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Megaamps, Megagauss and Megabars: Using the Sandia Z Machine to Perform Extreme Material Dynamics Experiments

Guest Lectures, Institute for Shock Physics
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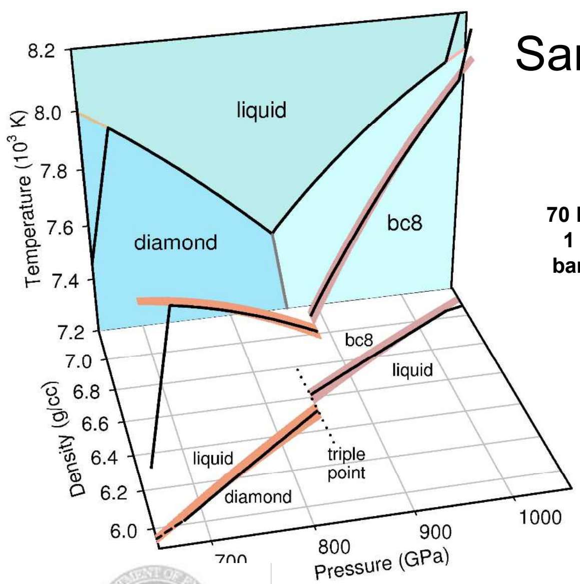

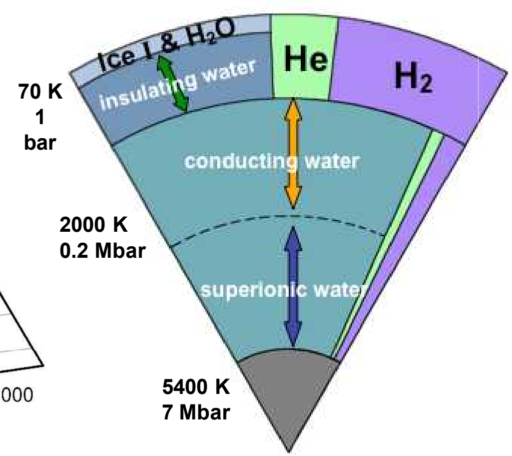

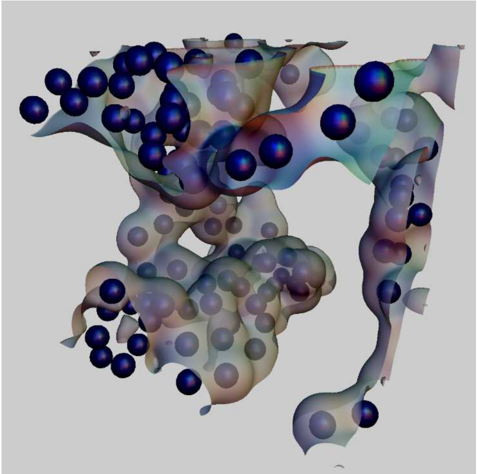

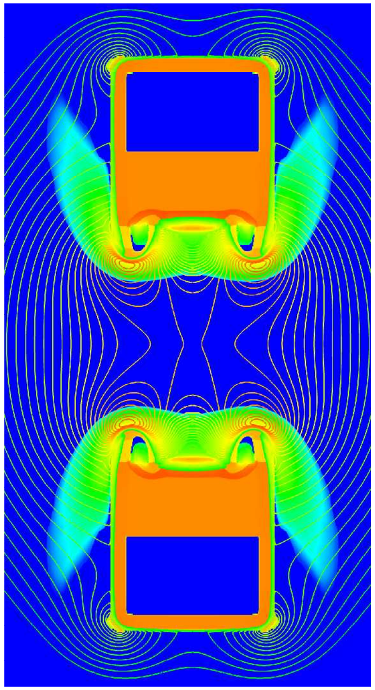

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Acknowledgements

- Mike Desjarlais, Thomas Mattsson
  - Quantum Molecular Dynamics (QMD) calculations
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  - Experimental design, data analysis
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  - MHD unfolds, Quicksilver simulations, current analysis
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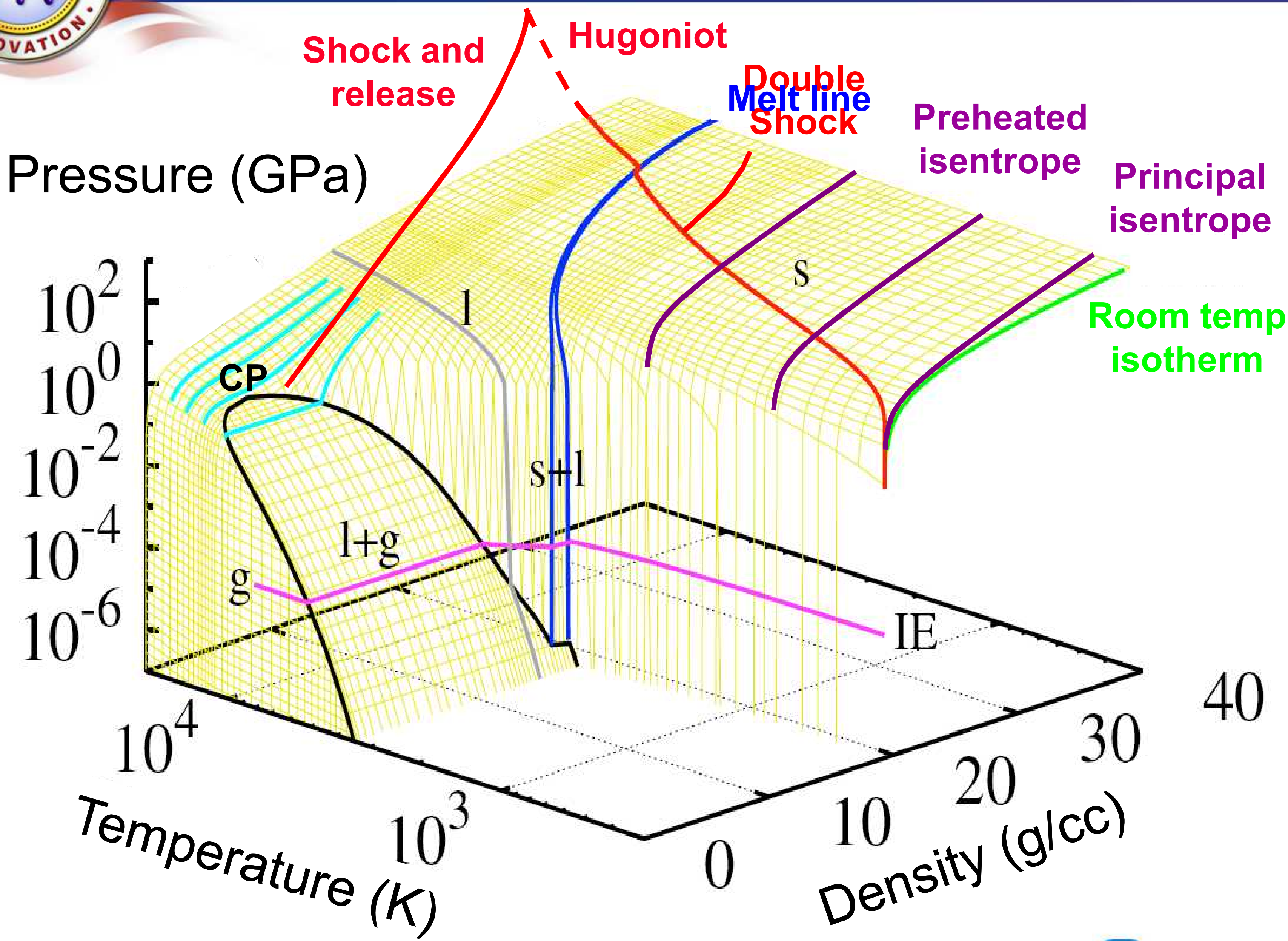
  - Bertha model, pulse shaping
- Dustin Romero, Devon Dalton, Charlie Meyer, Anthony Romero, entire Z crew…
  - Experiment support
- LANL: Rusty Gray, Dave Funk, Paulo Rigg, Carl Greeff
  - Ta samples and equation of state

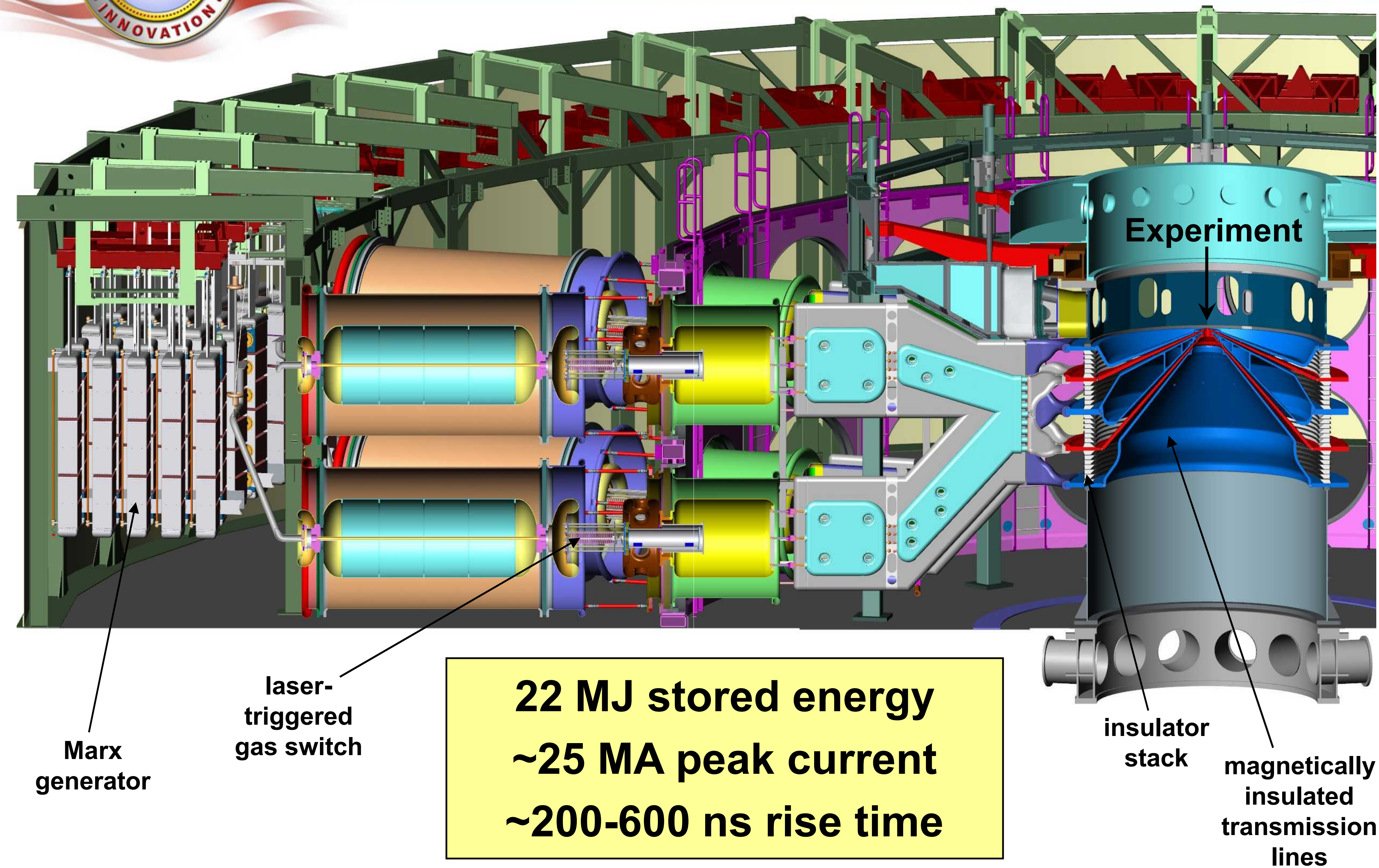
Outline

- Overview of magnetic compression
- Experimental load designs
  - Co-axial
  - Stripline
- Magneto-hydrodynamic modeling and optimization
- Integrated experimental design

Magnetic compression on Z enables access to a large region of the equation of state surface



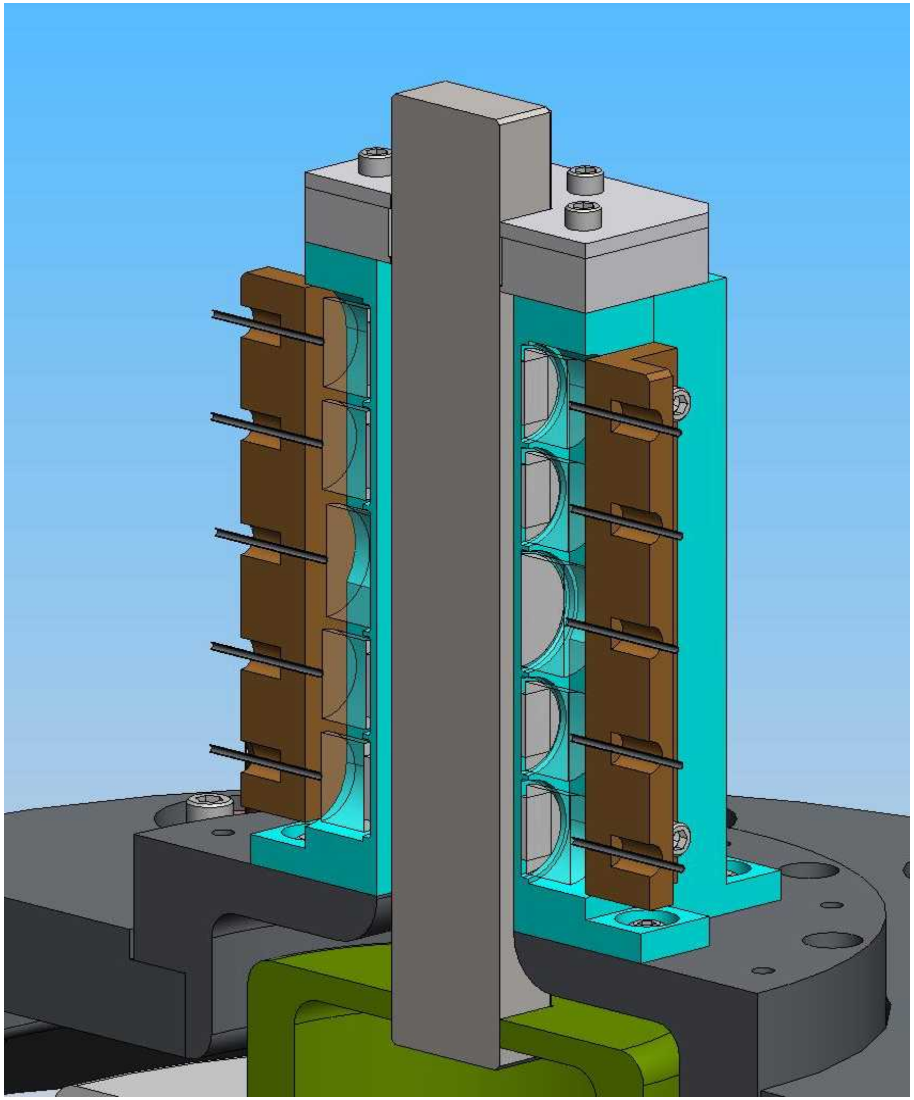
The Sandia Z Machine



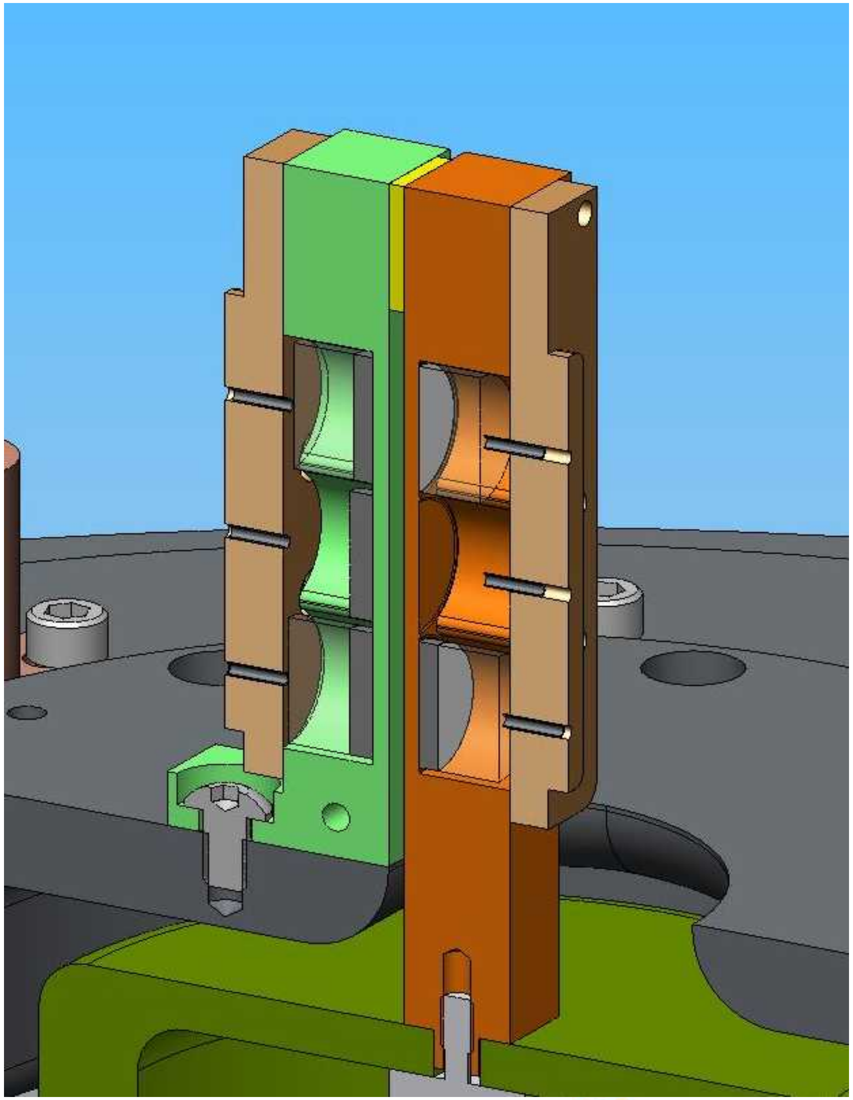
22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

Two different load designs have been used for material dynamics experiments on Z

Co-axial



Stripline



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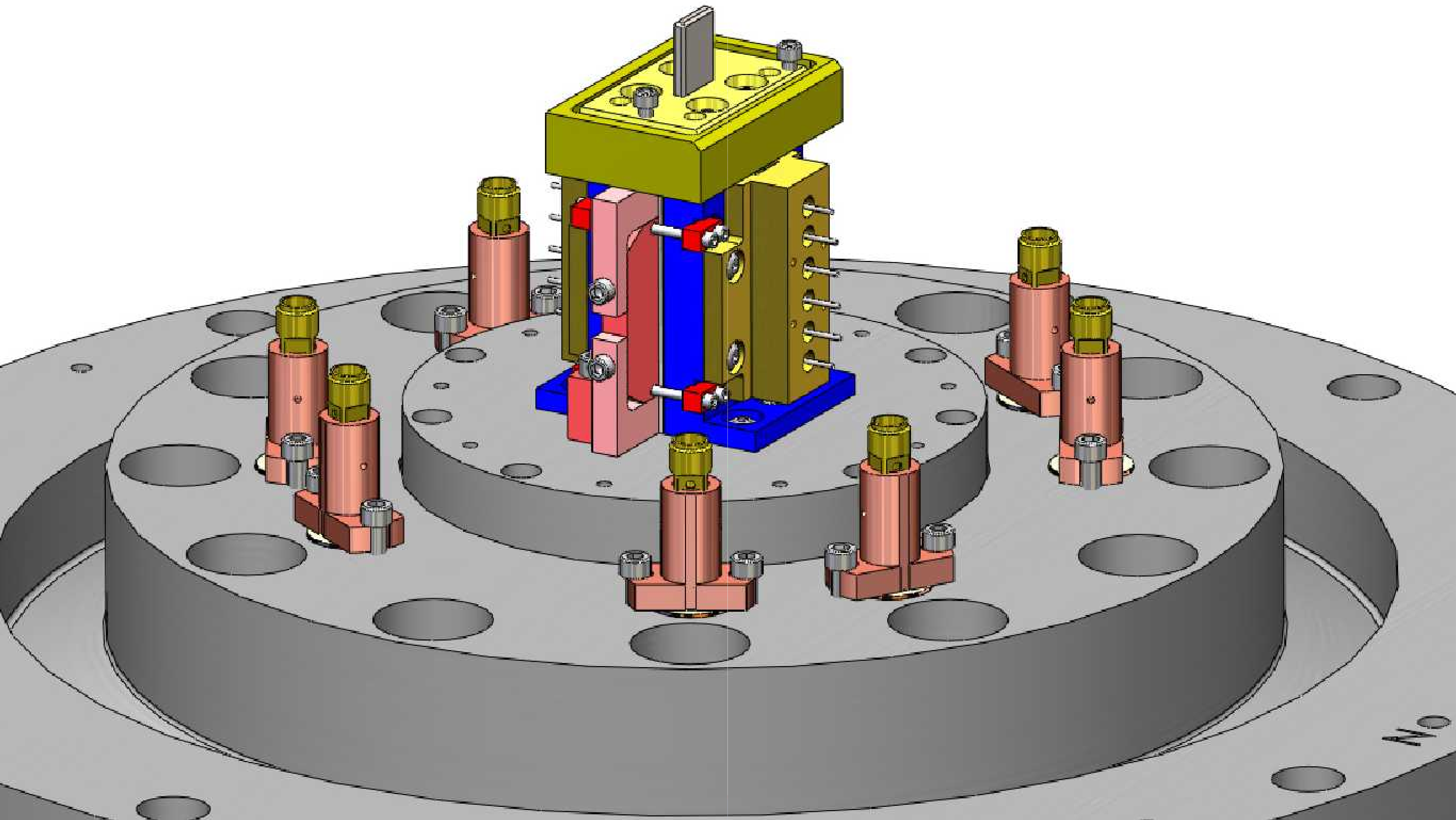
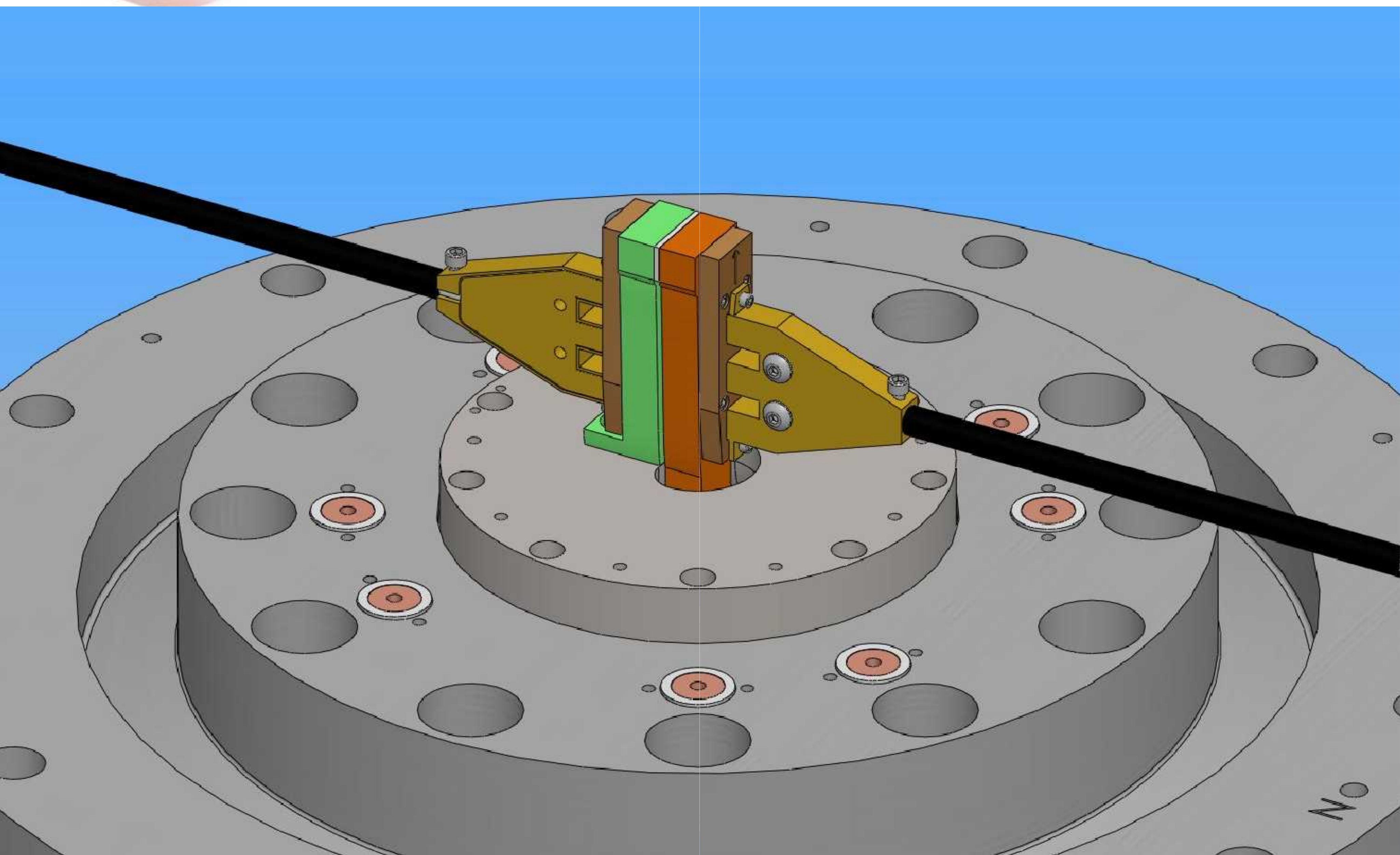
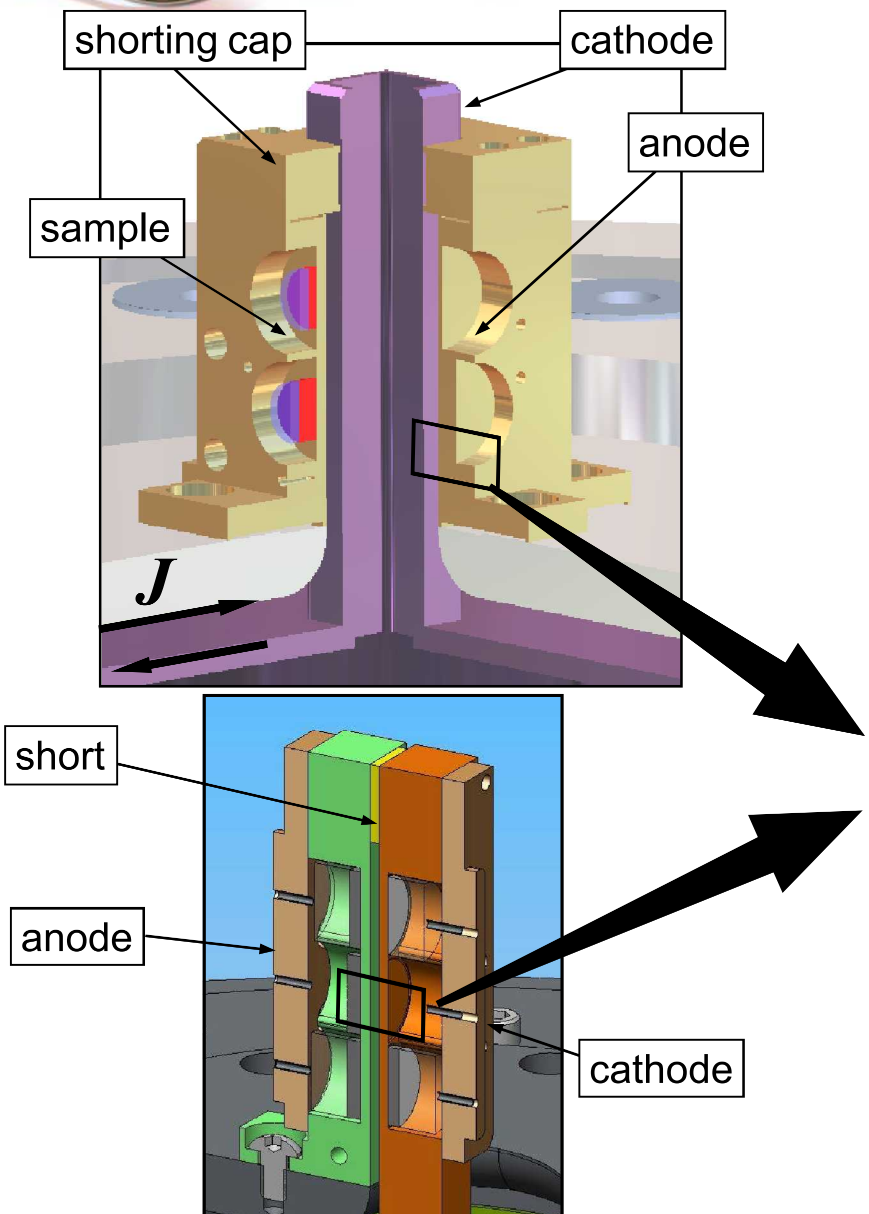
Typical coaxial load for multi-Mbar shock compression experiments on Z



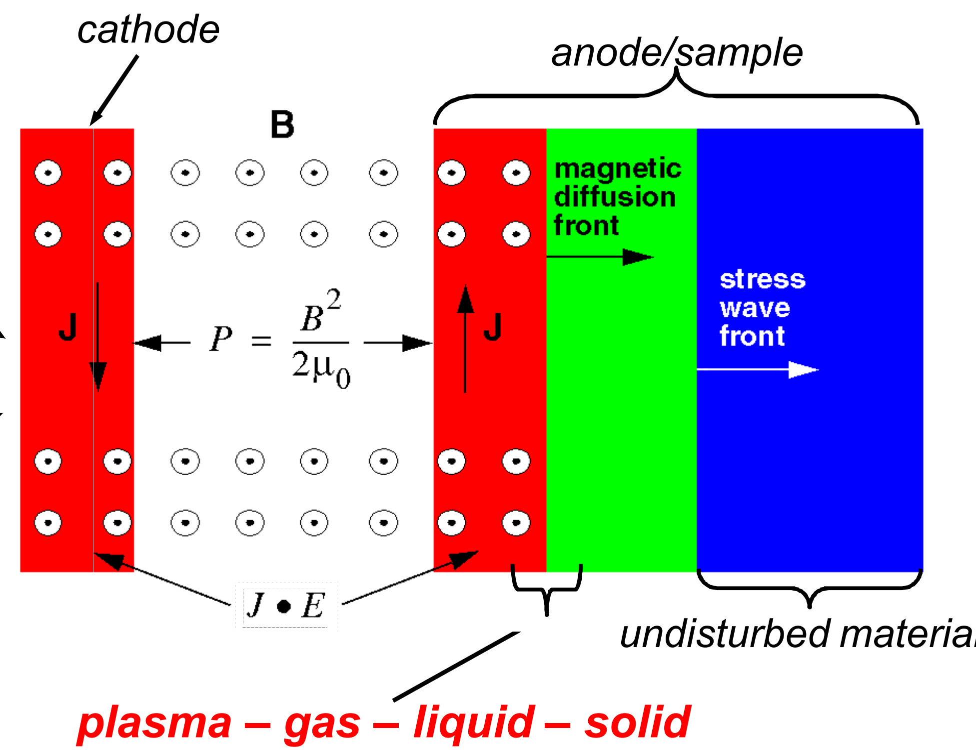
Typical stripline load for multi-Mbar ramp compression experiments on Z



Magnetic compression on Z produces smooth ramp loading to ultra-high pressures



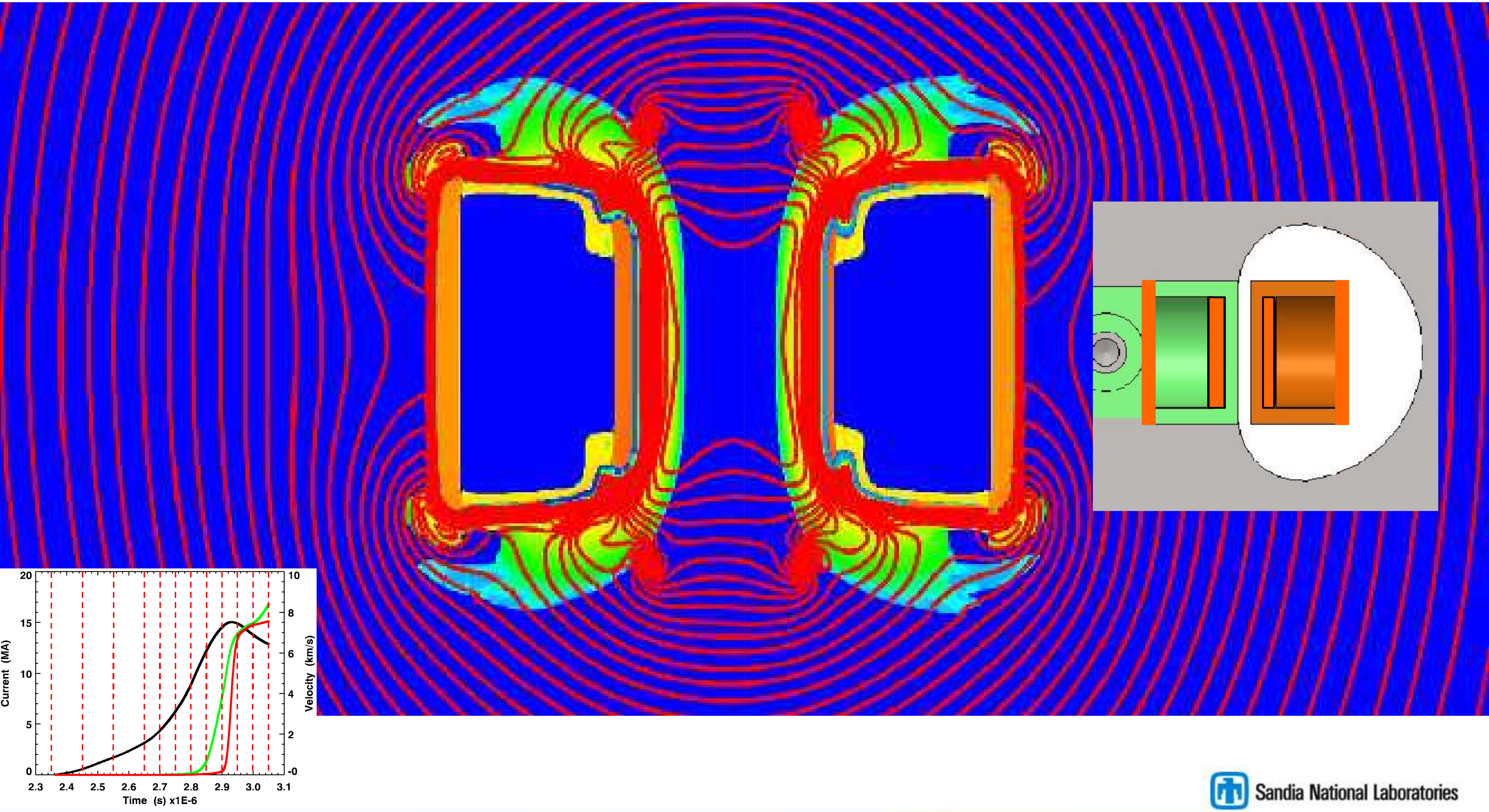
- pulse of electric current through experimental load (shorted at one end) induces magnetic field
- *J´B* magnetic force transferred to electrode material



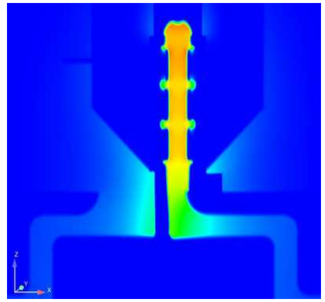
Fully self-consistent, 2-D MHD simulations required to accurately predict experimental load performance

10 mm wide stripline

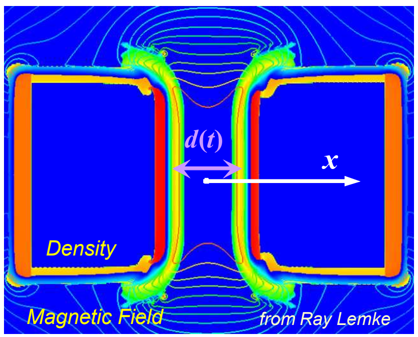
t = 690 ns

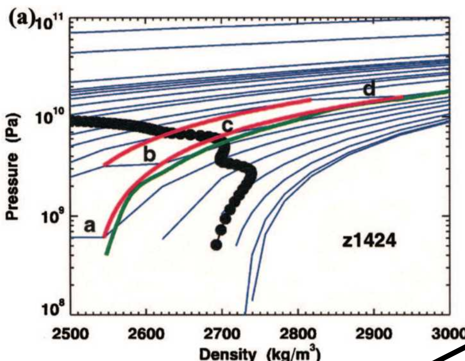


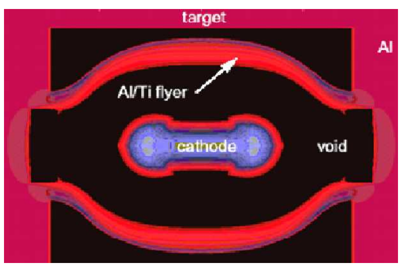
Success requires integration of theoretical, computational, and experimental capabilities

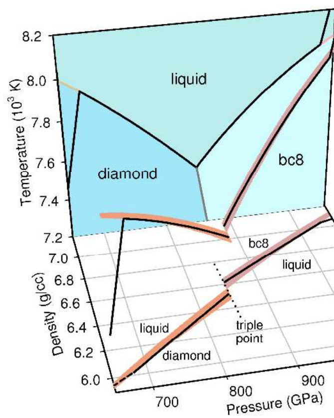


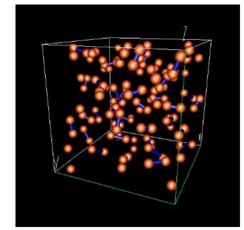
$$\sigma_{\mathbf{k}}(\omega)=\frac{2\pi e^2\hbar^2}{3m^2\omega\Omega}\sum_{\alpha=1}^{3}\sum_{j=1}^{N}\sum_{i=1}^{N}\left(F(\varepsilon_{i,\mathbf{k}})-F(\varepsilon_{j,\mathbf{k}})\right)\left|\left\langle\Psi_{j,\mathbf{k}}\middle|\nabla_\alpha\middle|\Psi_{i,\mathbf{k}}\right\rangle\right|^2\delta(\varepsilon_{j,\mathbf{k}}-\varepsilon_{i,\mathbf{k}}-\hbar\omega)$$

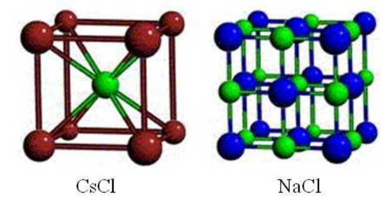


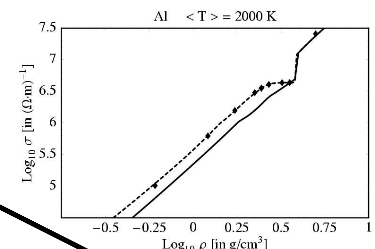


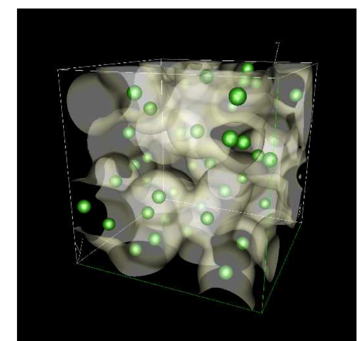


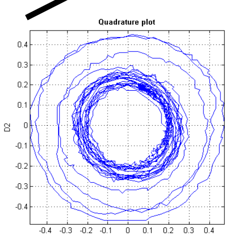


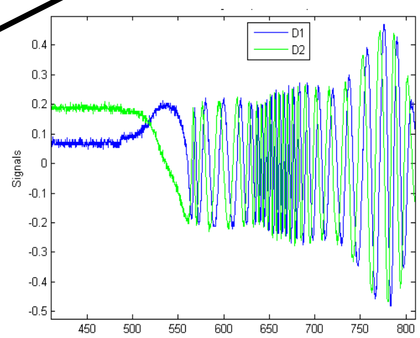


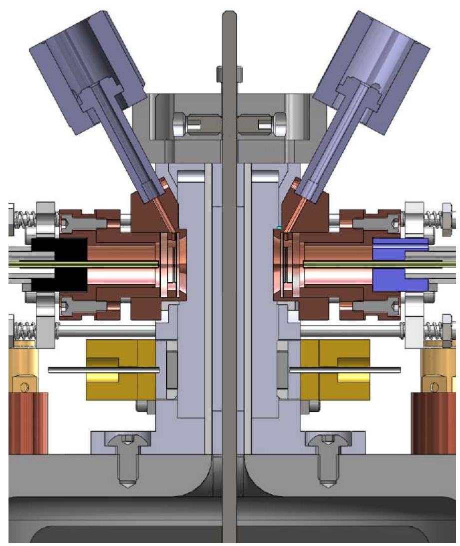


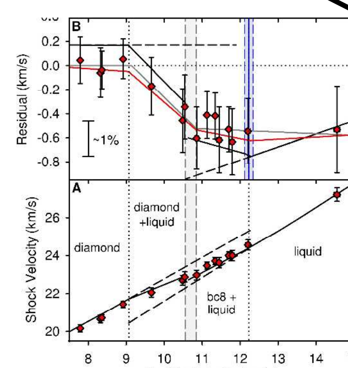


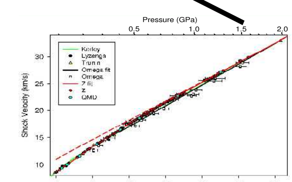




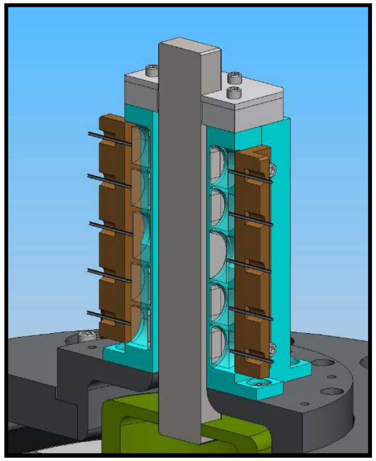


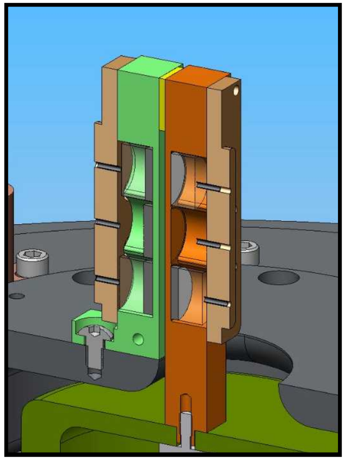






Two platforms have been developed for accurate equation of state studies – both major advances



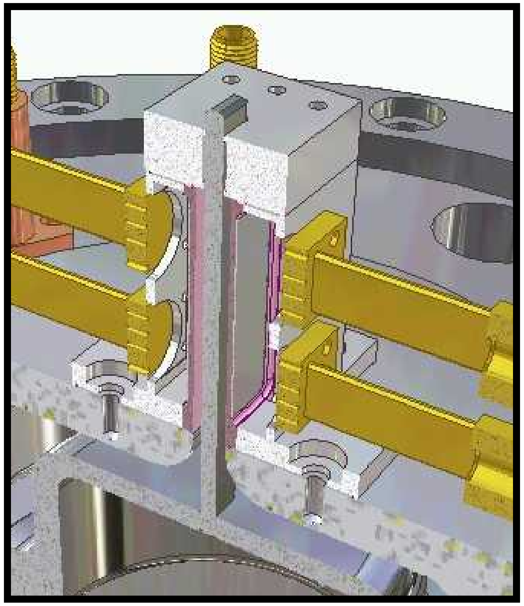


Isentropic Compression Experiments (ICE)*

Magnetically driven Isentropic Compression Experiments (ICE) to provide measurement of continuous compression curves to ~4 Mbar

- previously unavailable at Mbar pressures

* Developed with LLNL



Magnetically launched flyer plates

Magnetically driven flyer plates for shock Hugoniot experiments at velocities to > 40 km/s

- exceeds gas gun velocities by > 5X and pressures by > 10X with comparable accuracy

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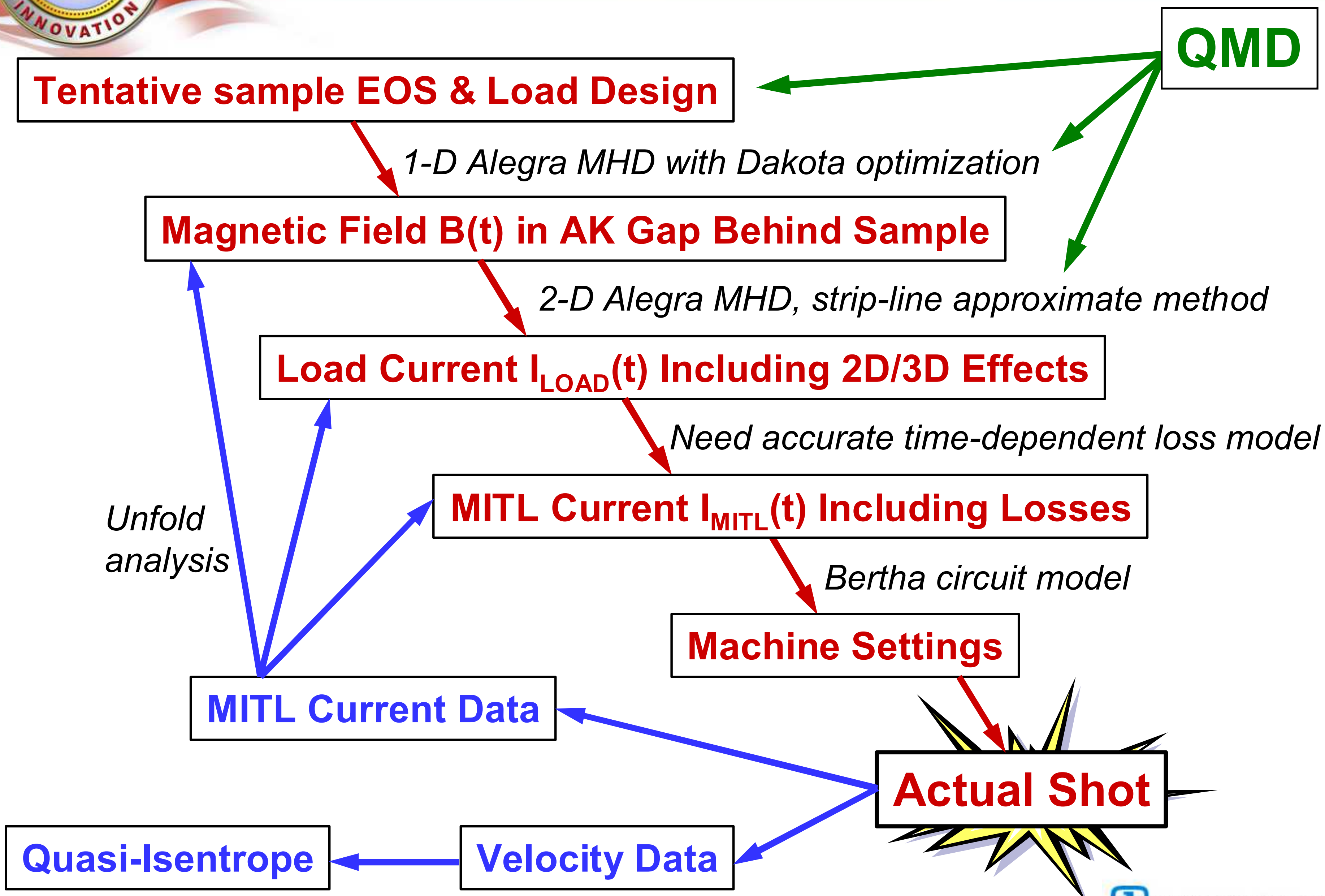
We have developed a robust methodology for experimental design and data analysis



Outline

- Overview of magnetic compression
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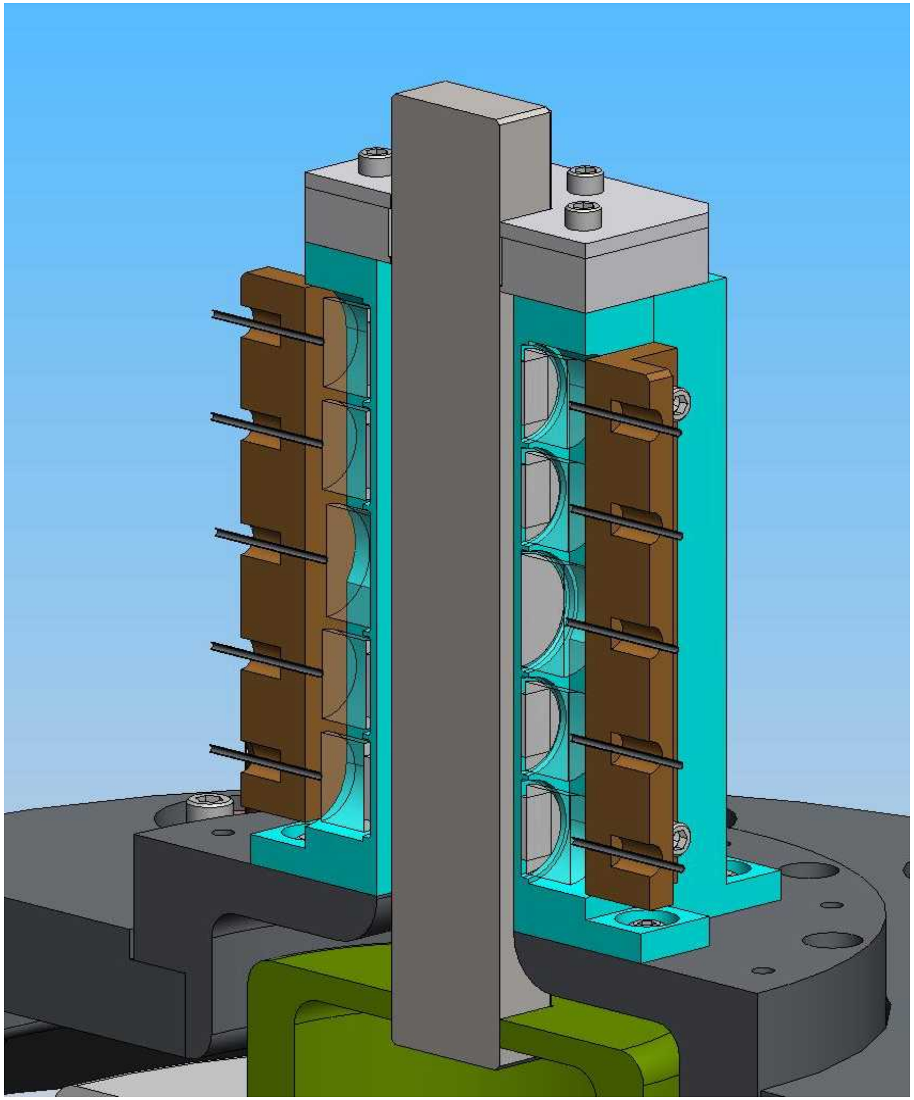
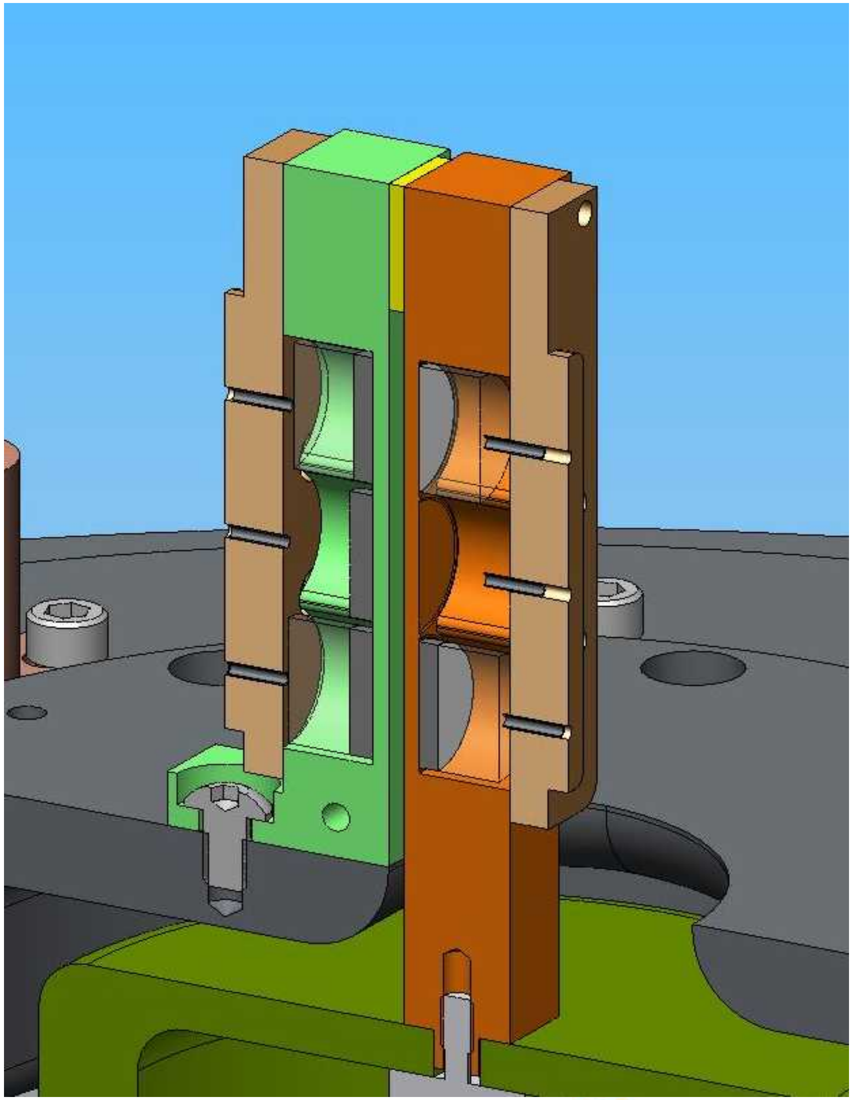
  - Co-axial
  - Stripline
- Magneto-hydrodynamic modeling and optimization
- Integrated experimental design

Two different load designs have been used for material dynamics experiments on Z

Co-axial



Stripline



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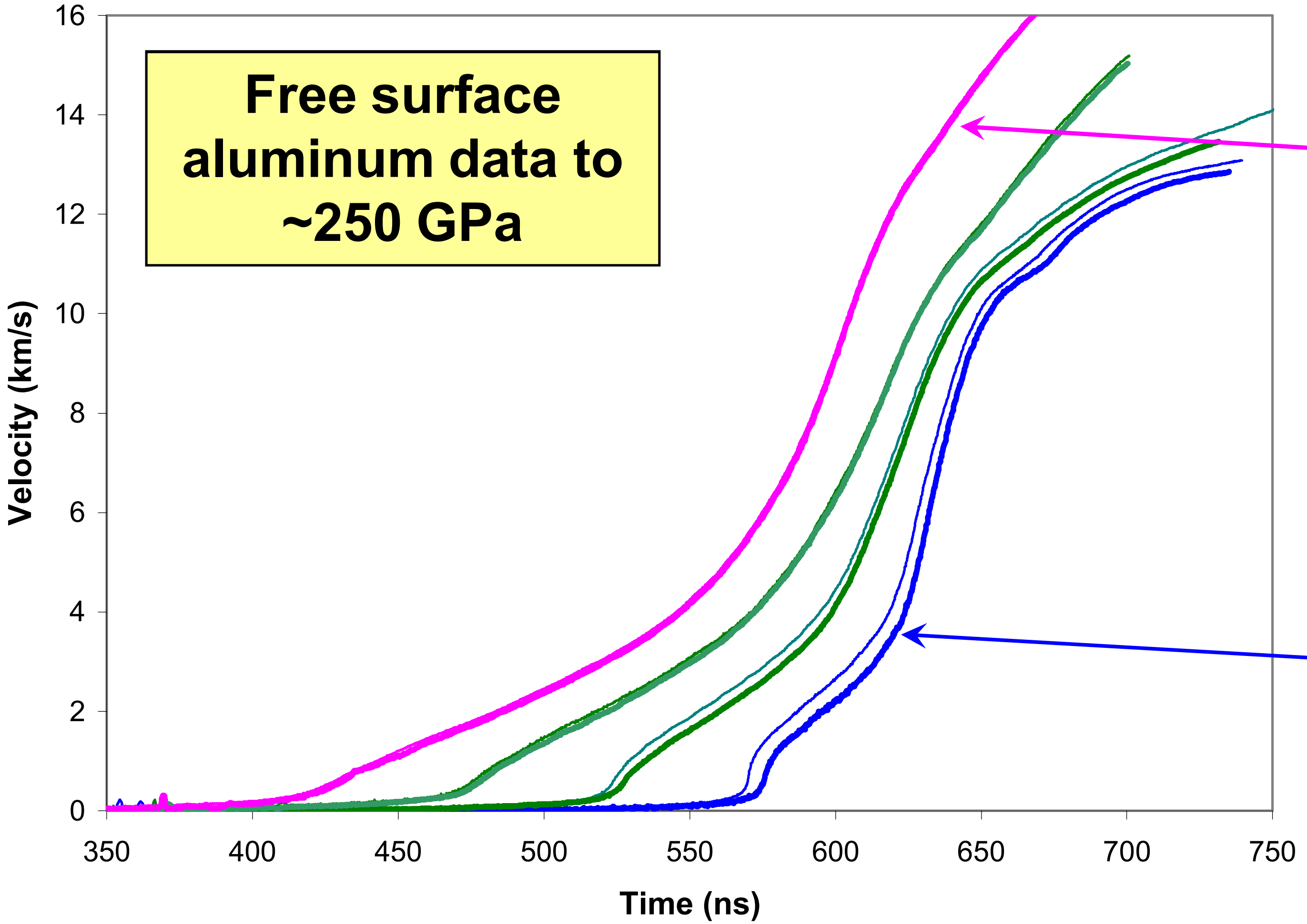
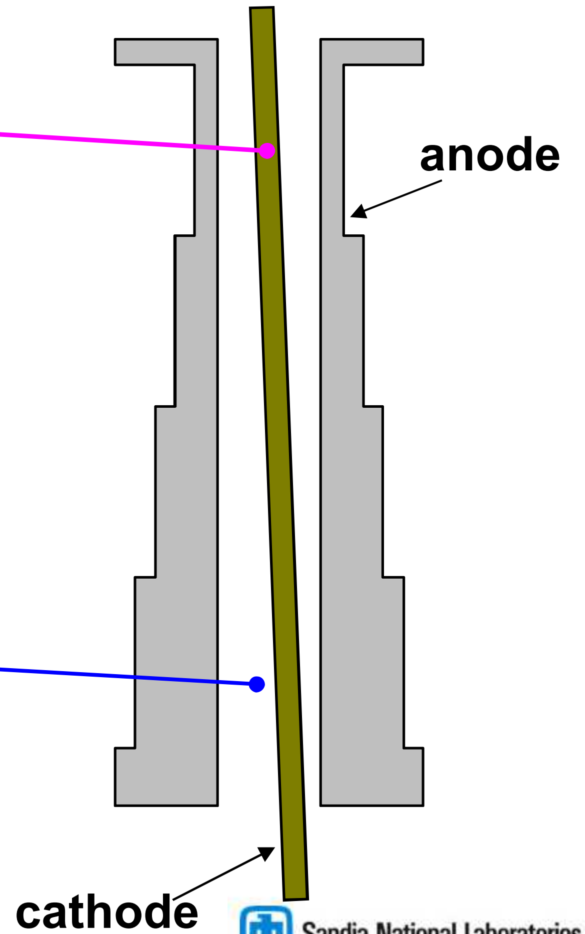
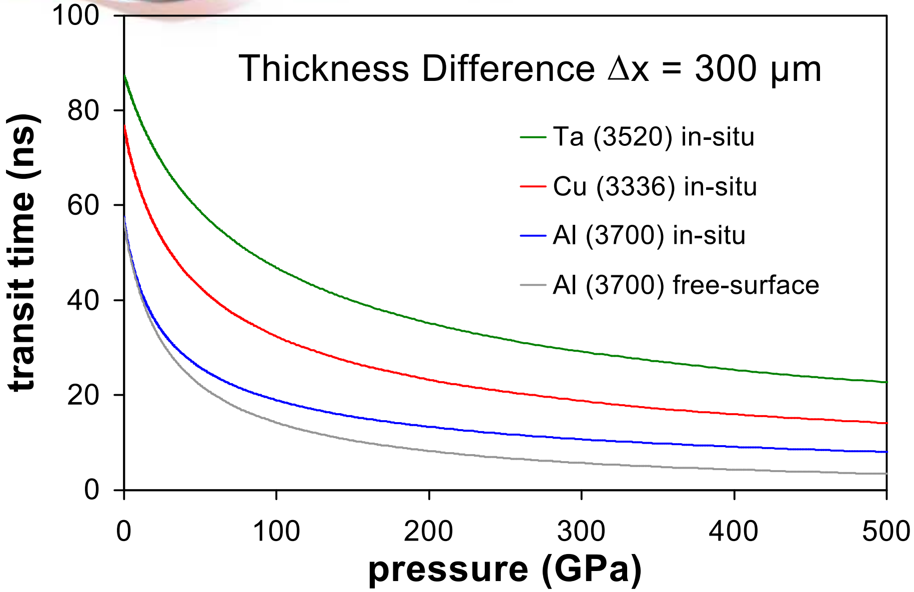
The coaxial design has some practical limitations for use in multi-Mbar ramp compression experiments

- Uniformity of magnetic field very sensitive to AK-gap alignment
- Field non-uniformity manifests as significant apparent time shifts
- 1% density accuracy requires 5 μm gap uniformity over 40 mm height

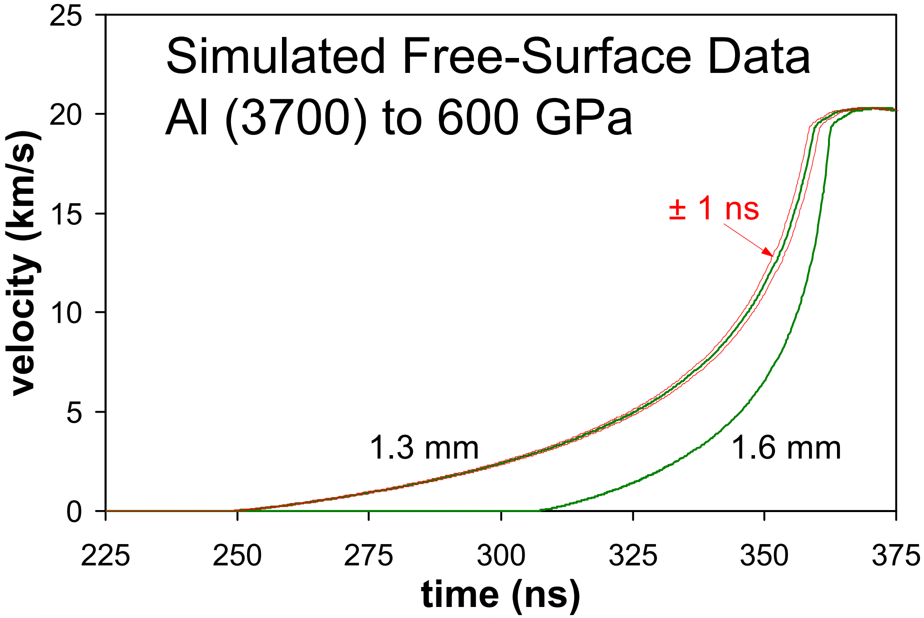


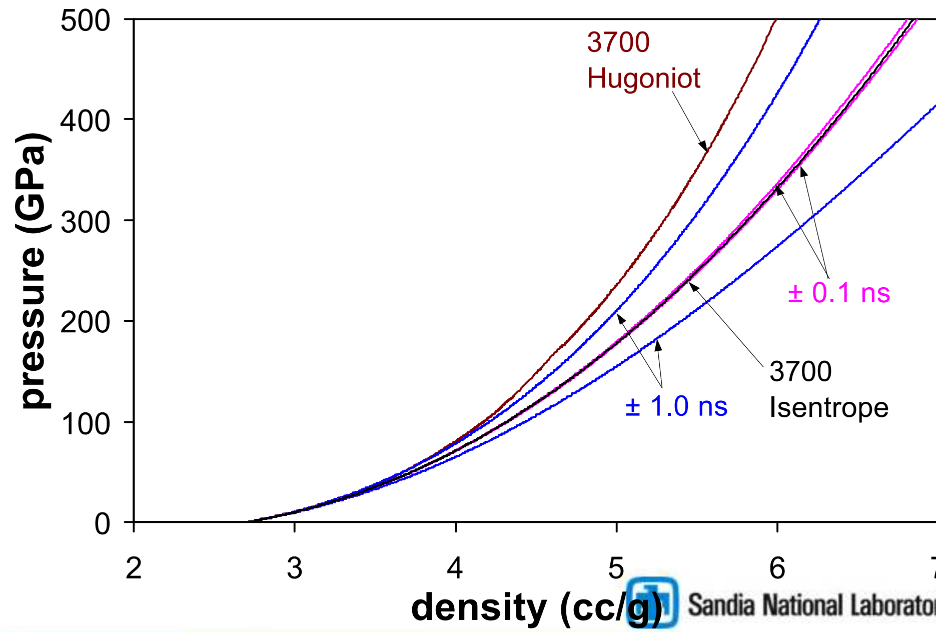


Accuracy of multi-megabar isentrope deduced from velocity data depends strongly on timing

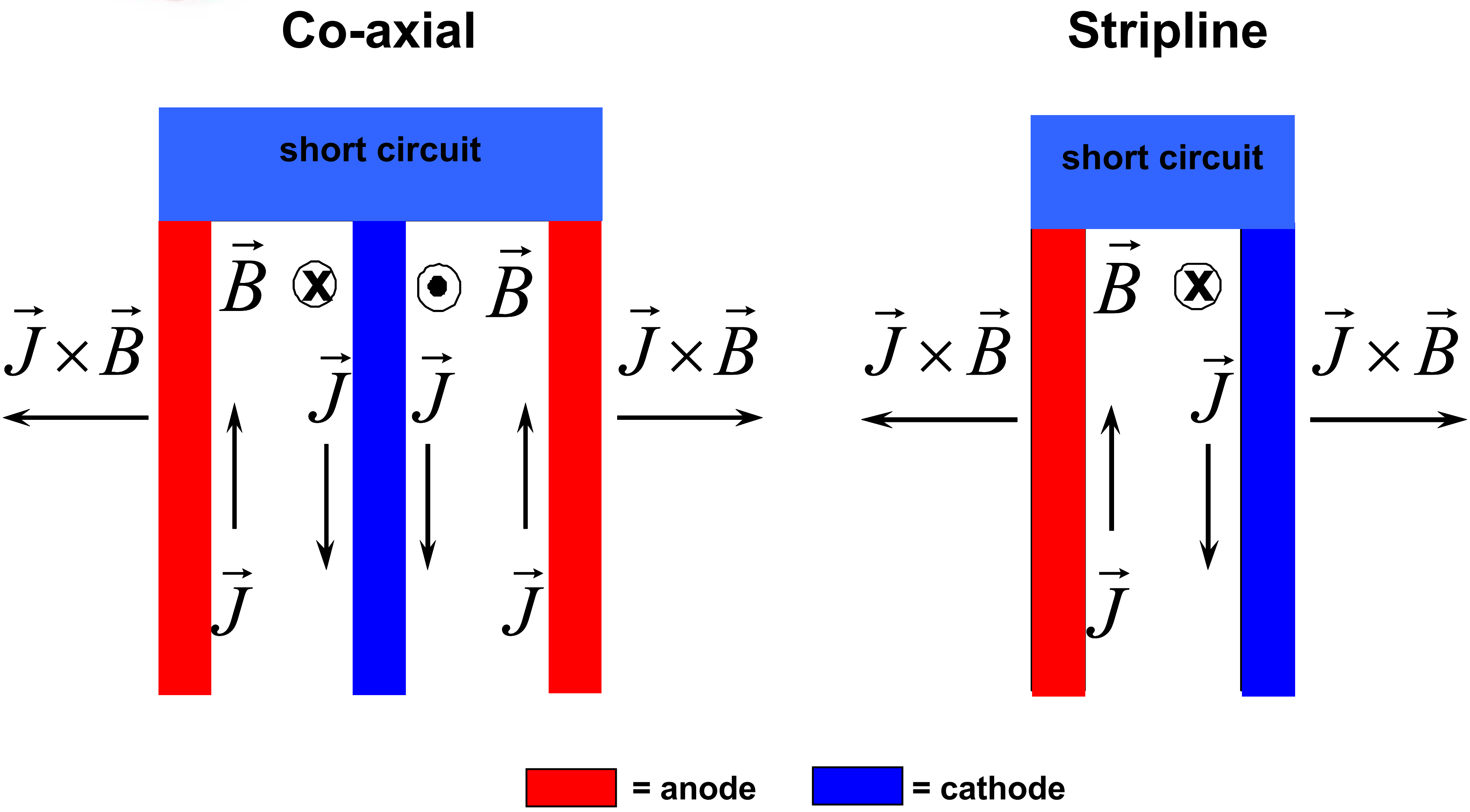


- **Very high Lagrangian sound speeds at high stresses result in small transit times, placing very stringent demands on timing accuracy.**
- **~100 ps timing accuracy required to obtain ~1% accuracy in density**

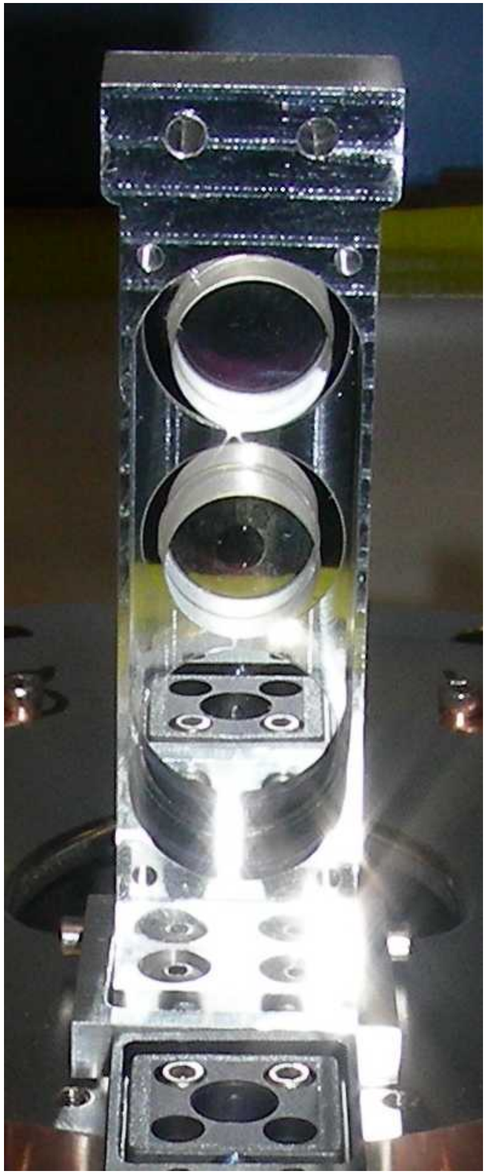


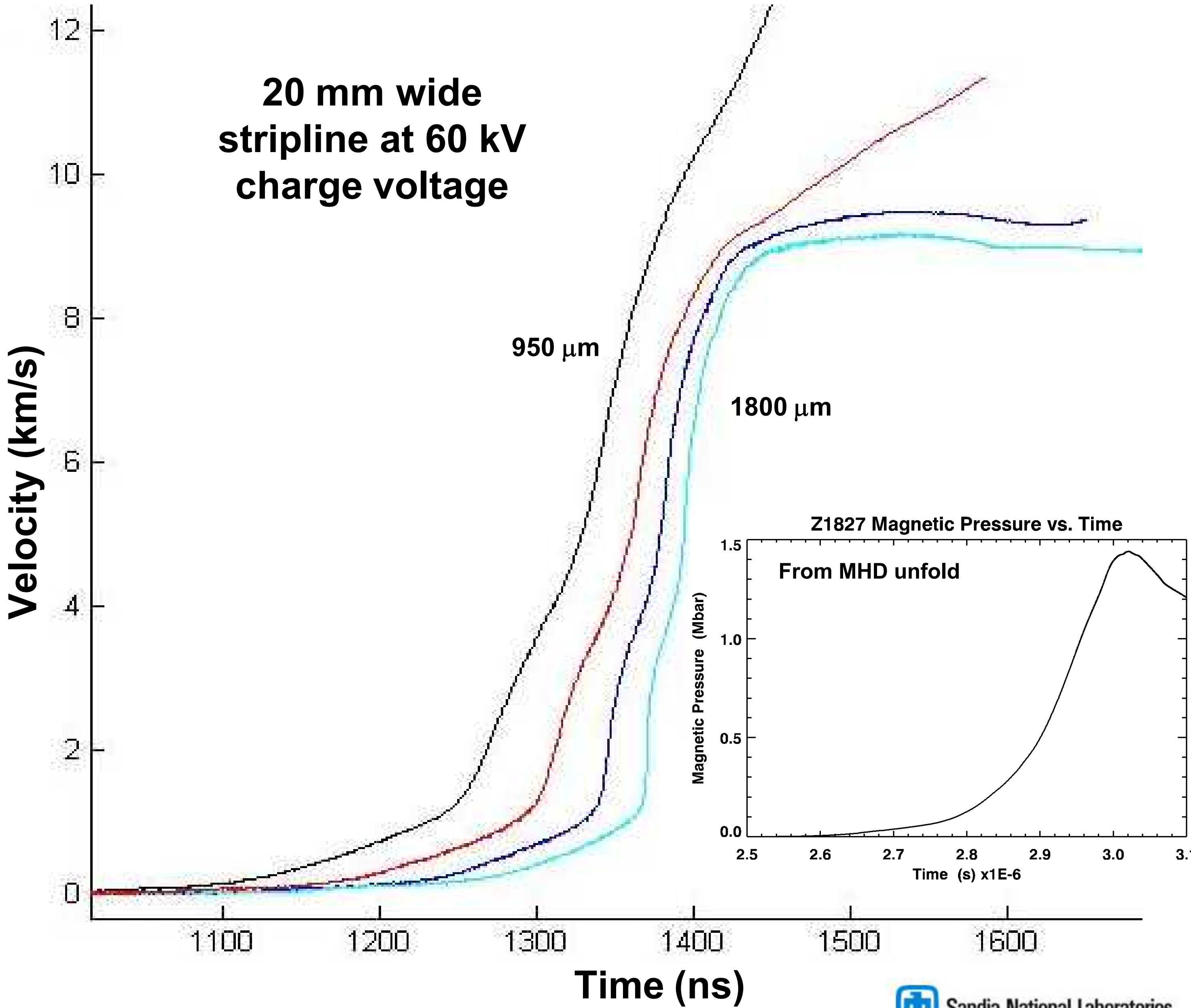


Stripline enables two samples to experience identical B-field, ensuring identical pressure histories



Early experiments with the stripline geometry were very encouraging and motivated further efforts





The stripline load offers many advantages and disadvantages over the co-axial load

• Samples mounted opposite each other on the anode and the cathode are driven by exactly the same magnetic field waveform

• A single AK gap can produce stronger magnetic field (hence higher pressure) for the same driving current

• The open geometry makes in-situ alignment easier

• Results are much less sensitive to misalignment

• Amenable to 1-D approximate analysis of dynamic deformation effects

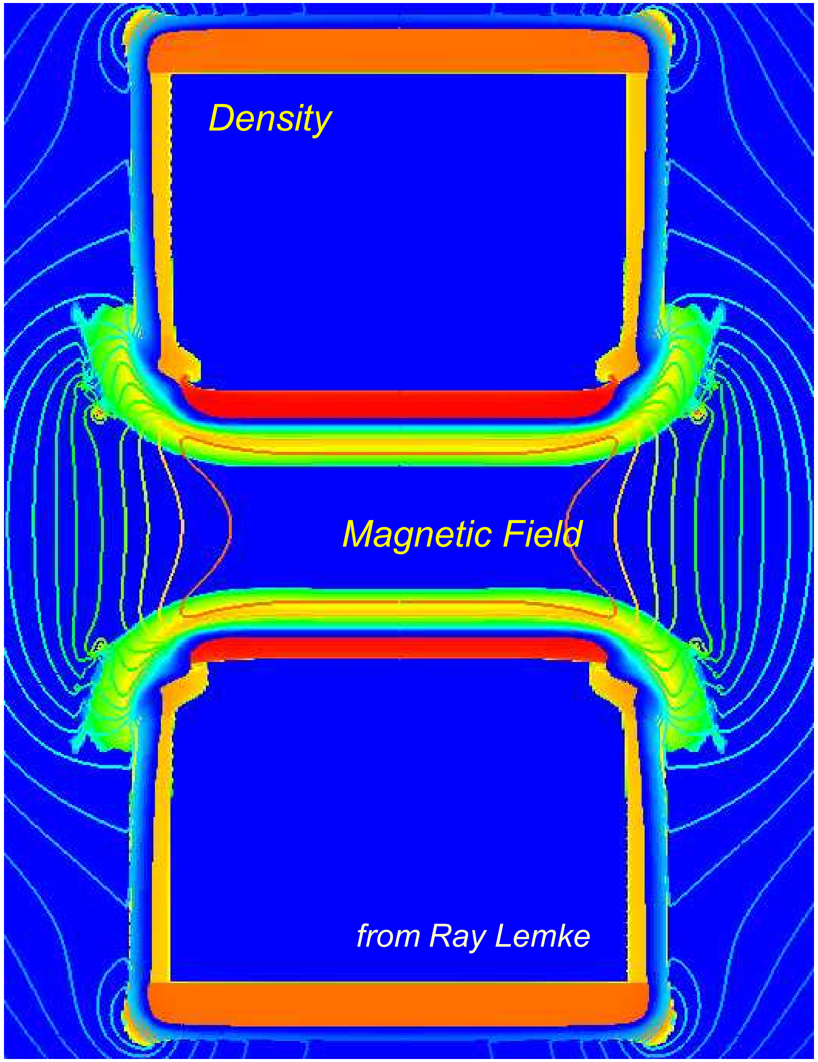
Several disadvantages had to be overcome:

• Diagnostics exposed to unconfined MGauss-level magnetic fields, MV-level voltages, and MA-level currents

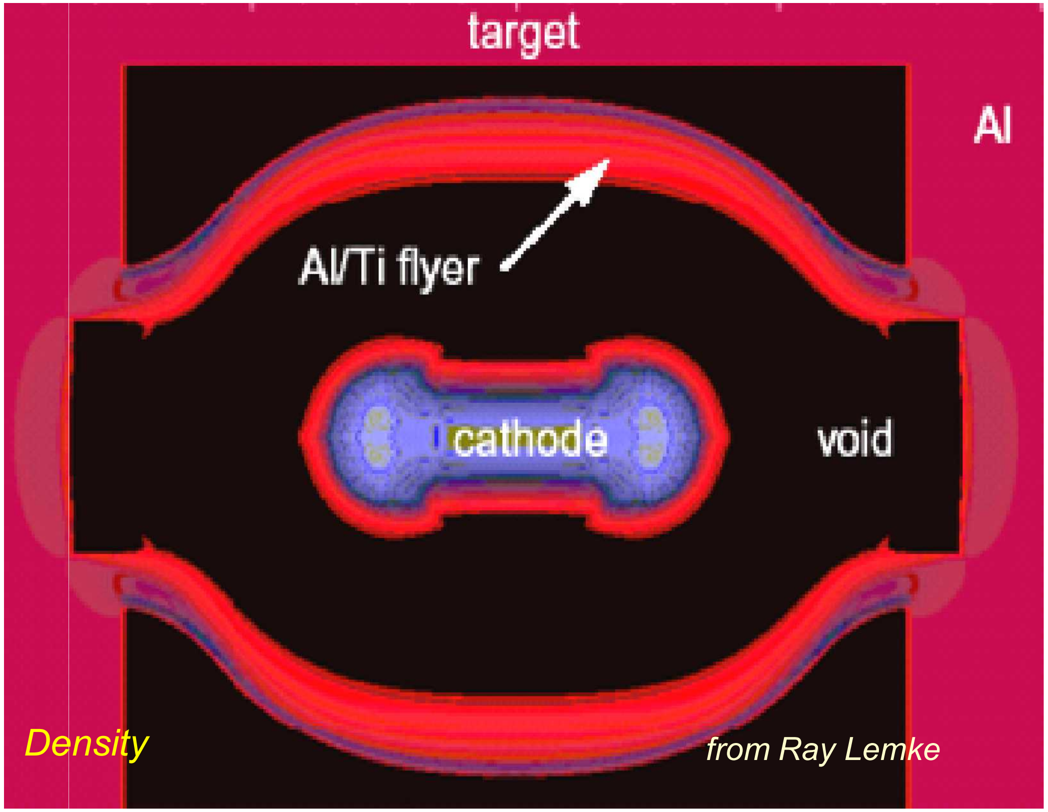
• Very high initial load inductance (~10.3 nH inside convolute)

• Large deformation effects as electrodes fly apart, significantly reducing peak drive pressure for given peak current

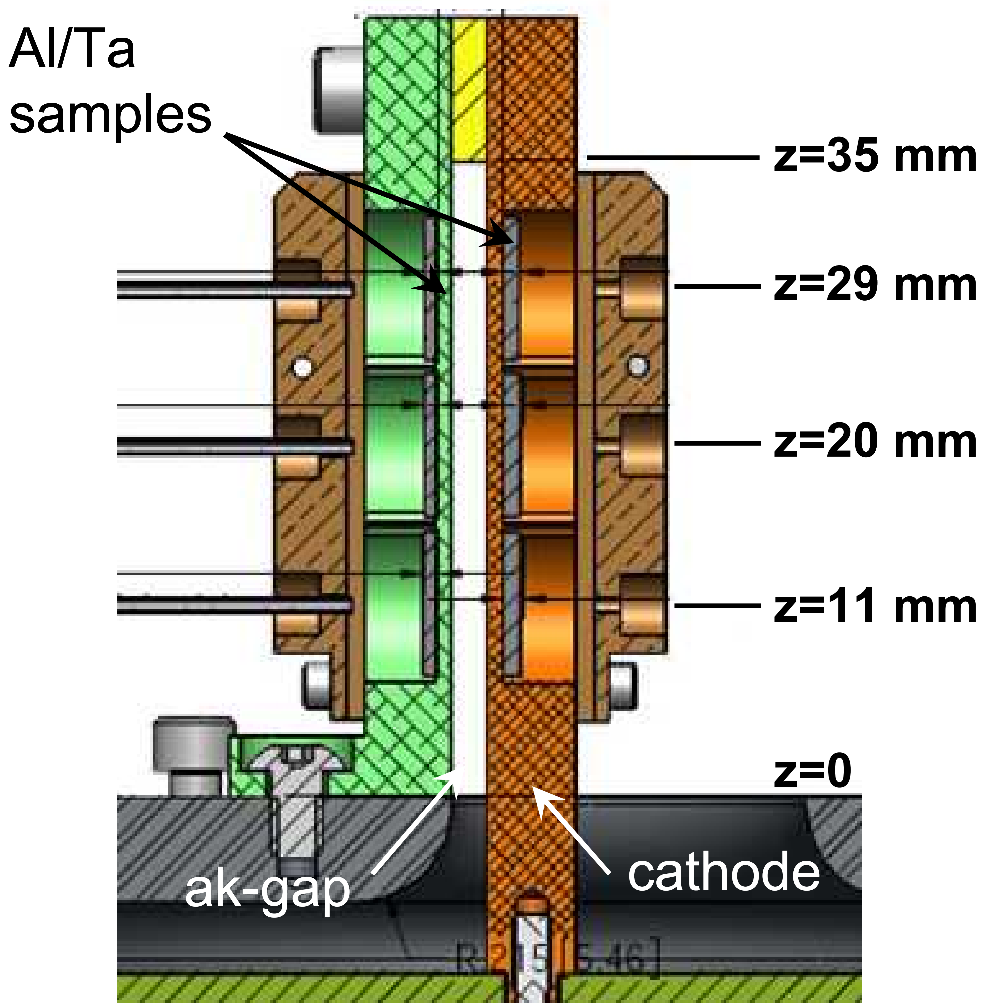
2D deformation effects are significantly reduced for the stripline compared to the coaxial geometry

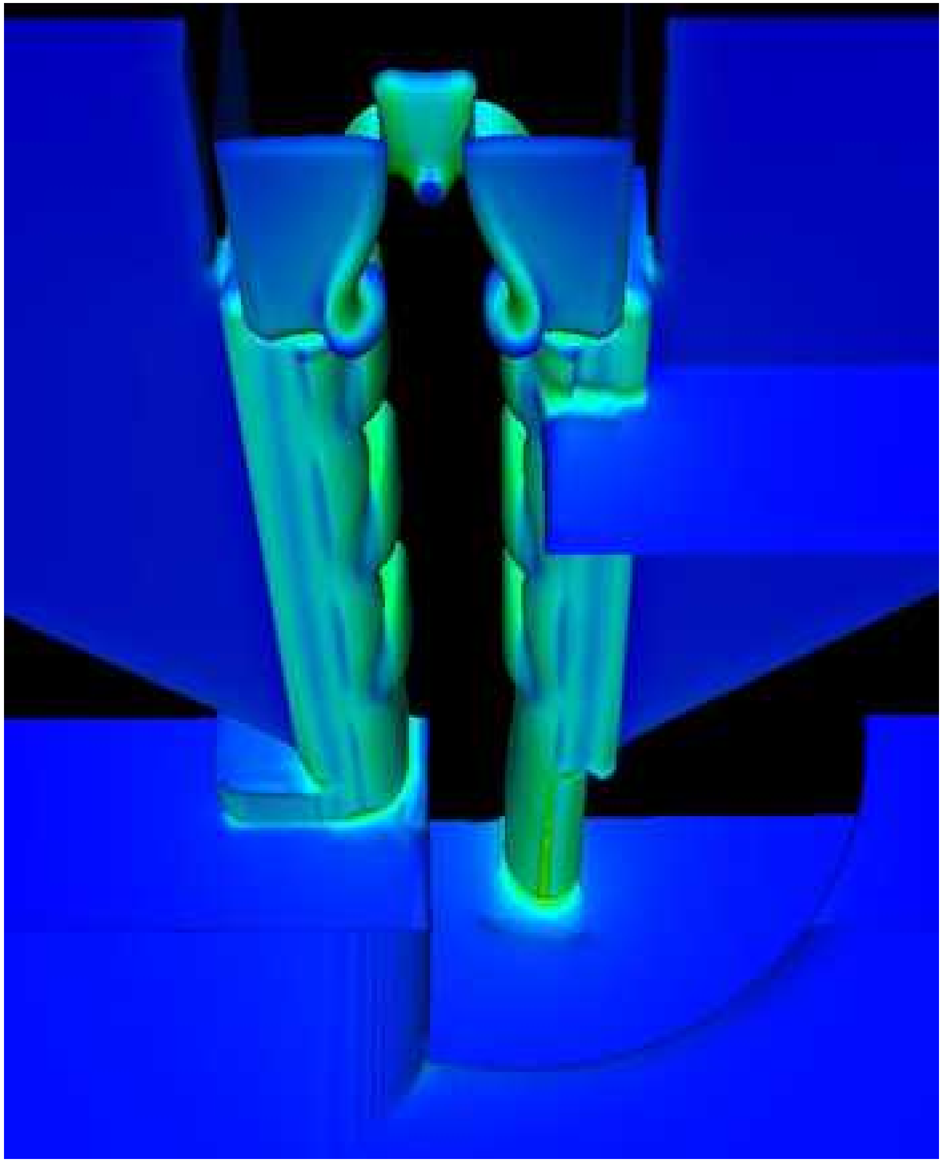


2D deformation effects are much more significant for coaxial geometry. Stripline geometry provides much better lateral uniformity



However the stripline geometry introduces additional complexities due to 3D current flow at the load





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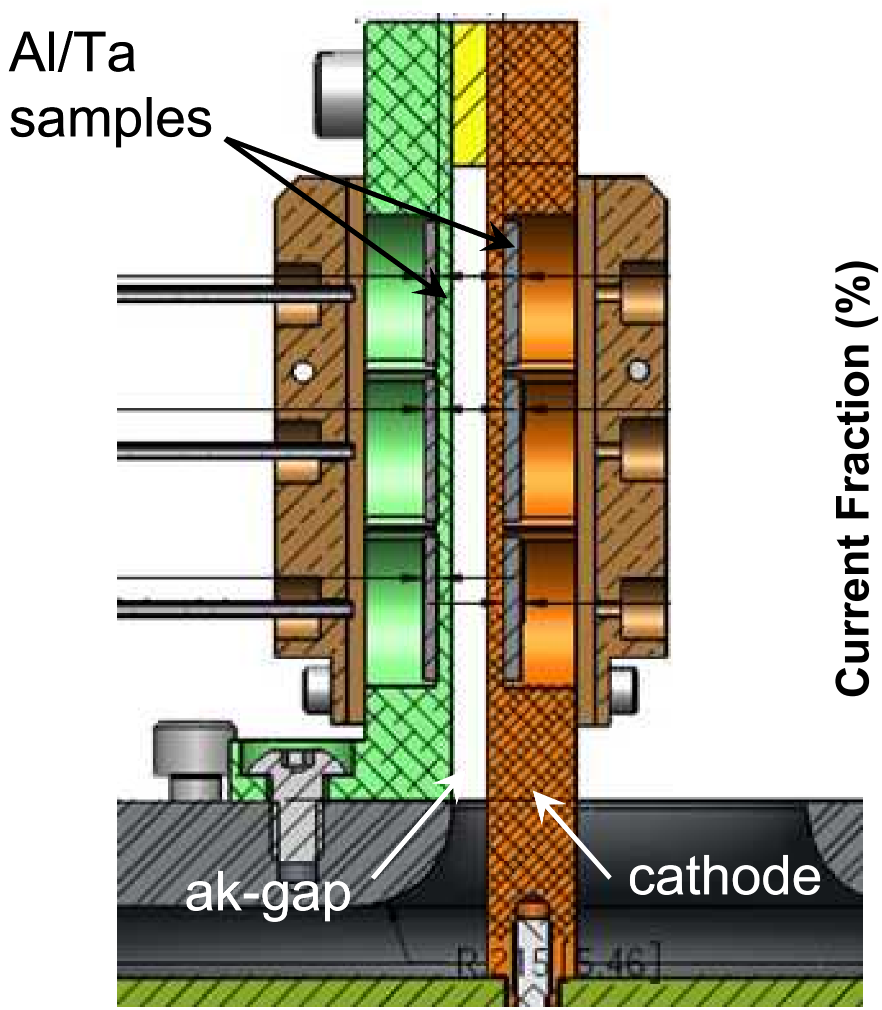

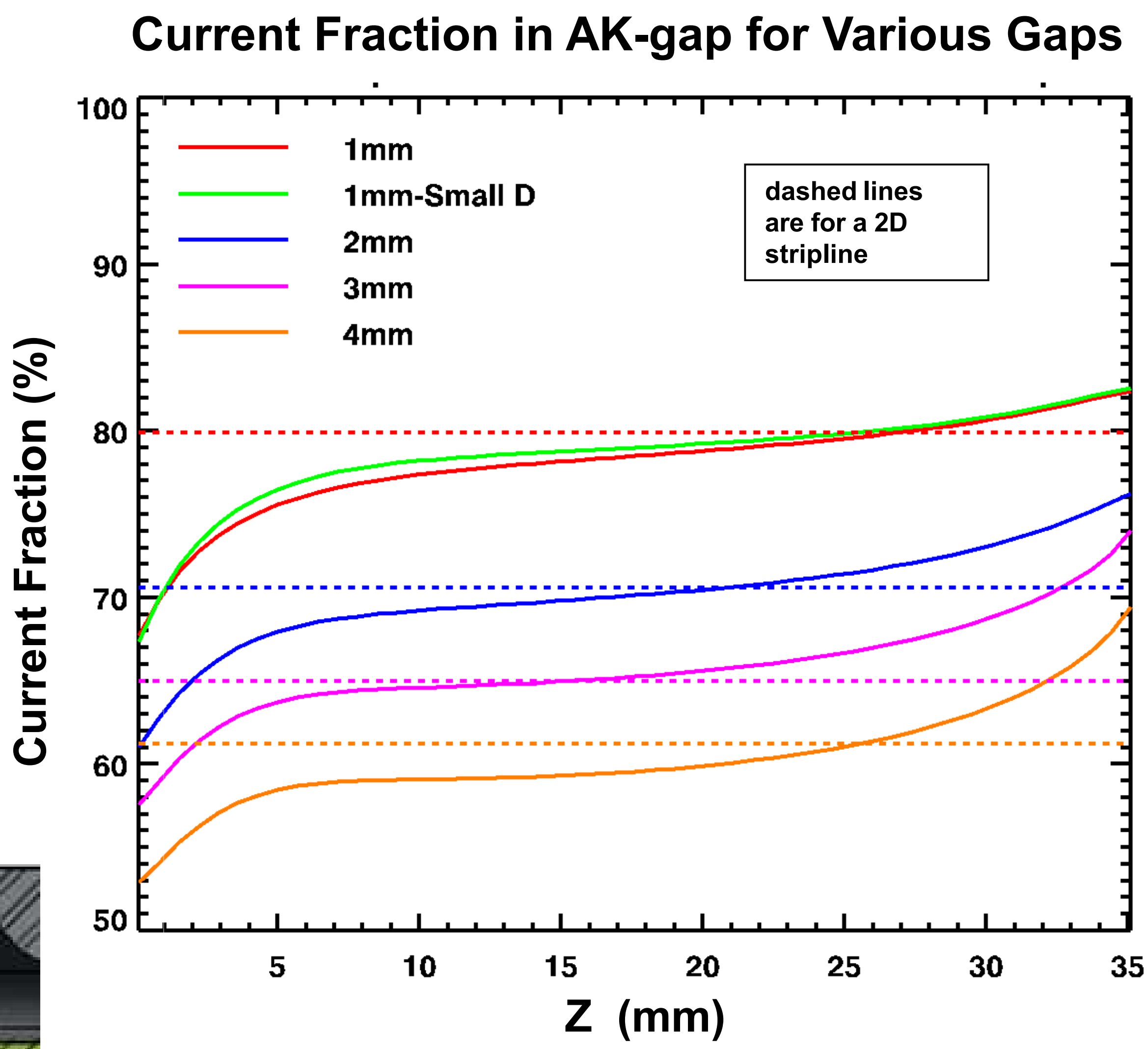

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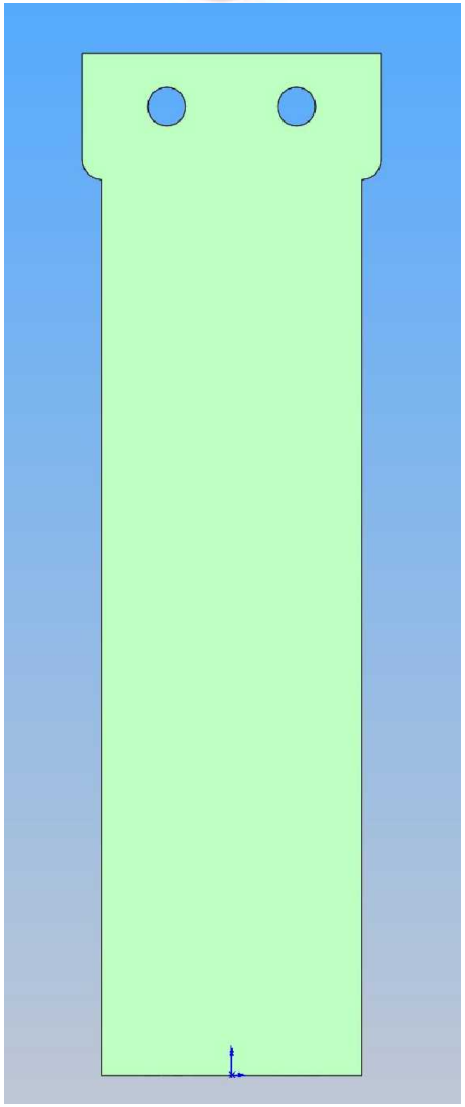
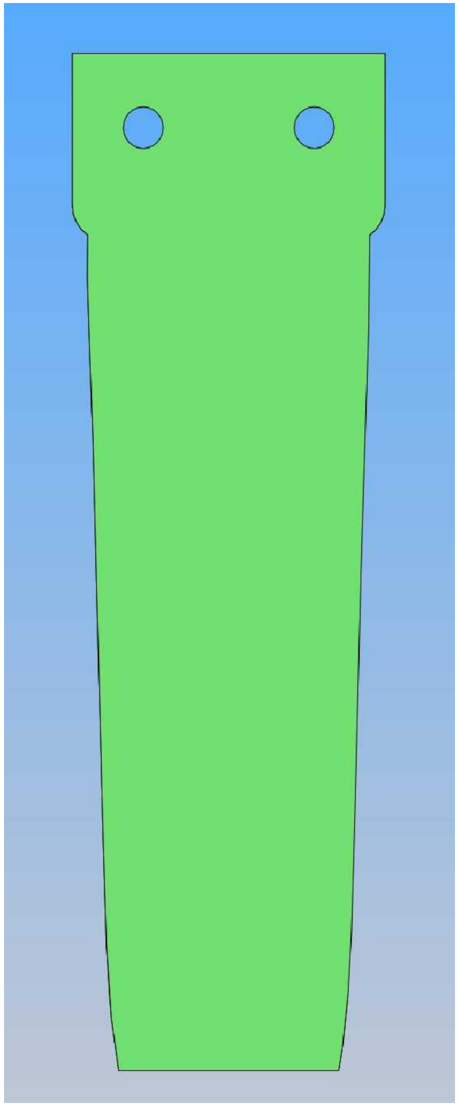
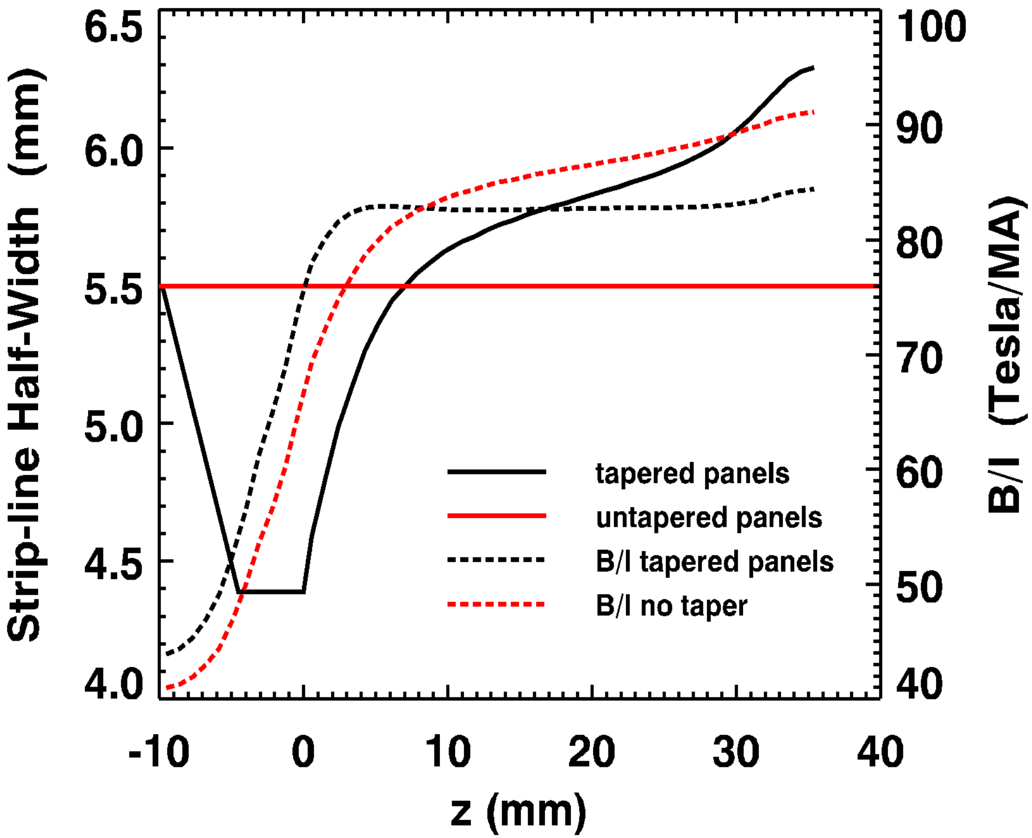
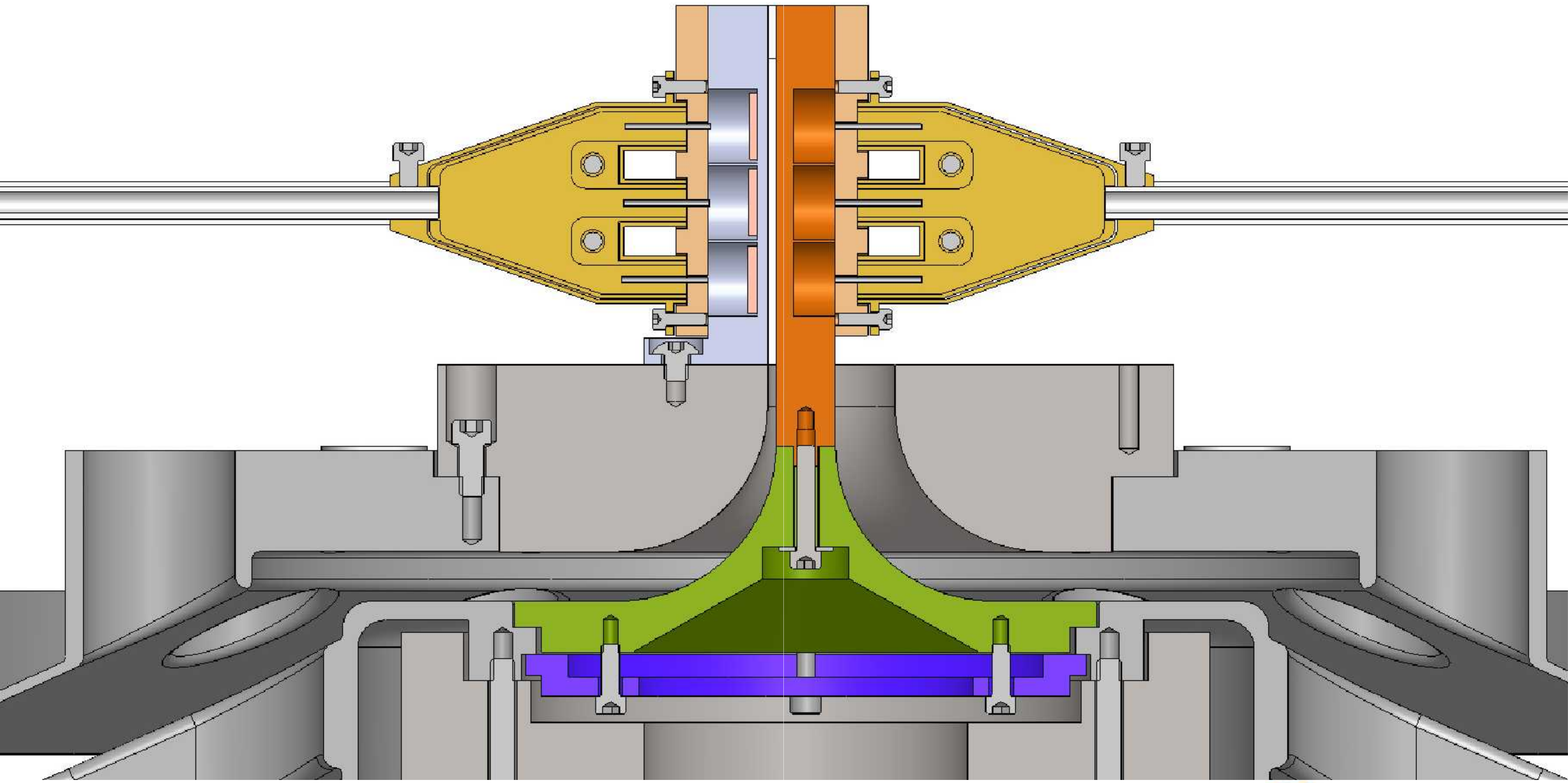




Panel Width & B/I vs. Height (3D EM simulation)



Remaining experimental definition includes electrode and sample thicknesses, and pulseshape



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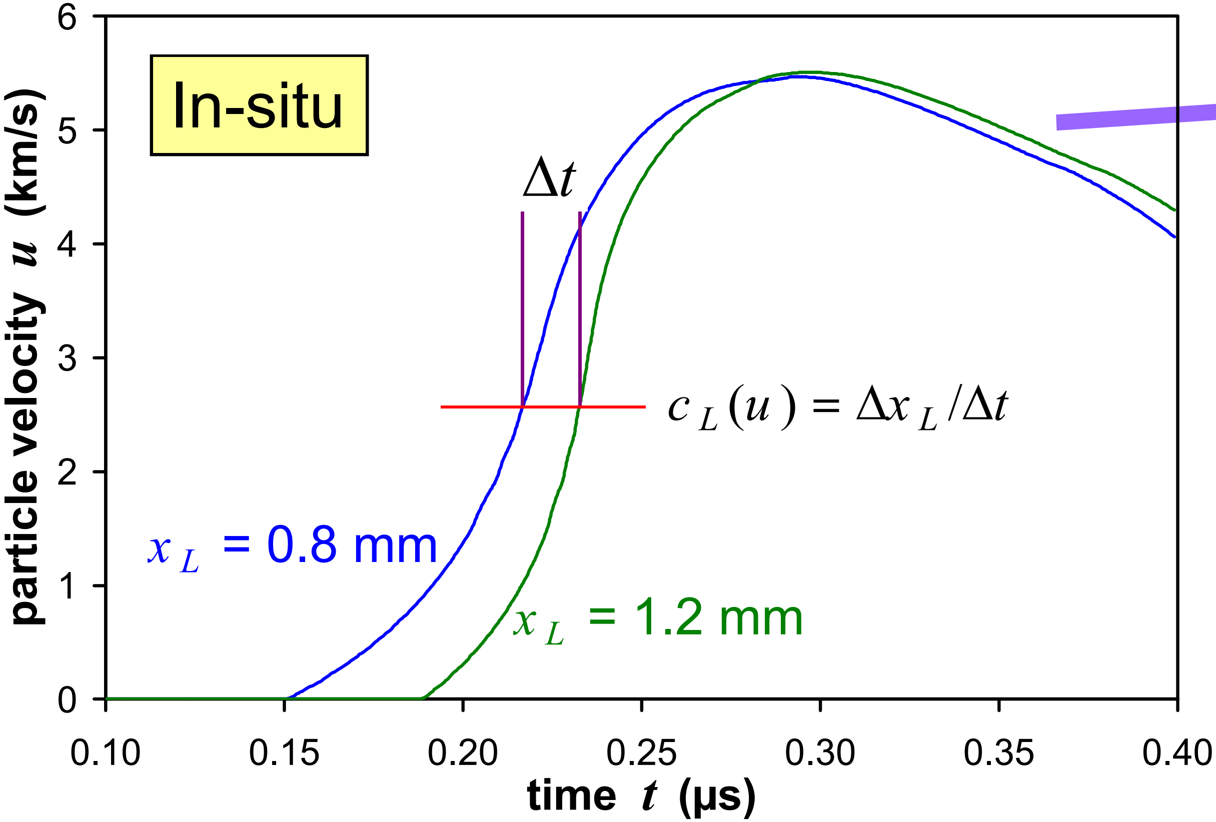
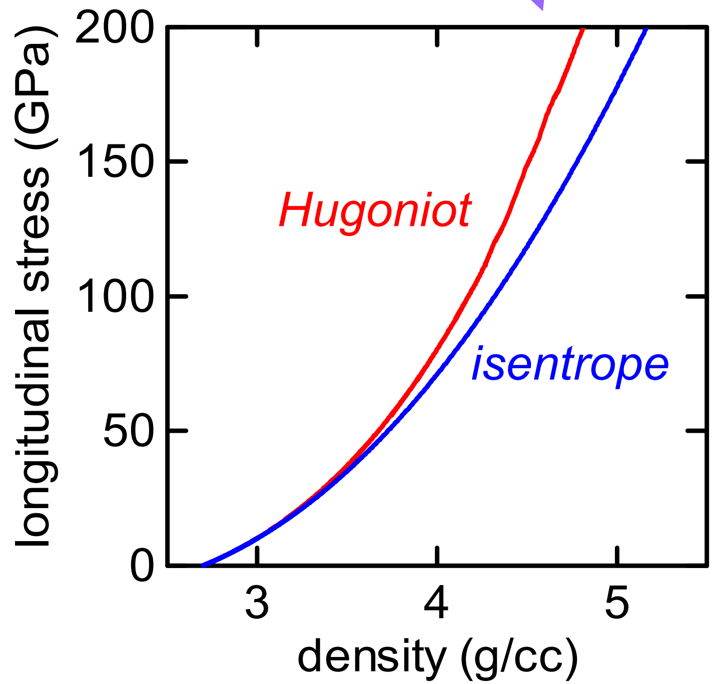
Ramp compression provides a measure of the stress-density response of a material to peak stress



conservation equations

$$d\sigma_x = \rho_0 c_L du$$

$$\frac{d\rho}{\rho^2} = \frac{du}{\rho_0 c_L}$$



- requires simple right-going waves
- compression is usually quasi-isentropic due to dissipative phenomena (plastic work, viscosity, thermal conduction, *etc.*)

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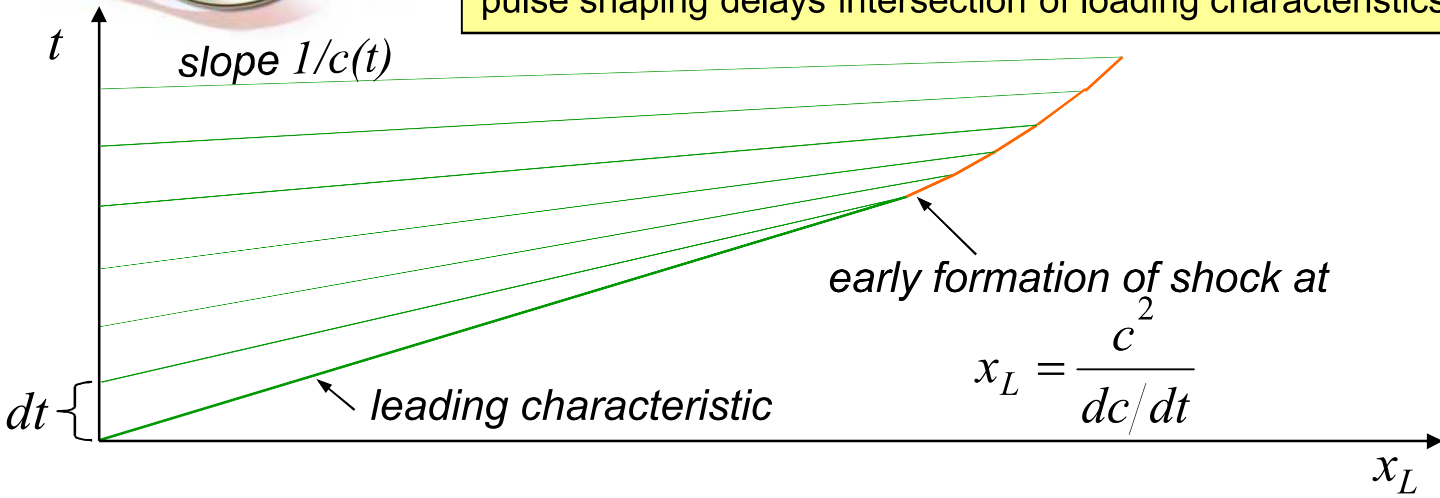
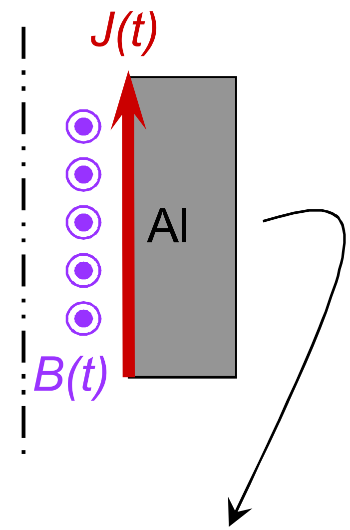
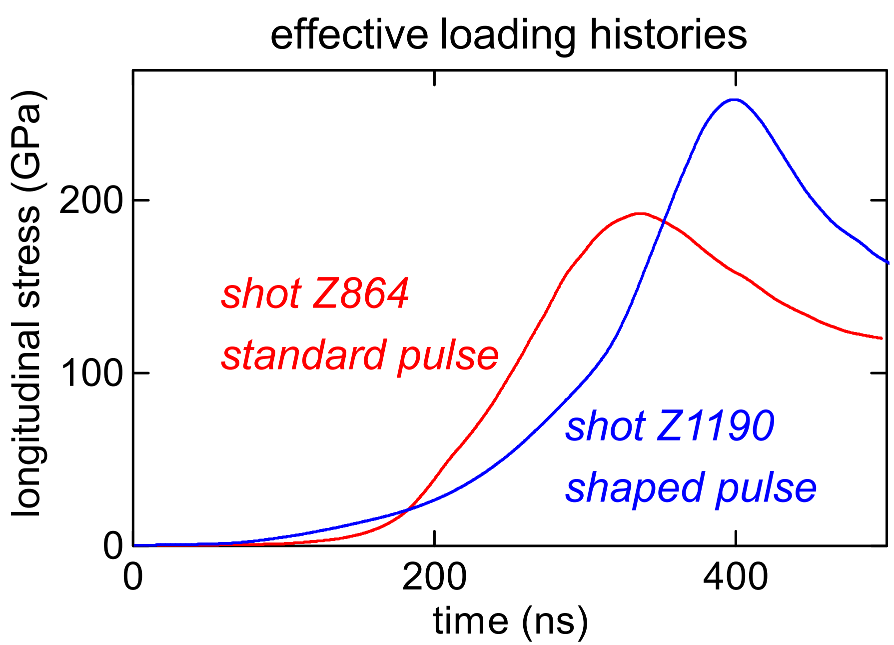
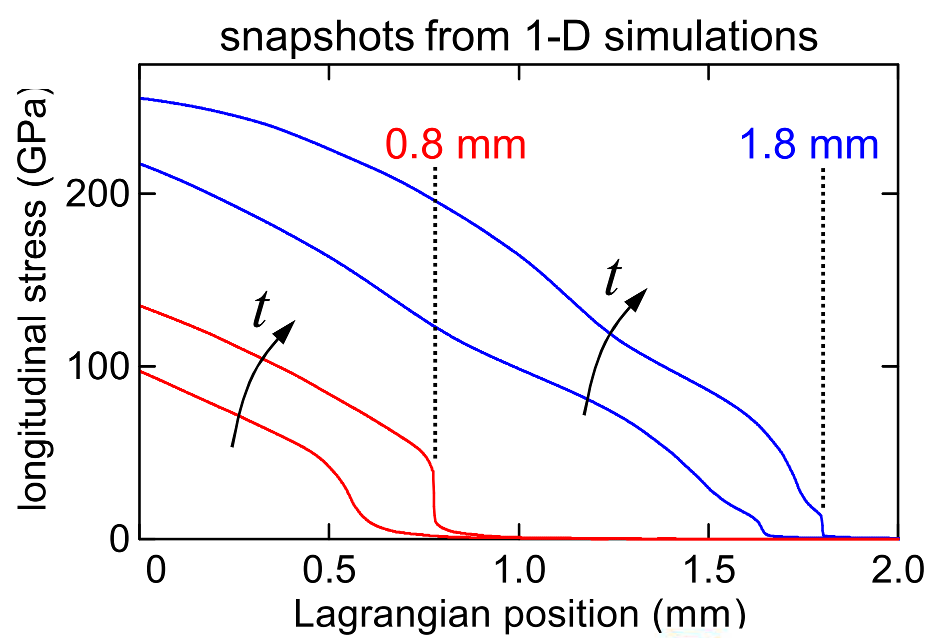
The rapid increase in sound speed requires pulse shaping to delay shock formation

pulse shaping delays intersection of loading characteristics

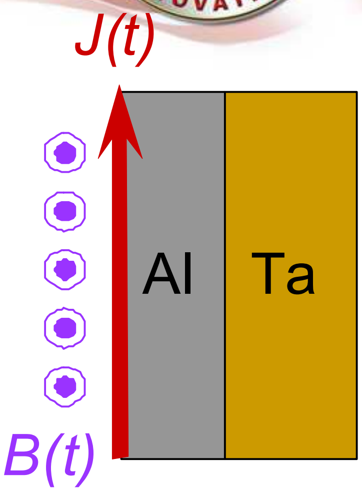


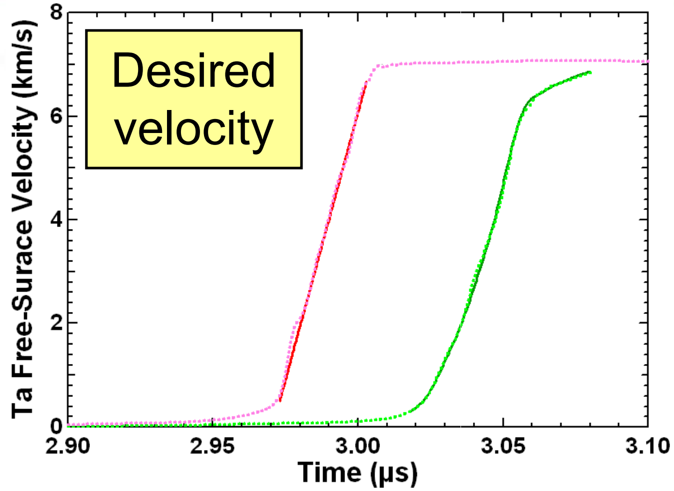


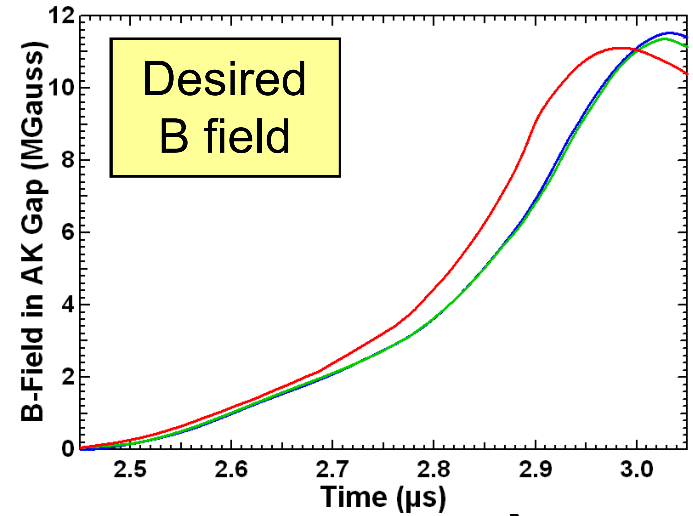


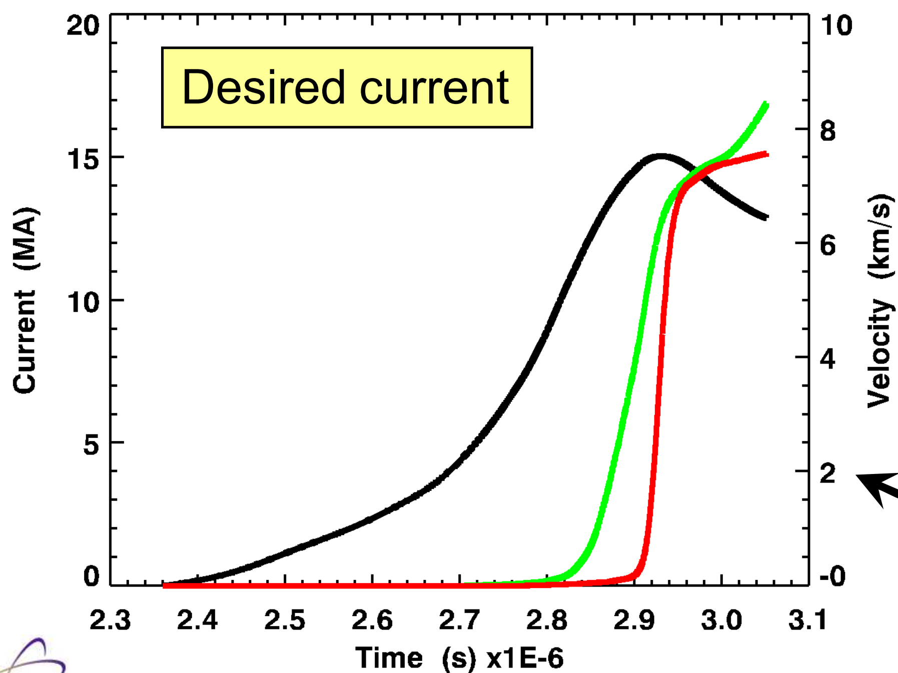


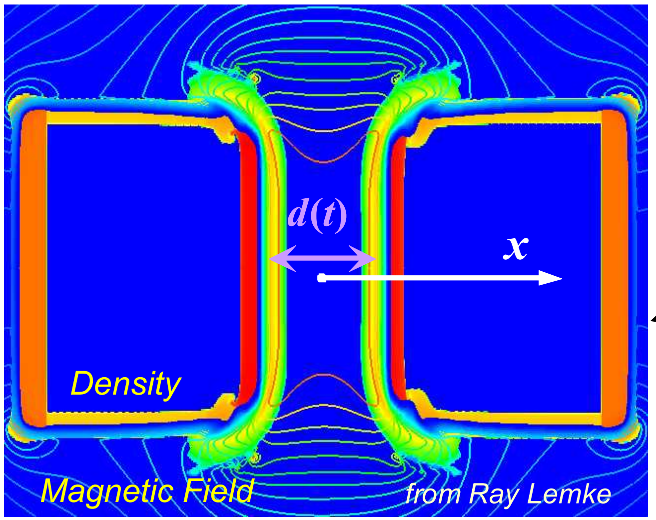
Desired current is determined through several iterative 1-D and 2-D MHD simulations











Simulation code is ALEGRA: 2D, 3D, radiation magneto-hydrodynamics (MHD)

- *ALEGRA physics:*
  - Self-consistent coupling of power flow to load (circuit model).
  - Resistive MHD: *self-consistent coupling of EOS, conductivity, Joule heating, hydrodynamics, and magnetic diffusion*.
- *Simulation methodology:*
  - Measurements provide the basis for model development and validation: *current and flyer/material velocity serve as benchmarks*.
  - Semi-emperical circuit model: *requires models of time dependent current loss (Z_{flow} impedance) and short circuit (crowbar)*.
  - Z_{flow} and crowbar models calibrated for a specific charge voltage (*standard & shaped voltage shots require separate calibration*).
  - Apply model to produce existing data; predict future shot performance.

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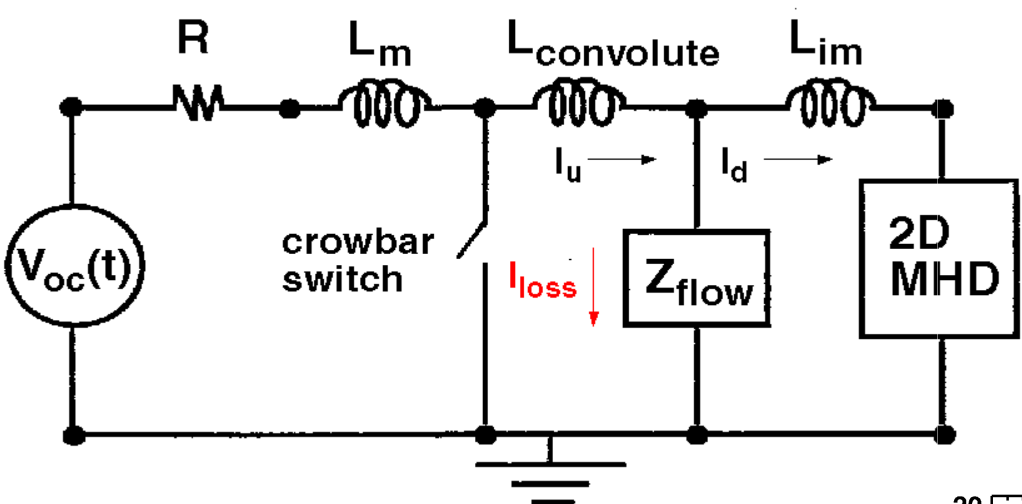
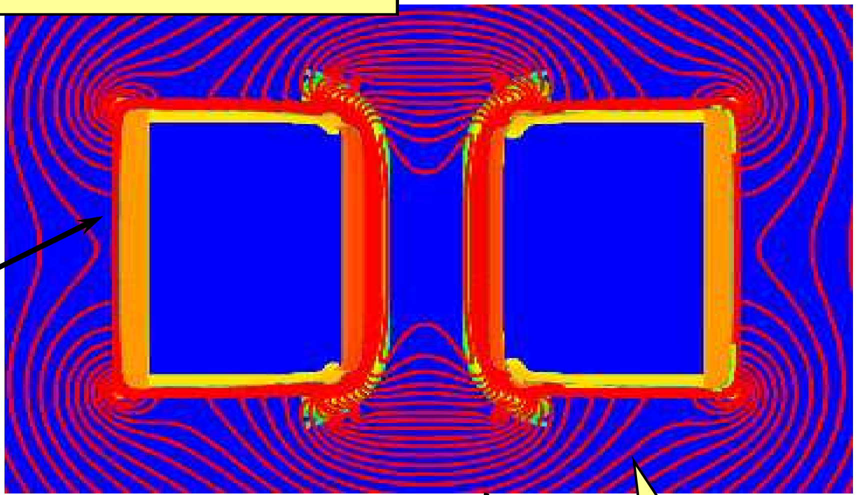
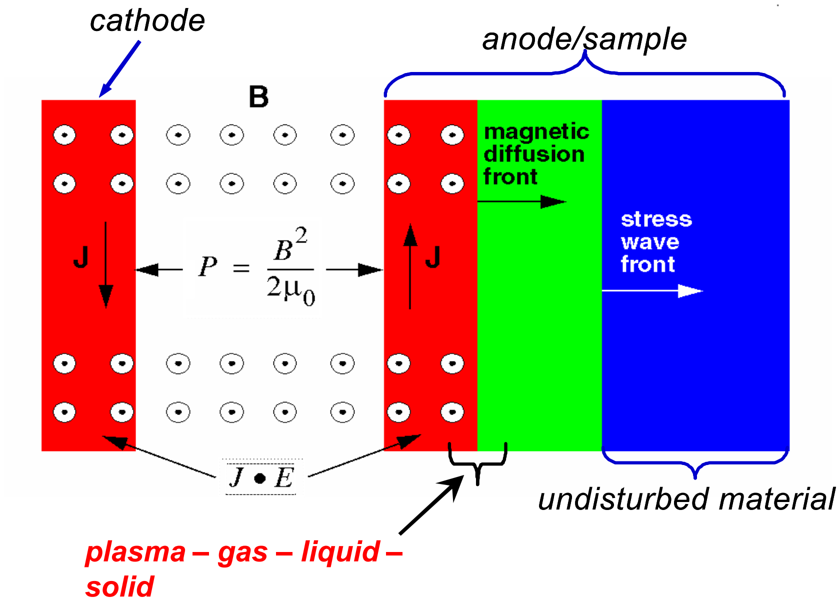
Accurate determination of 2D effects requires the use of a self-consistent circuit description of Z

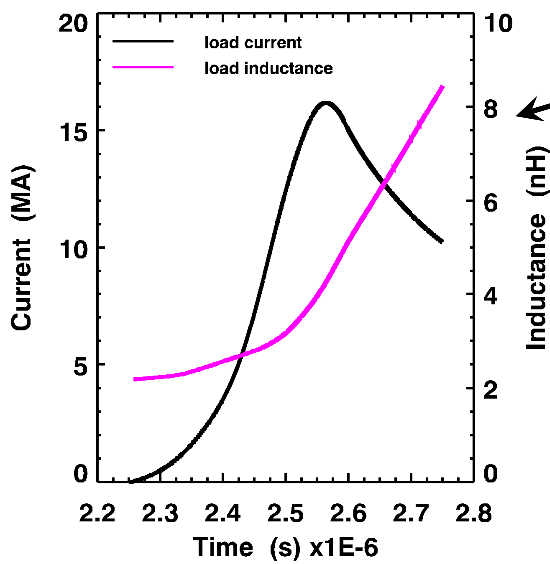
Z circuit for 2D MHD simulation



2D MHD geometry







Length in 3D handled by circuit-MHD coupling algorithm

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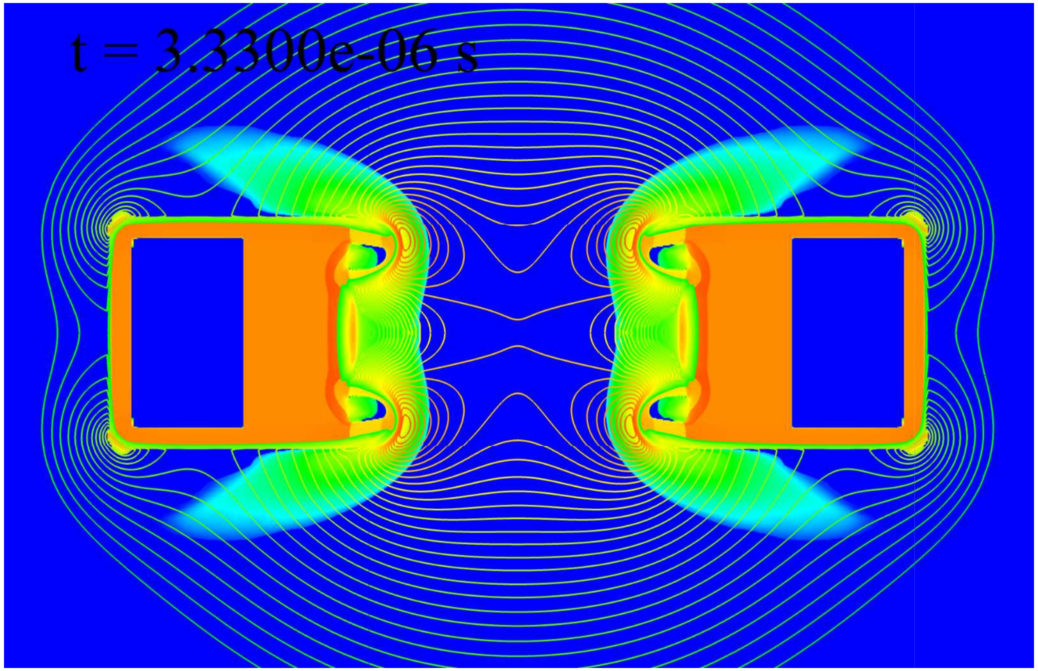
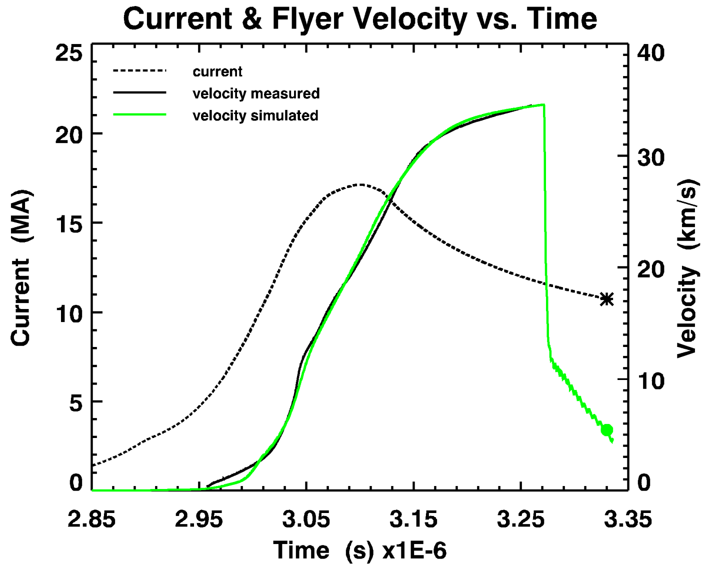
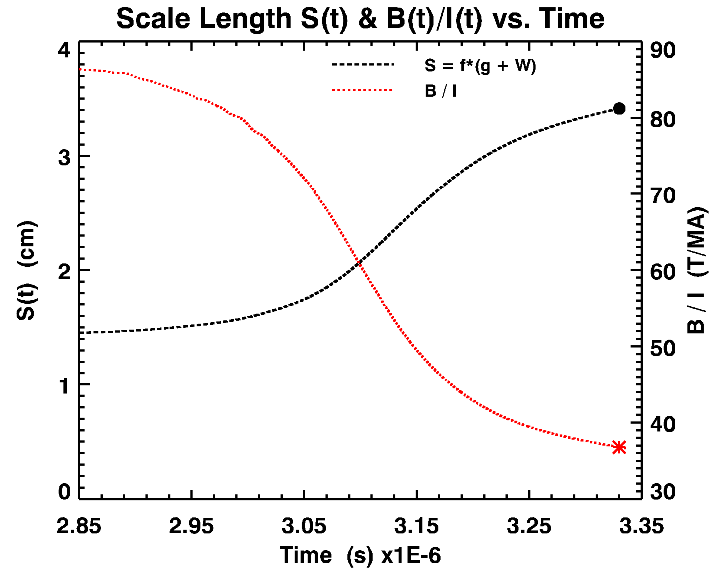
A truly predictive MHD modeling capability has been developed over the last several years

Simulation 2-sided, 11 mm strip-line, 900 µm Al flyers, density & magnetic field







Agreement between simulation and experiment at the ~1% level can be achieved

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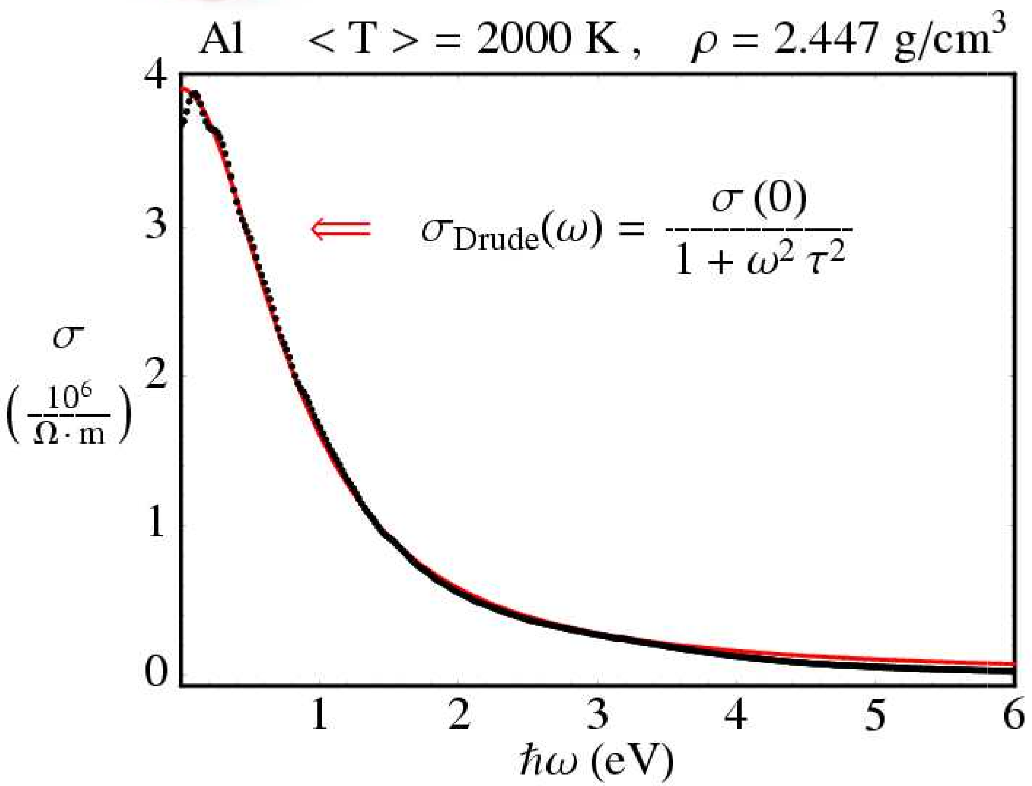
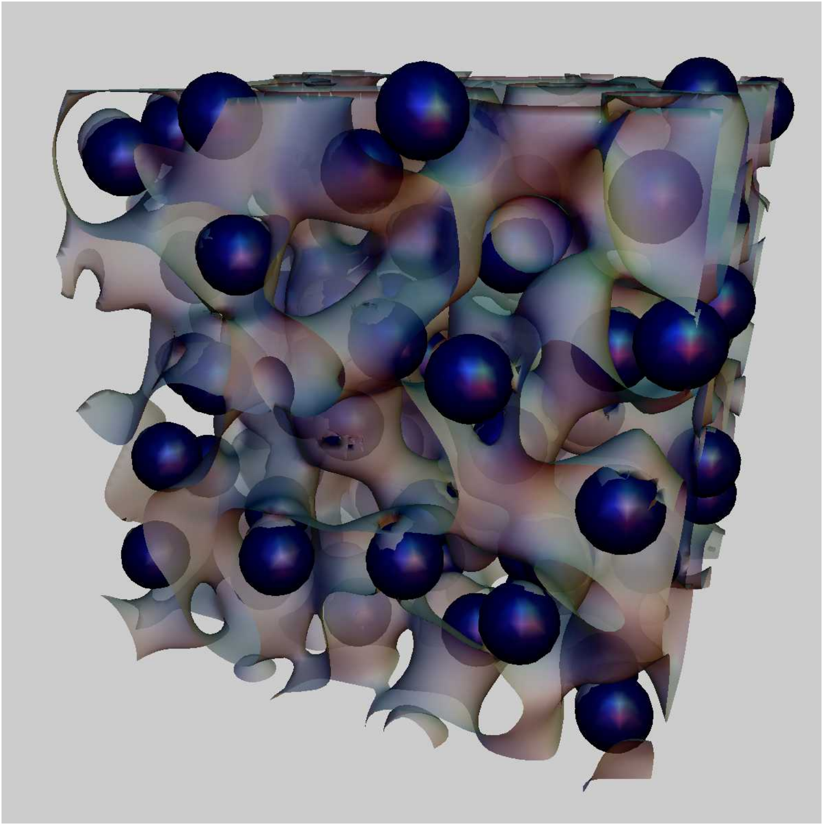
An improved aluminum conductivity model was found to be necessary for meaningful simulations



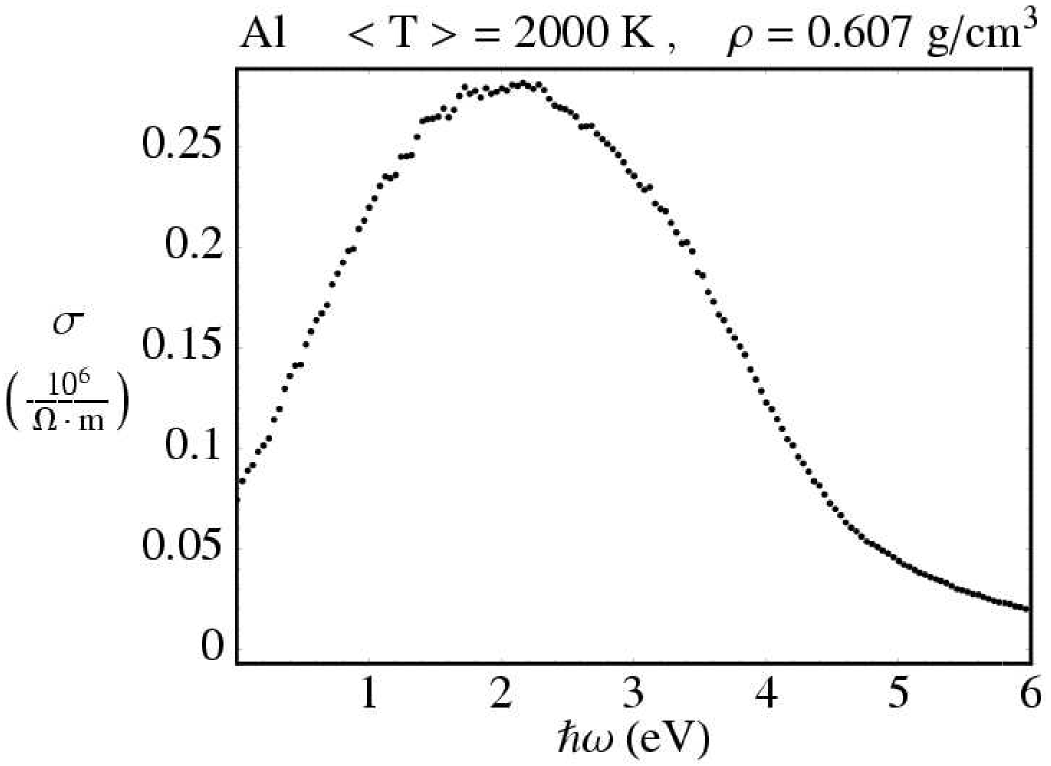
The agreement with the Drude model indicates 'nearly free' electrons



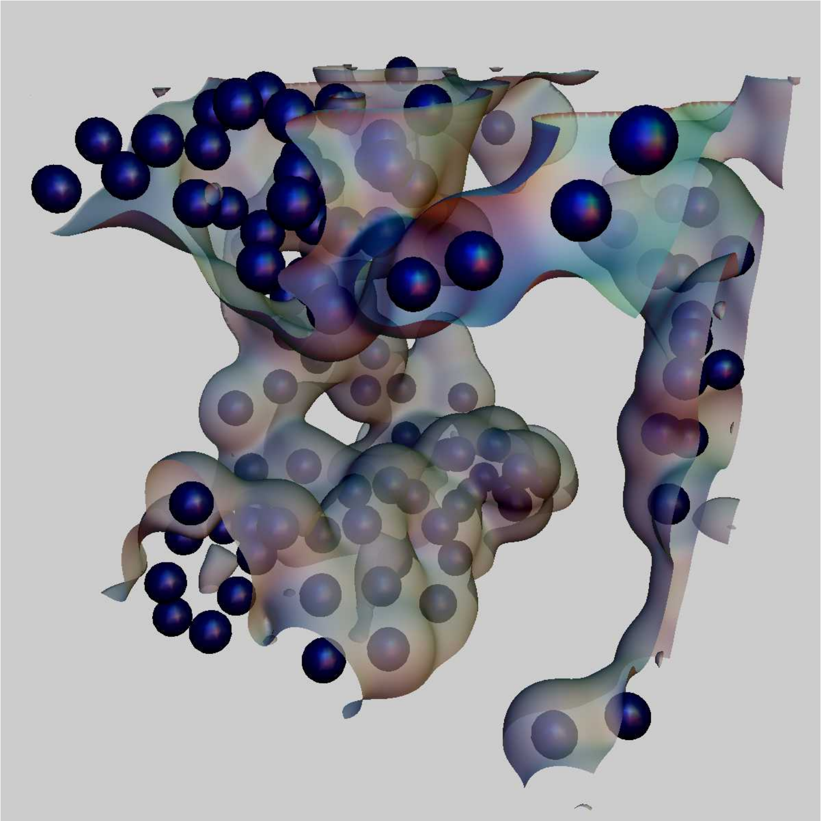
Ion cores displayed with iso-surfaces of the mean valence charge density

At liquid densities just below solid, the optical conductivity is well fit by the Drude model

An improved aluminum conductivity model was found to be necessary for meaningful simulations



The dc conductivity has dropped by a factor of 25 for a factor of 4 drop in density



Note the pronounced separation into liquid and void (vapor) regions

At lower density, where phase separation is pronounced, a gap begins to form at low energy

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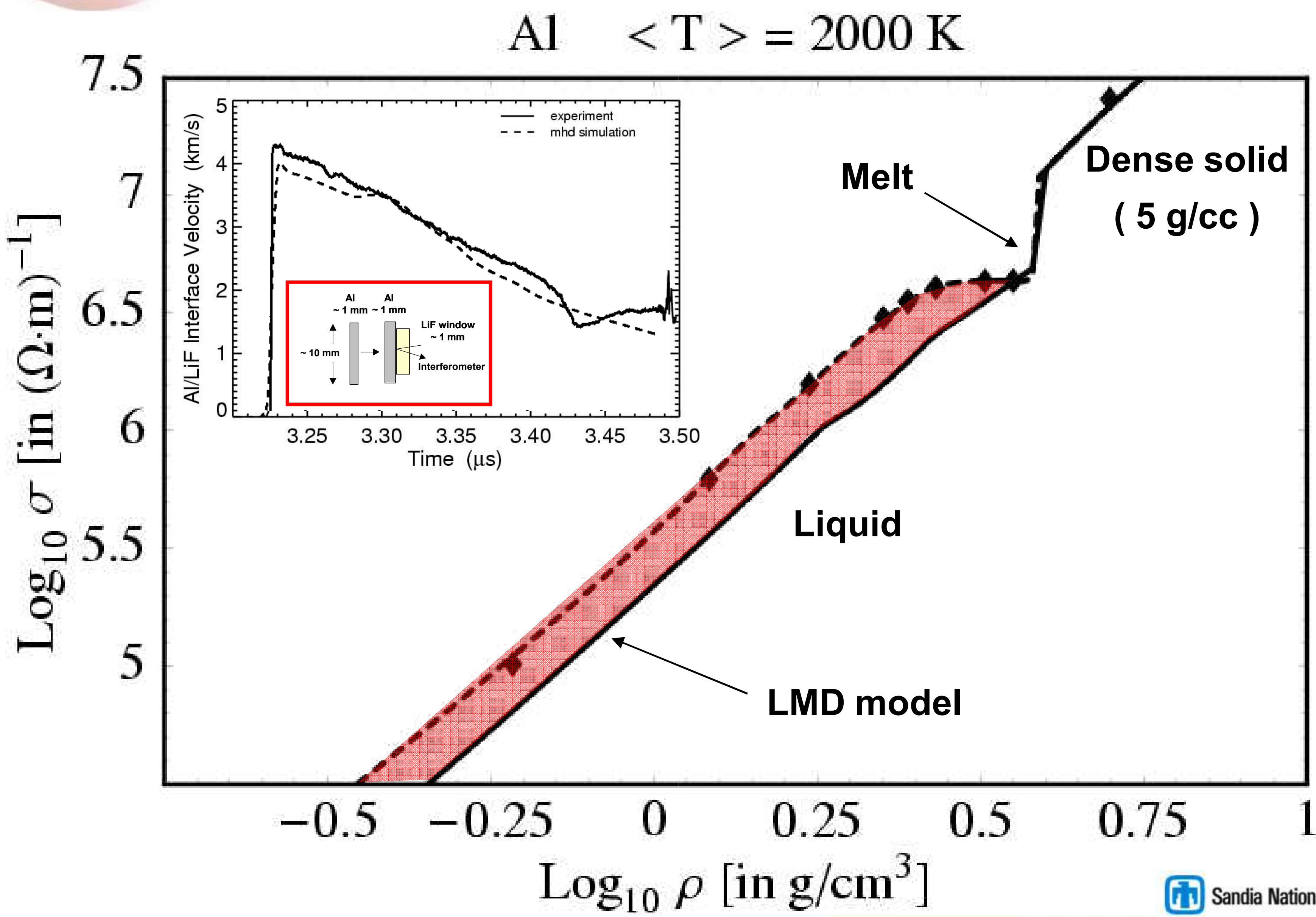
QMD conductivity model significantly improved agreement between experiment and simulation



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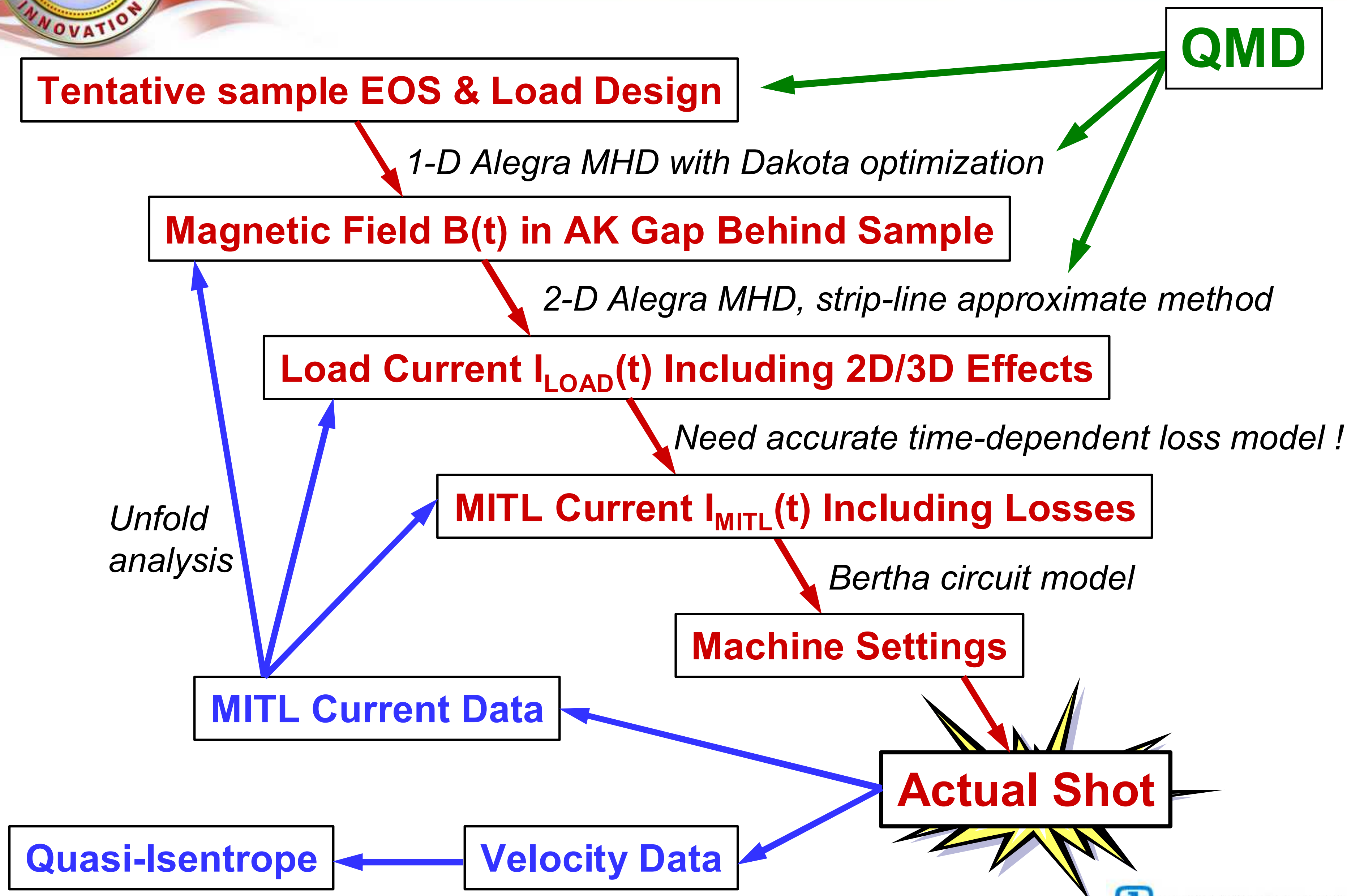
Outline

- **Overview of magnetic compression**
- **Experimental load designs**
  - **Co-axial**
  - **Stripline**
- **Magneto-hydrodynamic modeling and optimization**
- **Integrated experimental design**

We have developed a robust methodology for experimental design and data analysis



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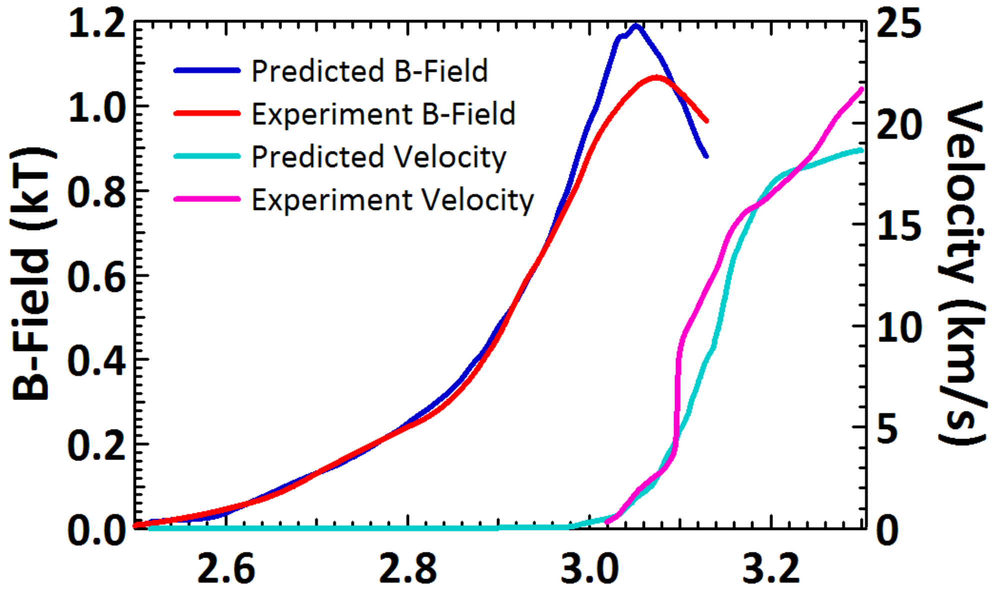
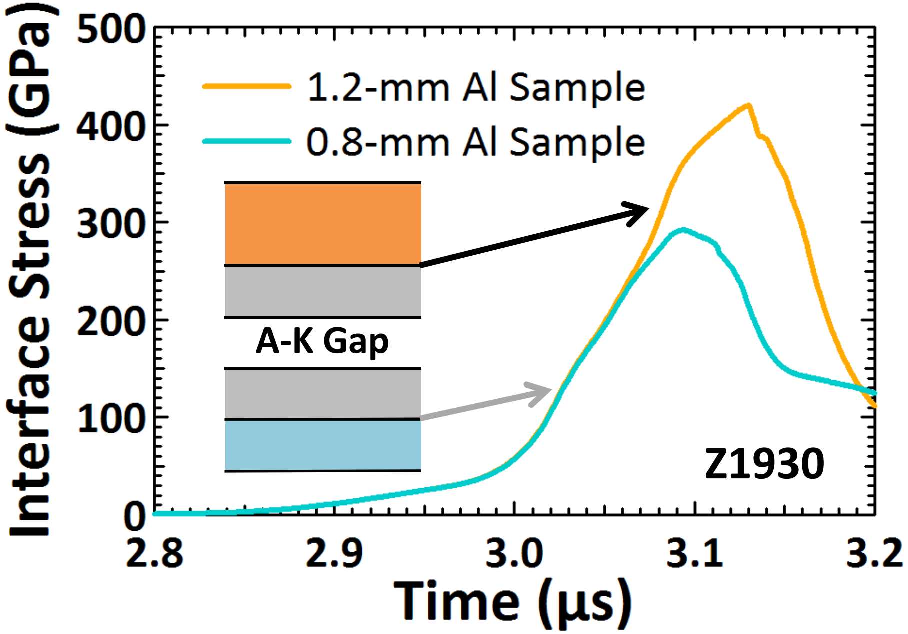
Experiment design typically is a balance between competing constraints





Shock formation results in a constraint on the maximum thickness of the samples in a ramp wave experiment

Wave reverberation results in a constraint on the minimum thickness of the samples in a ramp wave experiment

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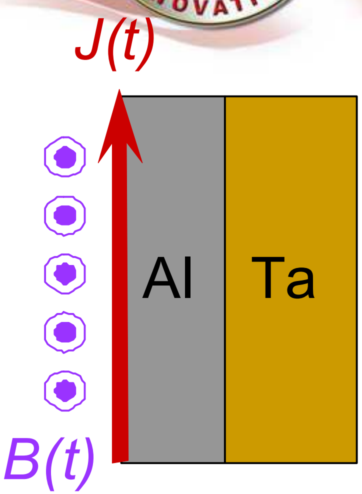
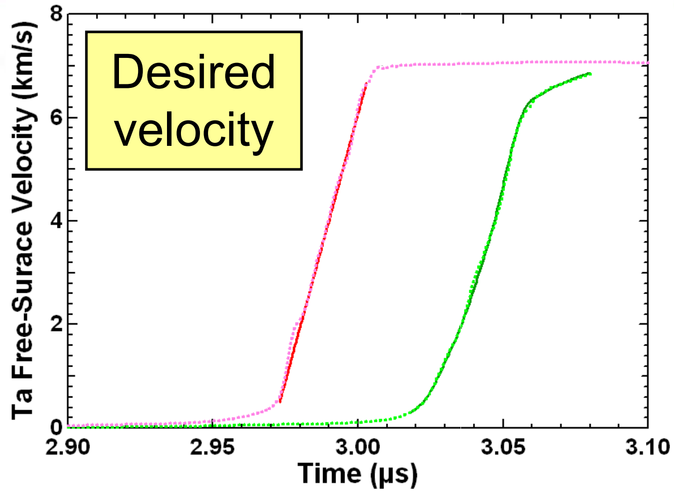
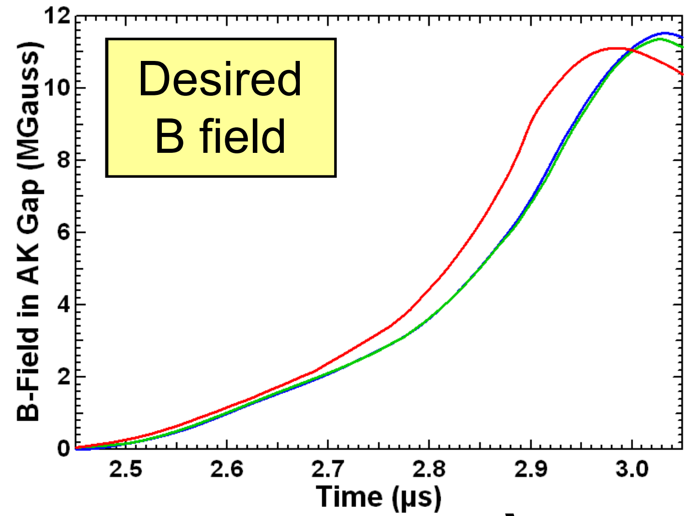
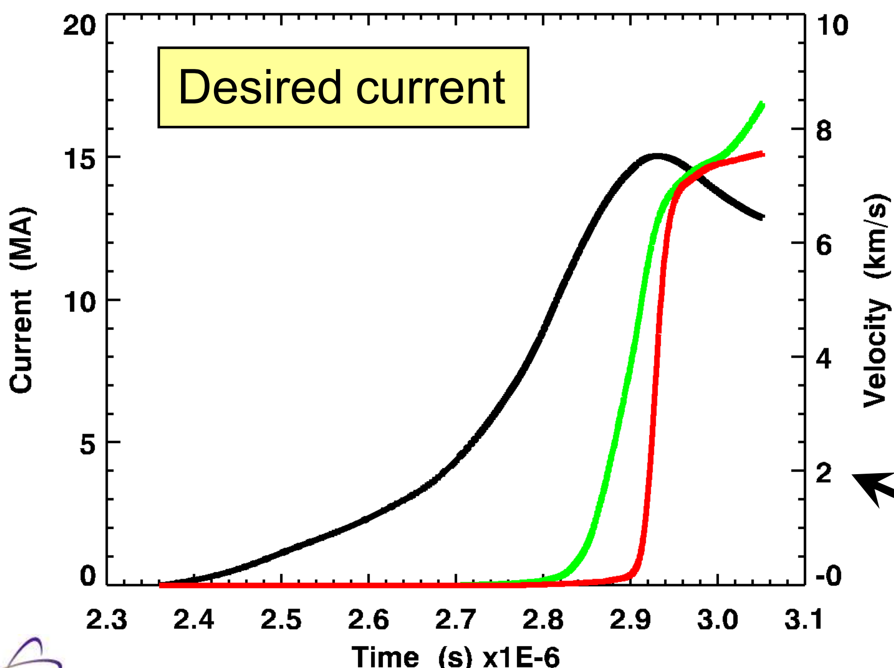
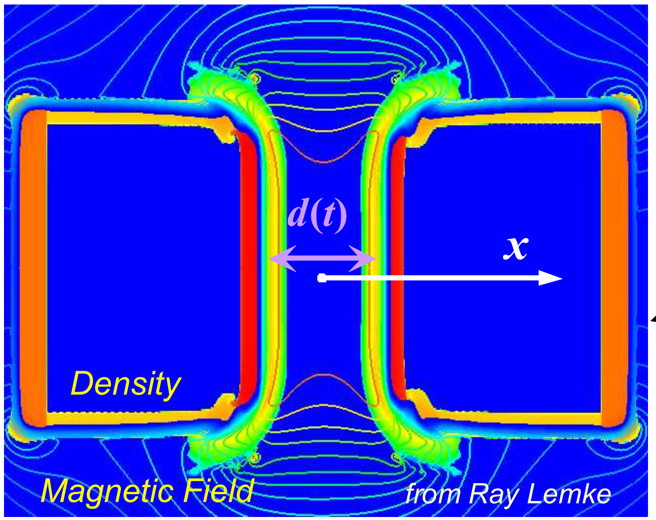
Desired current is determined through several iterative 1-D and 2-D MHD simulations



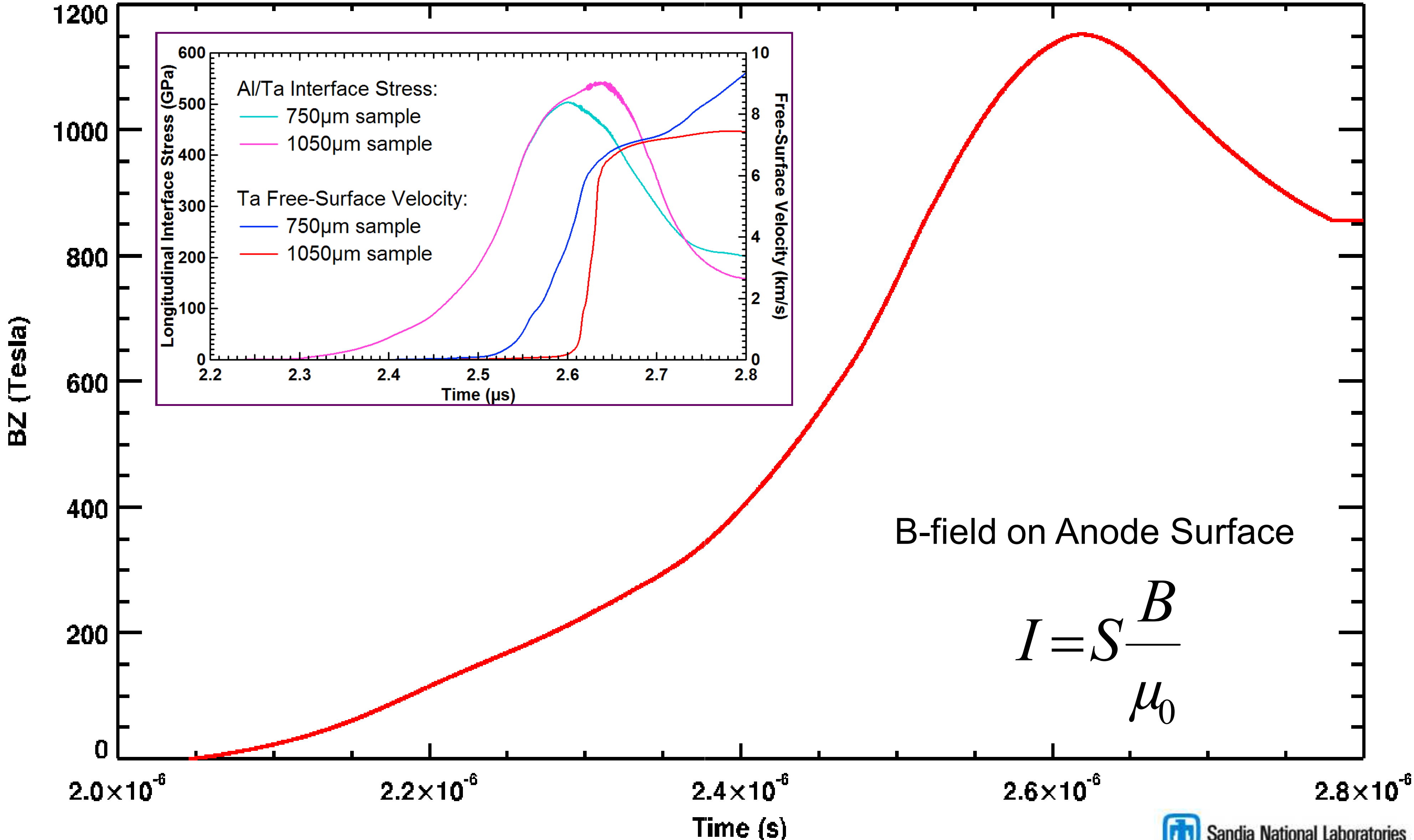








1D MHD provides B-field needed on the anode surface and evaluation of shock and reverberation



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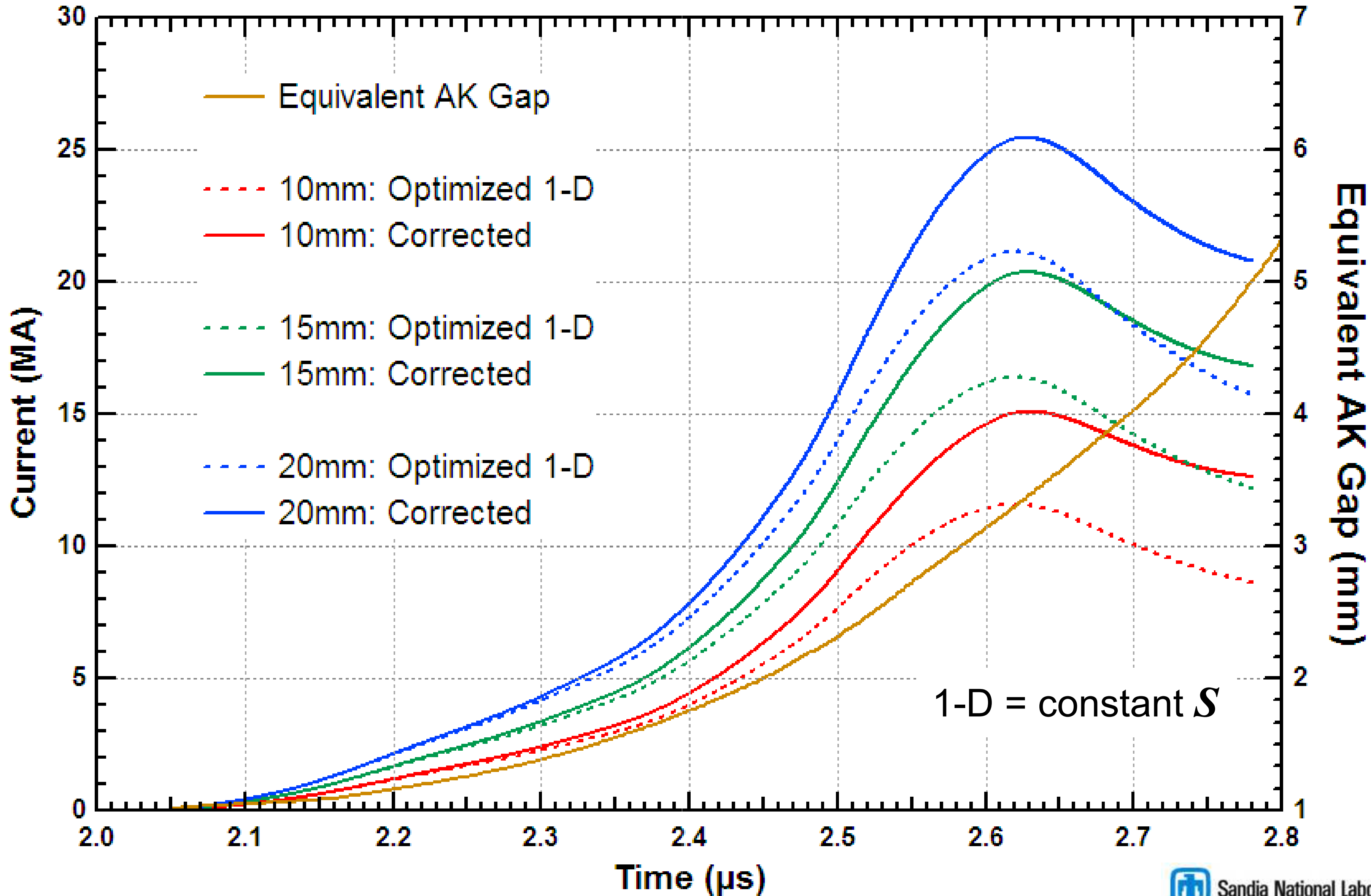
2D simulations and loss models provide the target current needed to drive the experimental load



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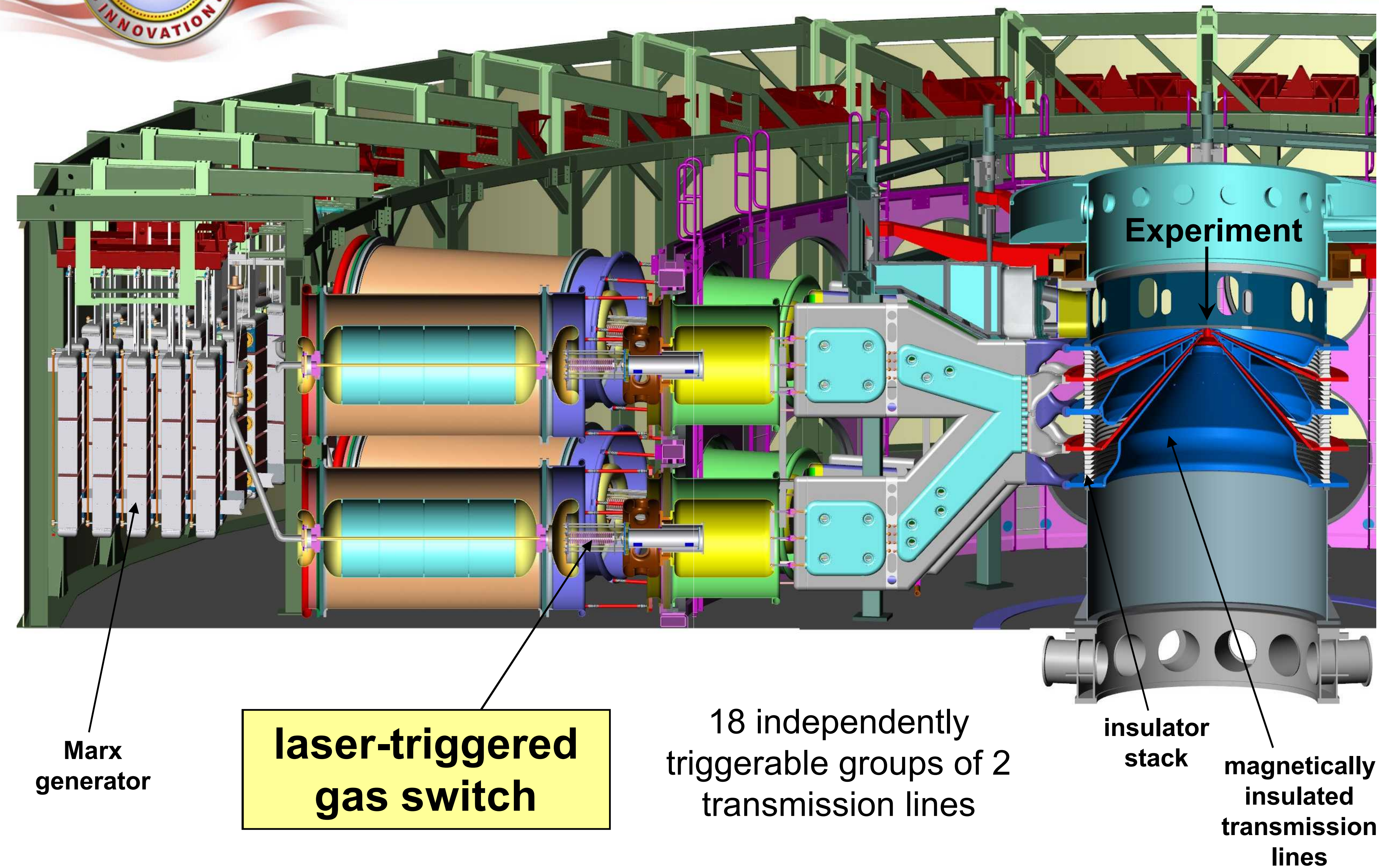
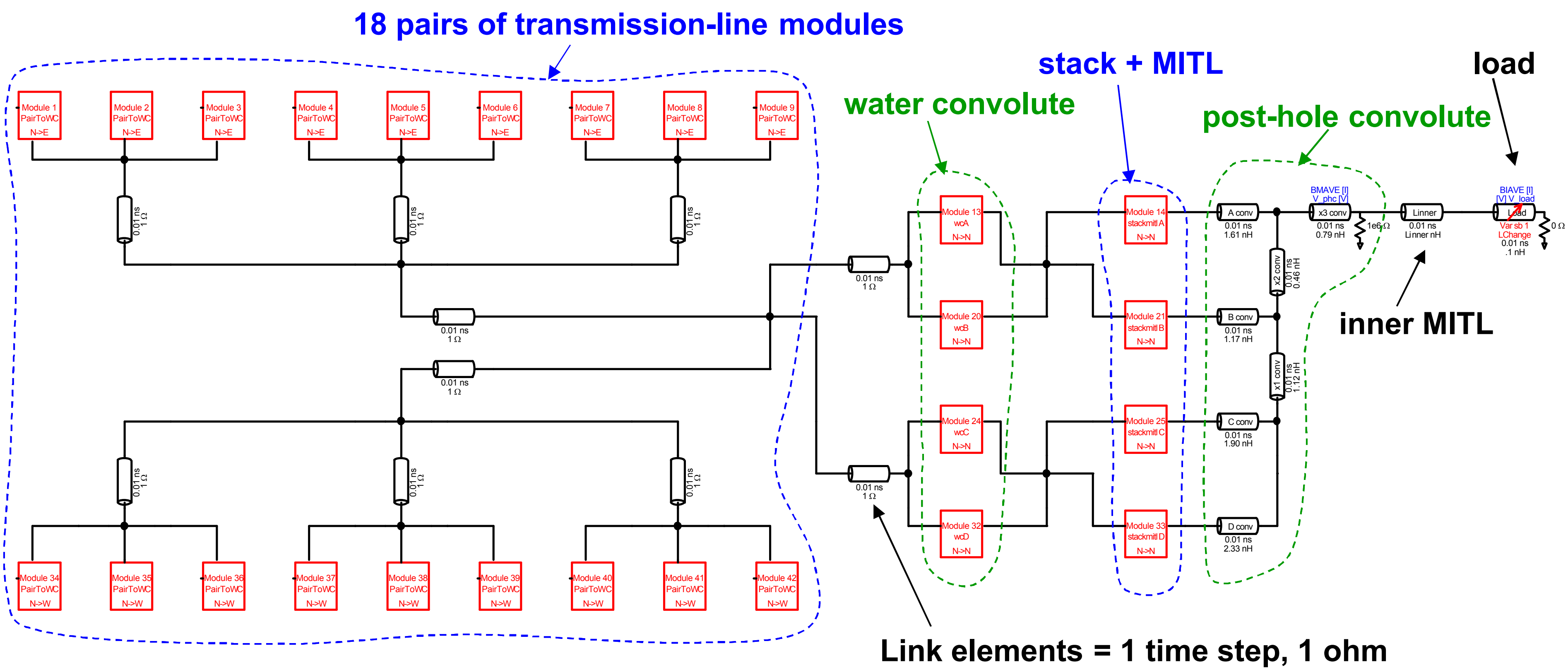
Independently triggerable gas switches provide the variability necessary for pulse shaping



Switch times are determined using a 1-D transmission-line circuit model for Z

Machine settings are currently determined through a manual process – this will eventually be coupled to a genetic algorithm for optimization



Bertha model written and maintained by Dave Hinshelwood at NRL

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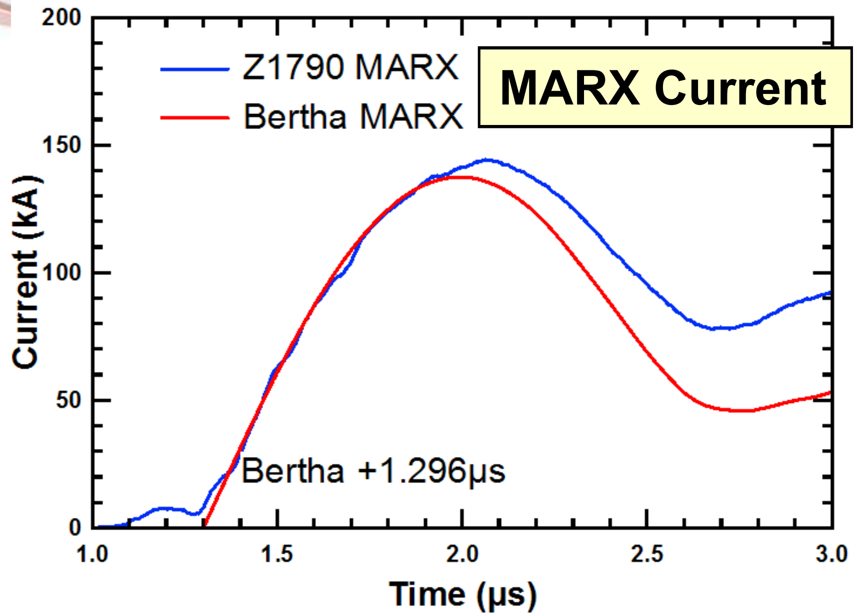
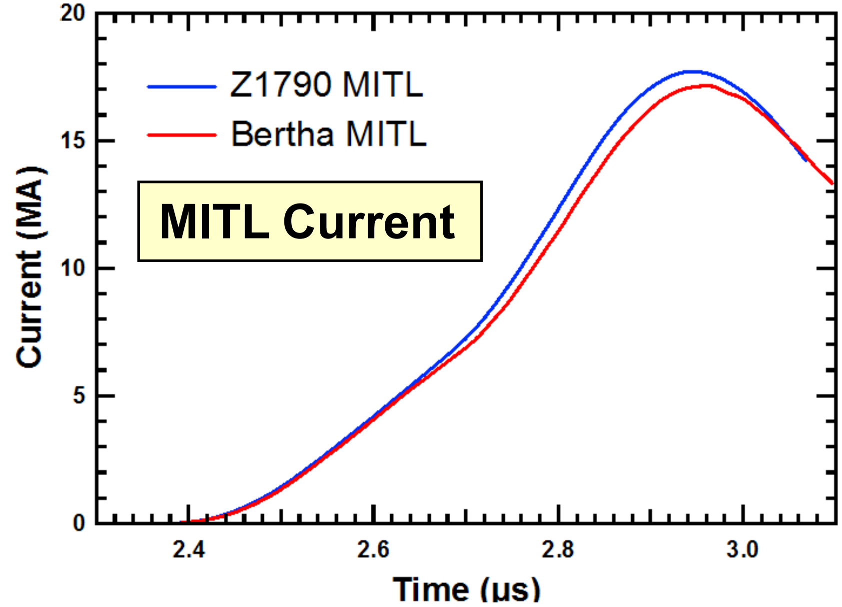
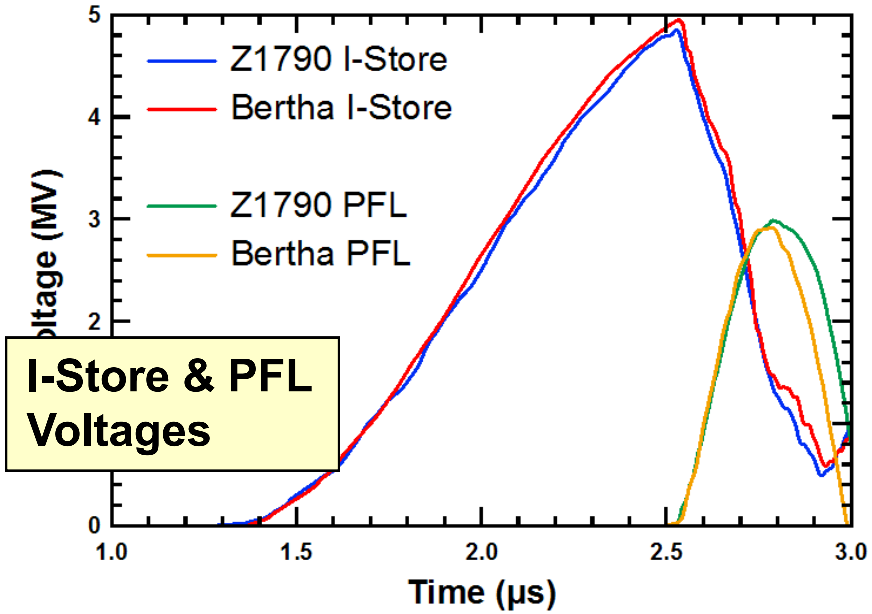
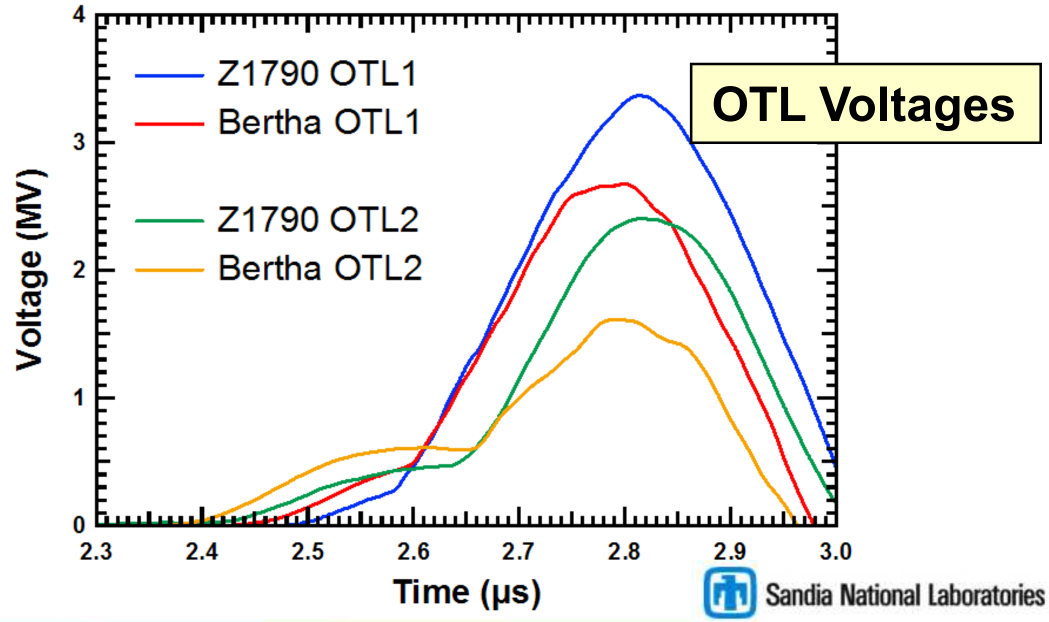
The present 1-D Bertha model matches machine diagnostics reasonably well in long-pulse mode









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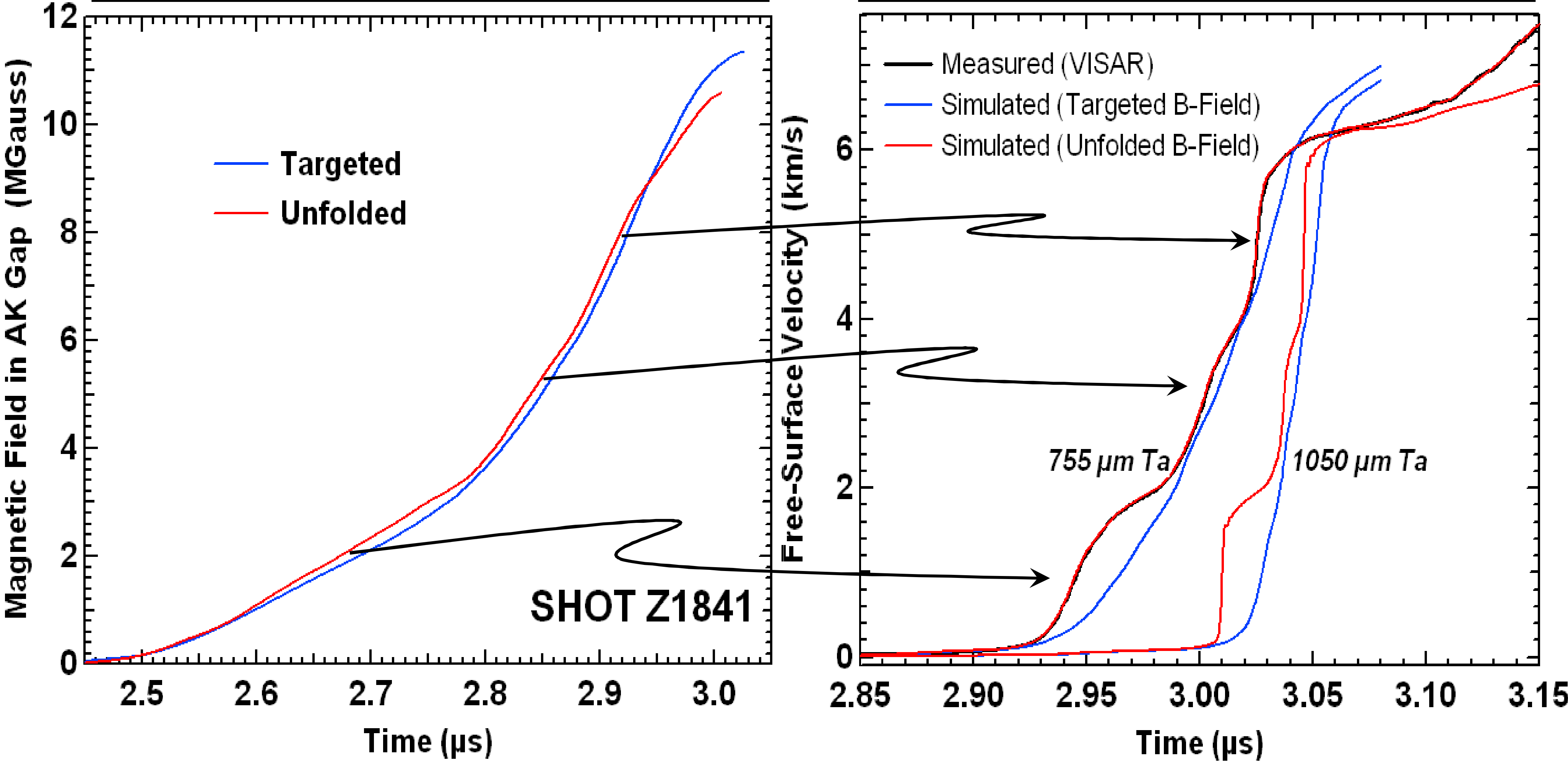
The Bertha circuit model enables fairly accurate prediction of machine performance

Current comparison

Wave profile comparison



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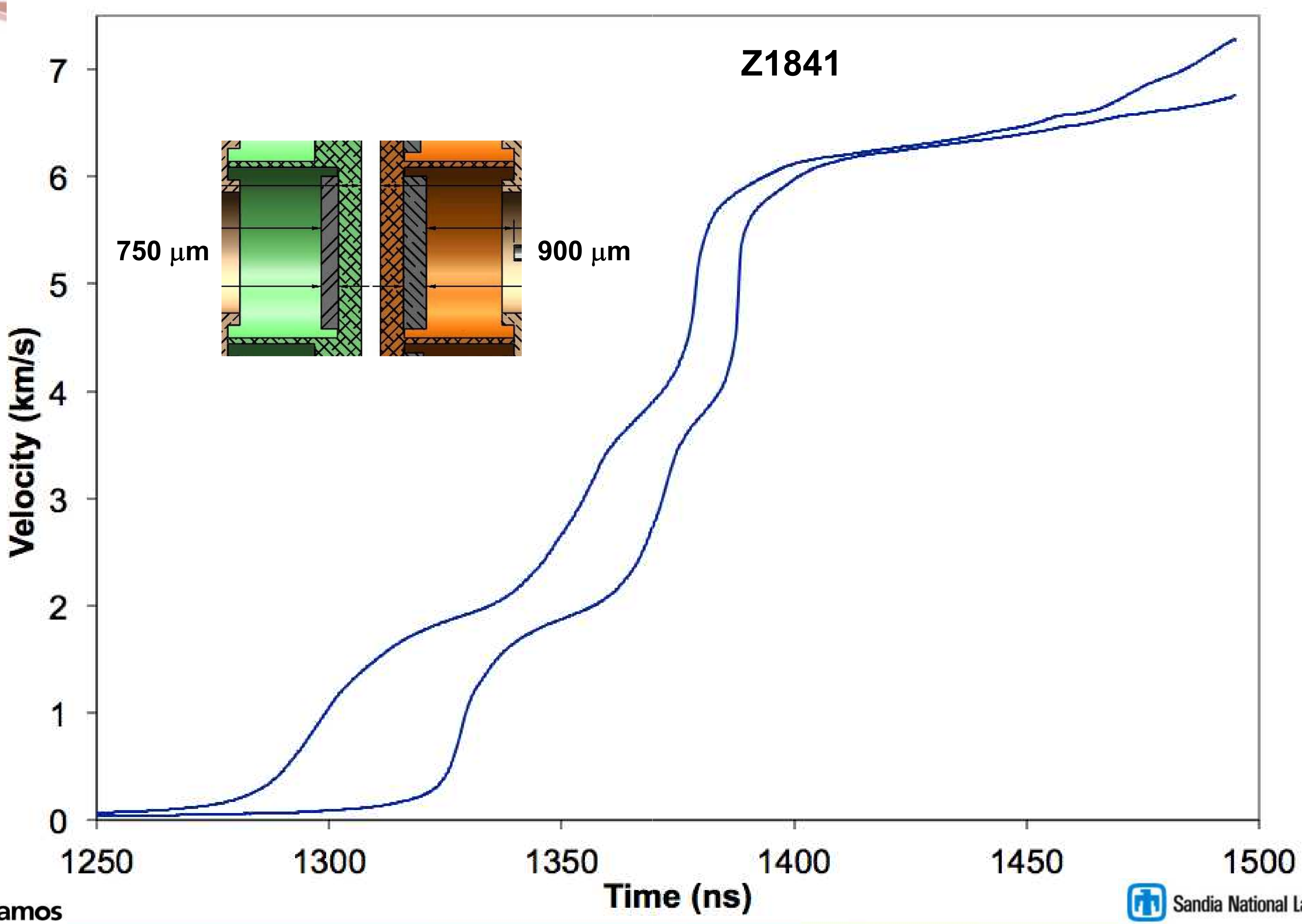
Recent ramp compression data have enable extraction of the Ta isentrope to over 400 GPa



Los Alamos

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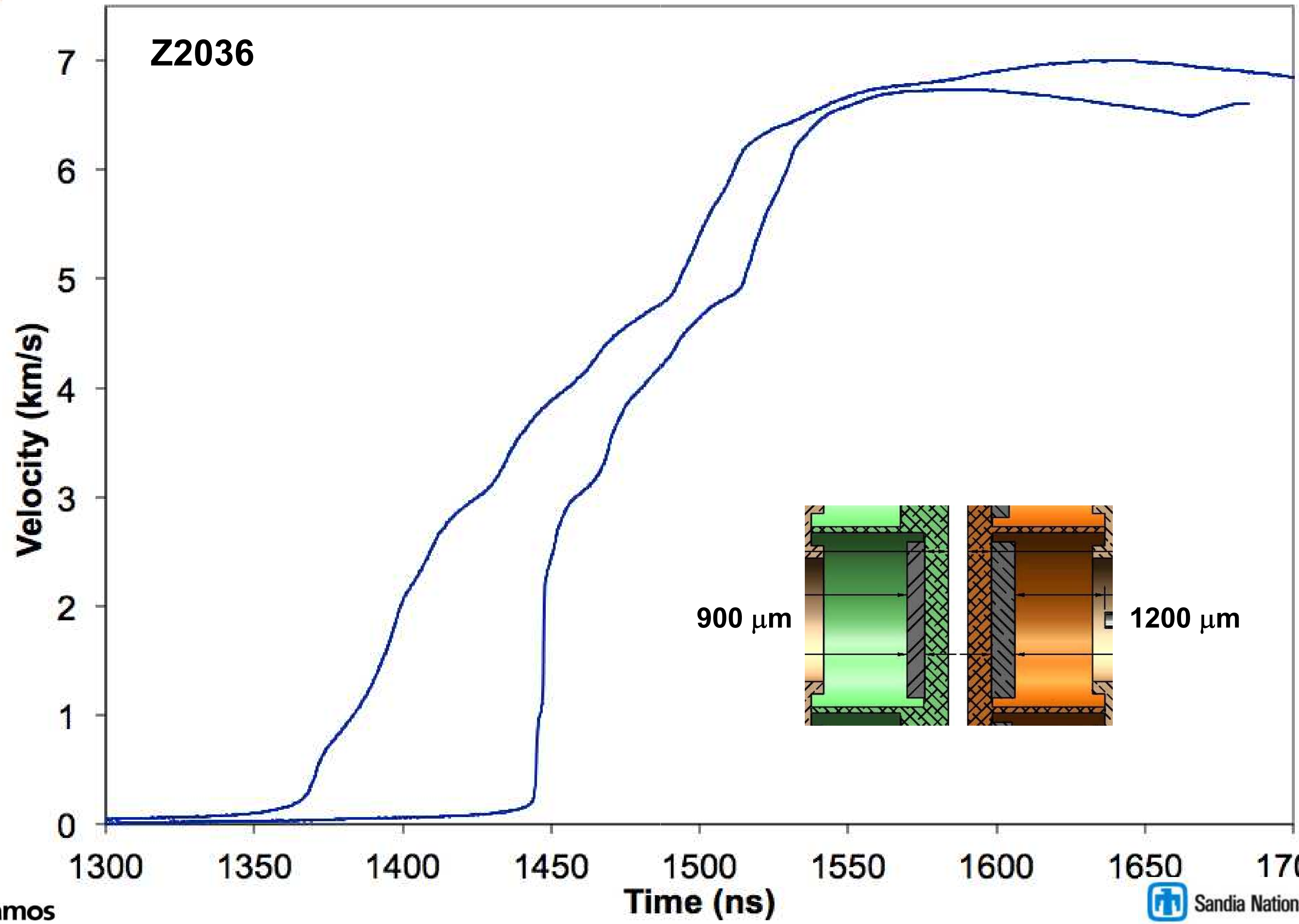

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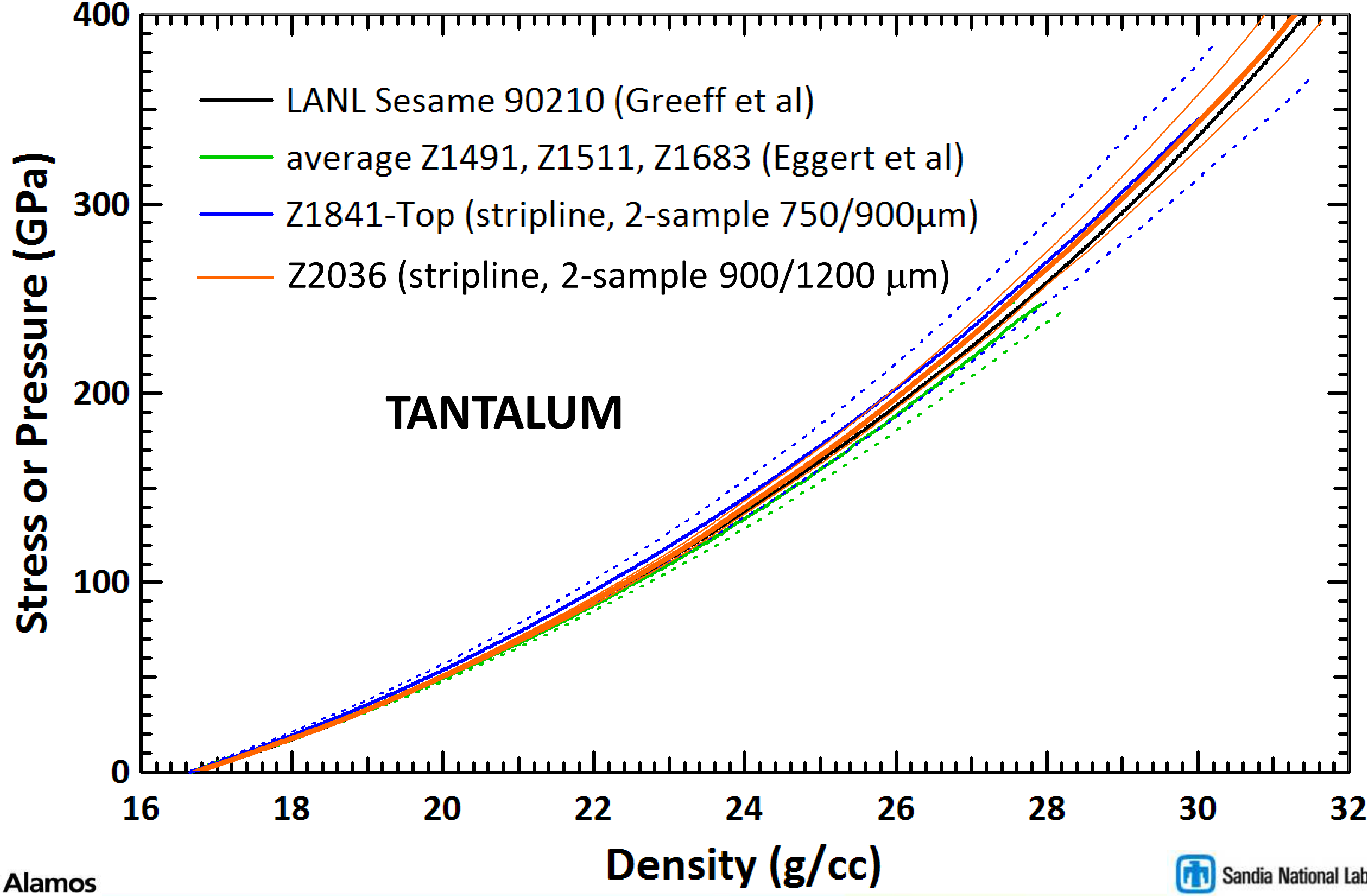

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