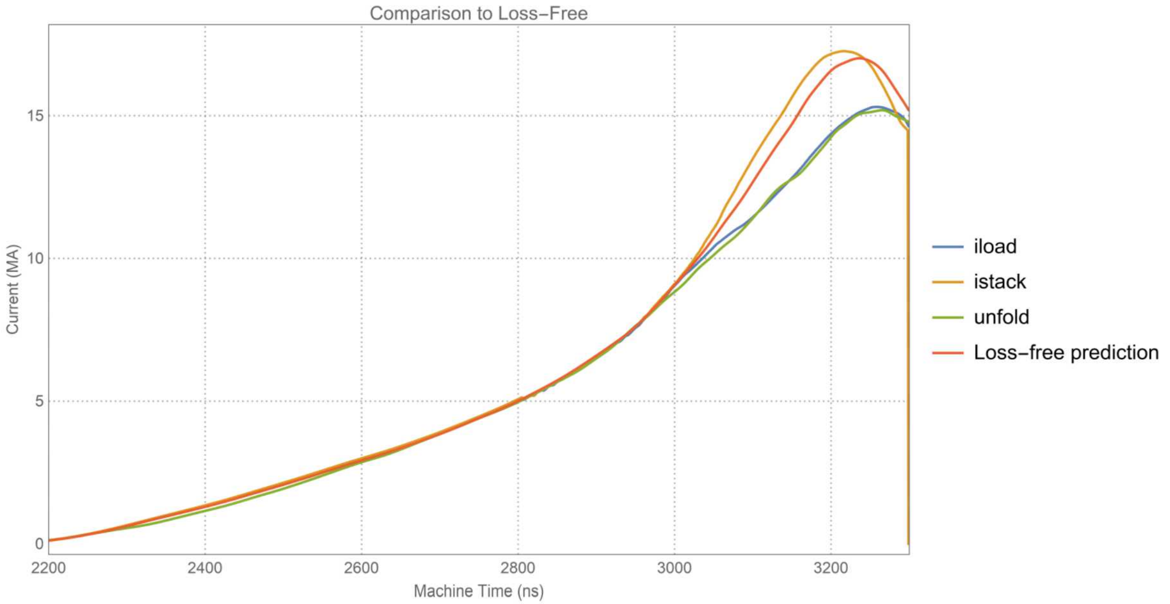


Comparison to Other Large Inductance Experiments









Conclusion

- We have demonstrated predictability for convolute-dominated load current loss on Z across a range of pulse shapes.
- Loss changes load current delivery, thus changing drive pressure history, resulting in sample shocks or not achieving target peak pressure.
- Convolute loss occurs when the load inductance is larger than the driver was designed to accommodate, which is true for many Z DMP loads.
- Predictive loss modeling is enabling a higher success rate on Z DMP experiments.

Thank you for your time.

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