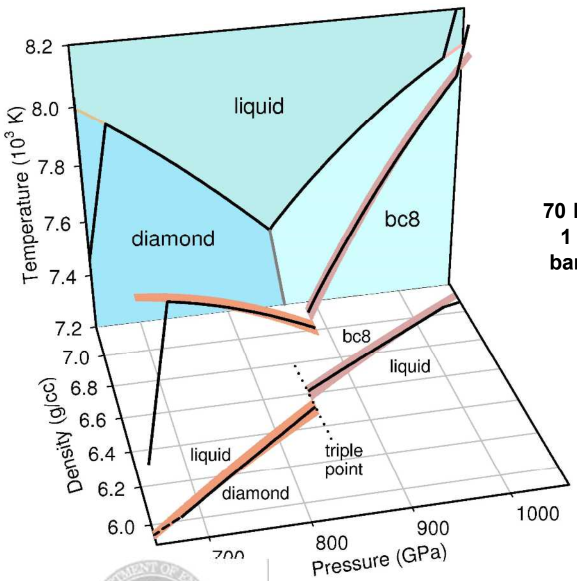
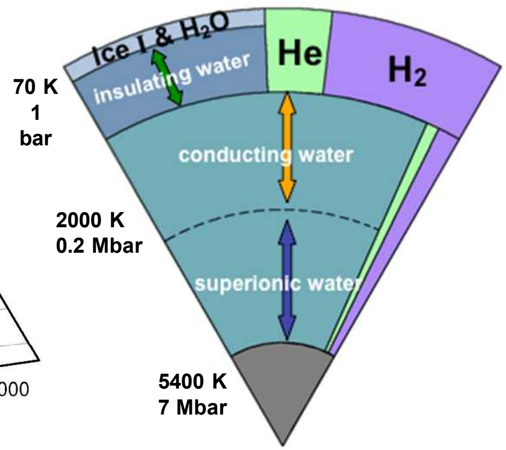
SAND2014-17924PE

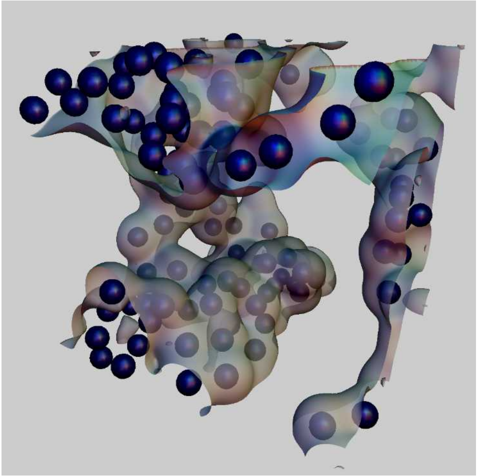
Megaamps, Megagauss and Megabars:
Using the Sandia Z Machine to Perform Extreme Material Dynamics Experiments

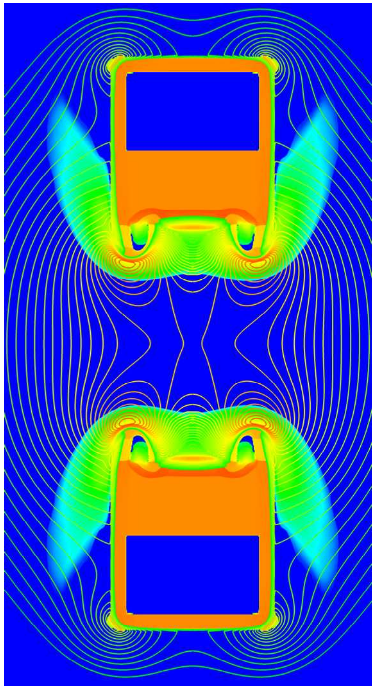
Marcus D. Knudson

Sandia National Laboratories, Albuquerque, NM









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  - Bertha model, pulse shaping
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  - Experiment support
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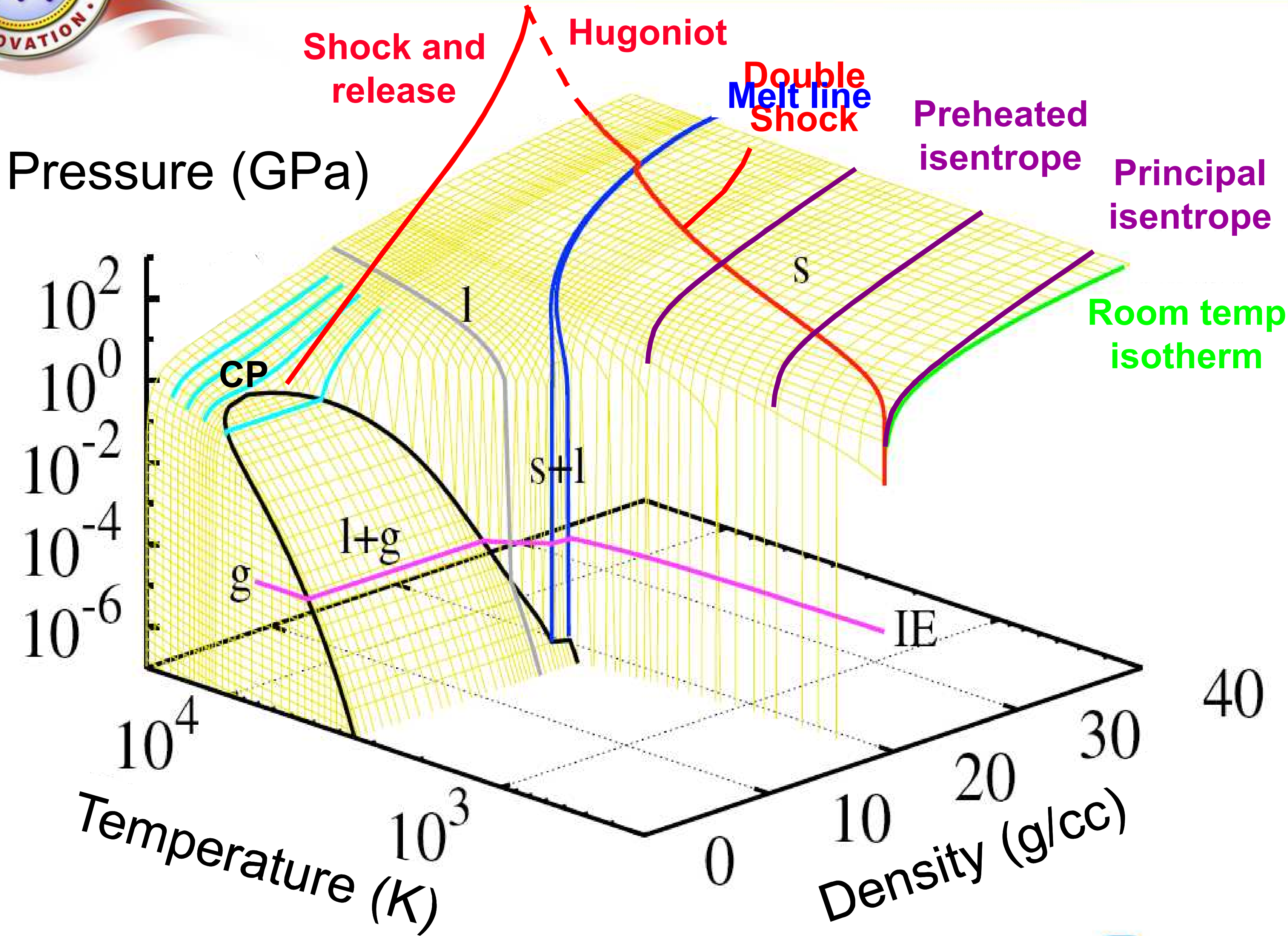
  - Ta samples and equation of state

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



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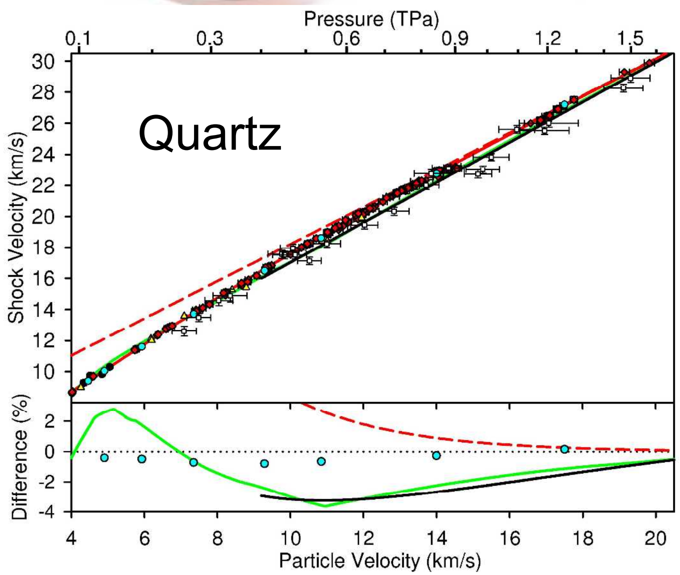
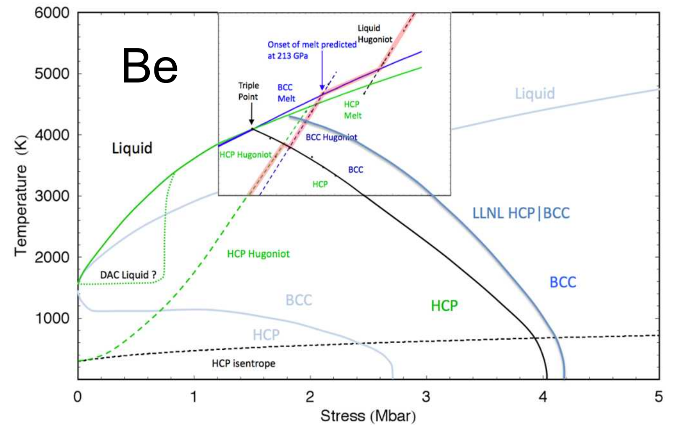
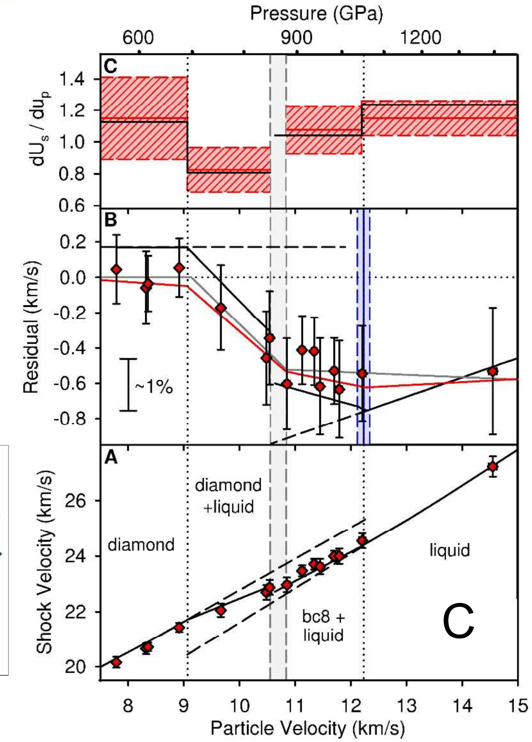
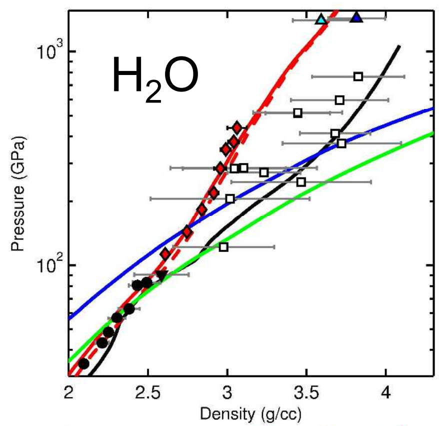
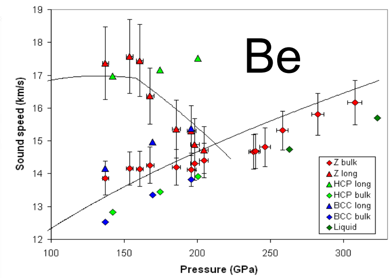
Z has been used to address several interesting problems in the multi-Mbar regime

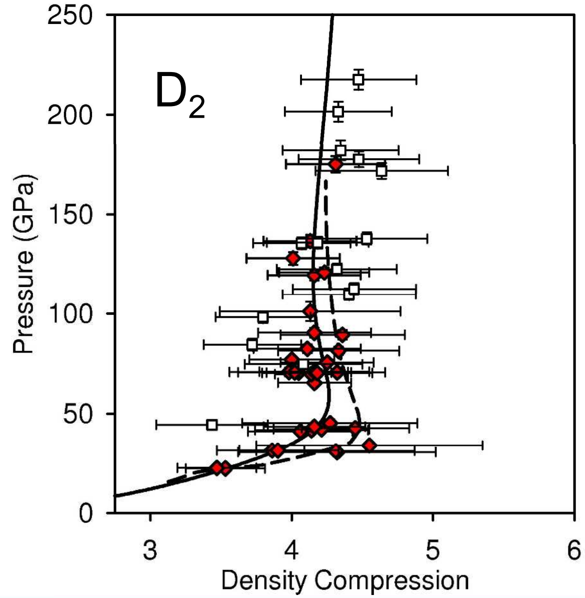


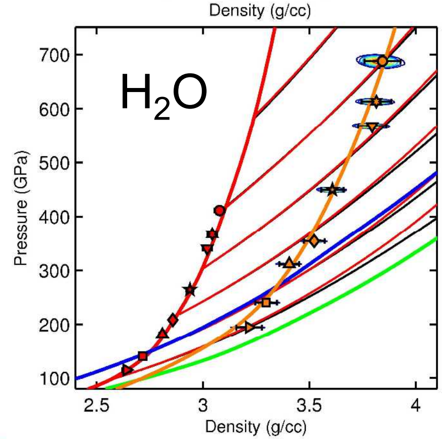


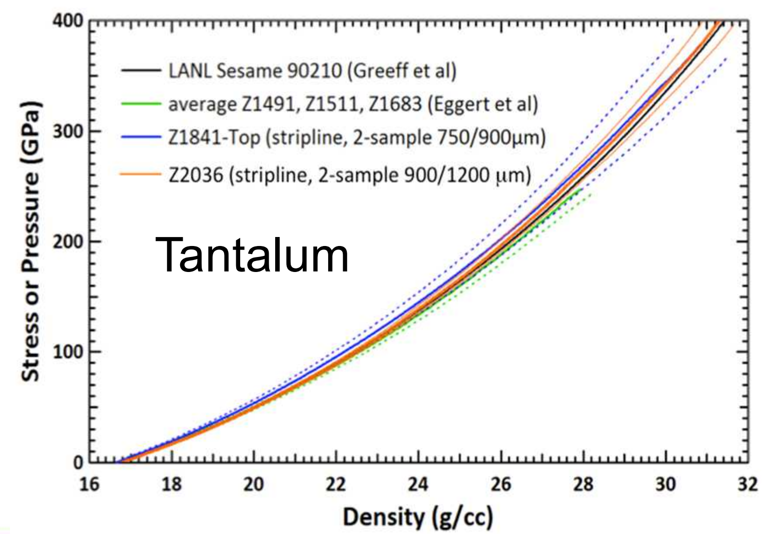




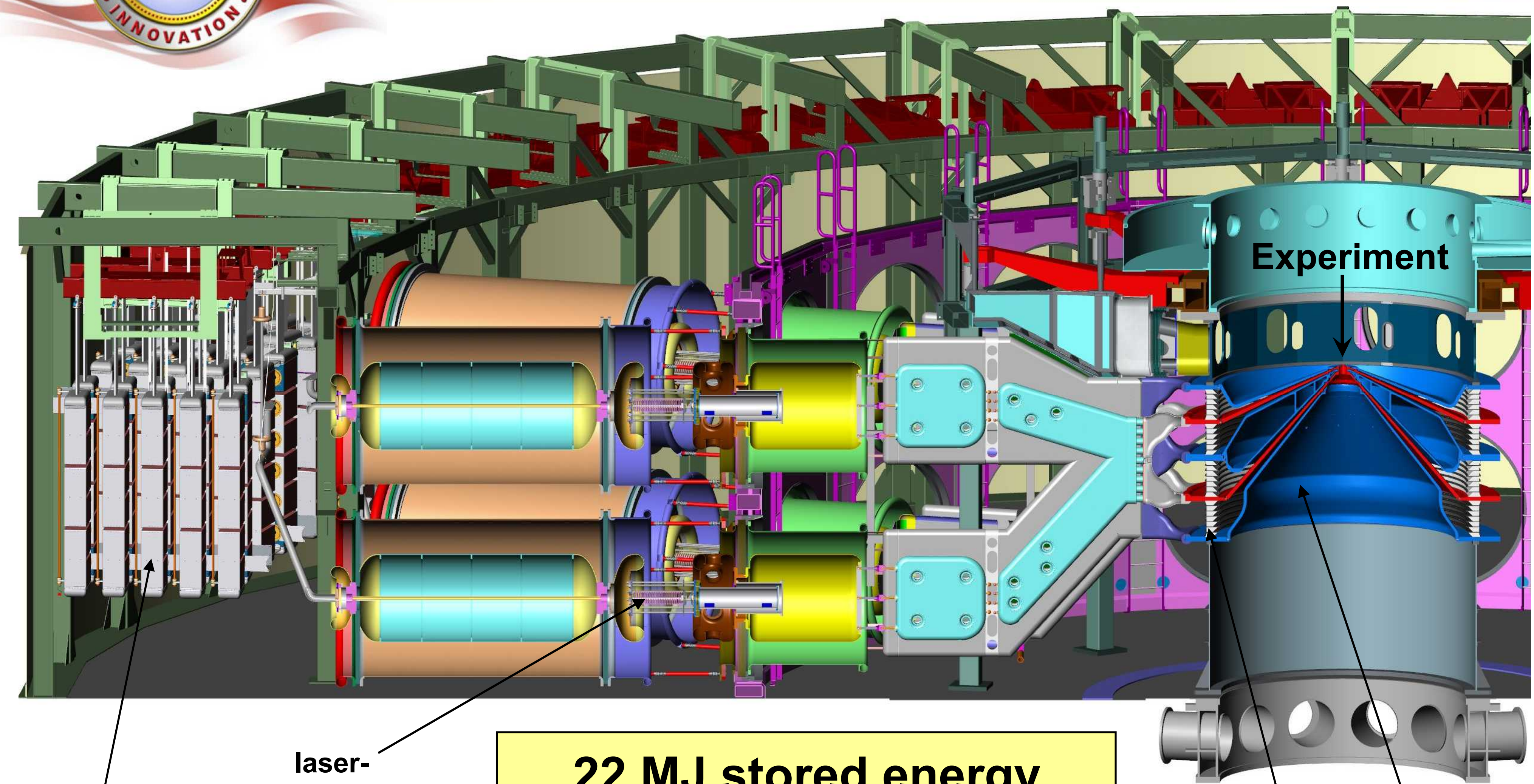






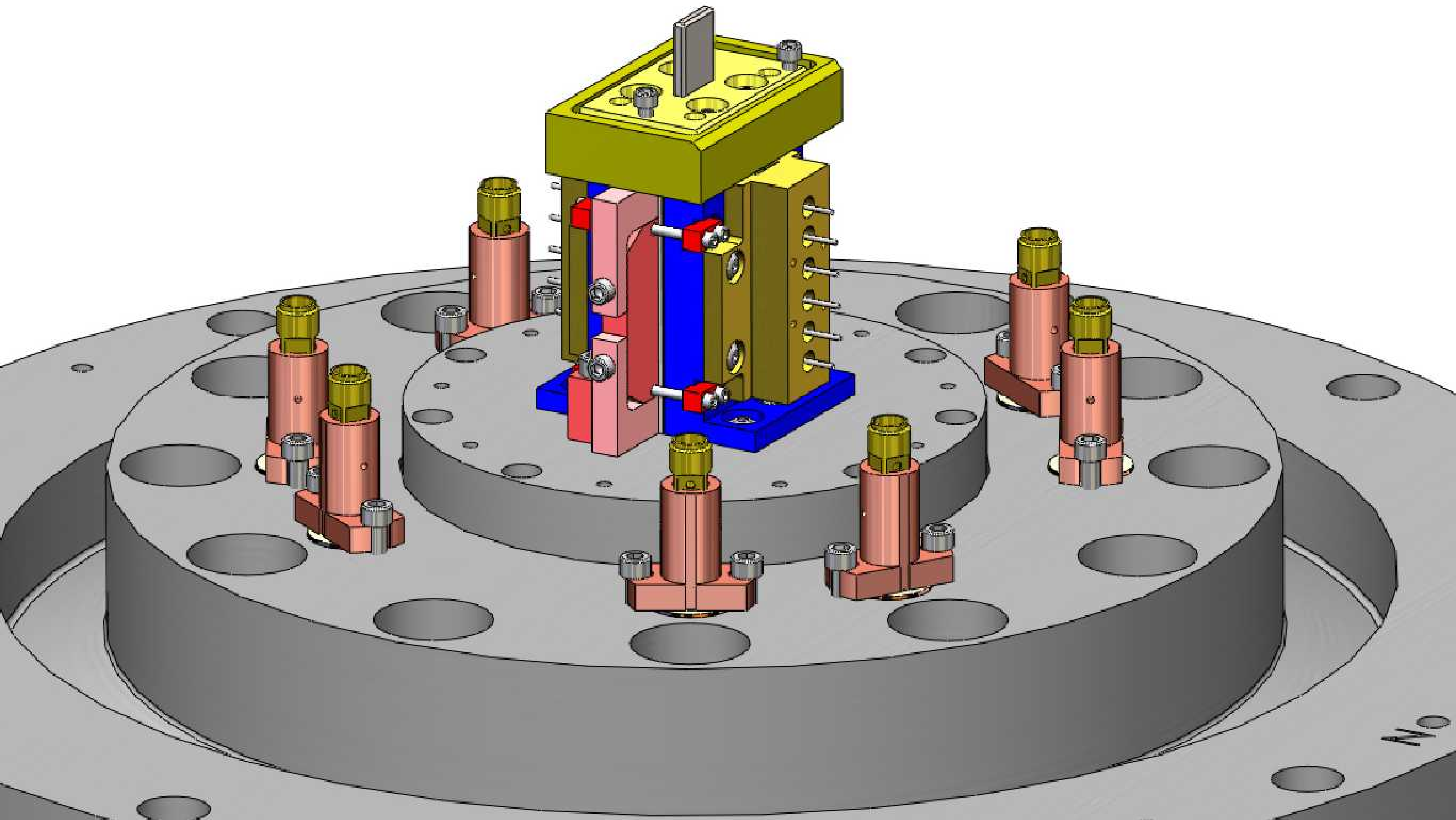


The Sandia Z Machine

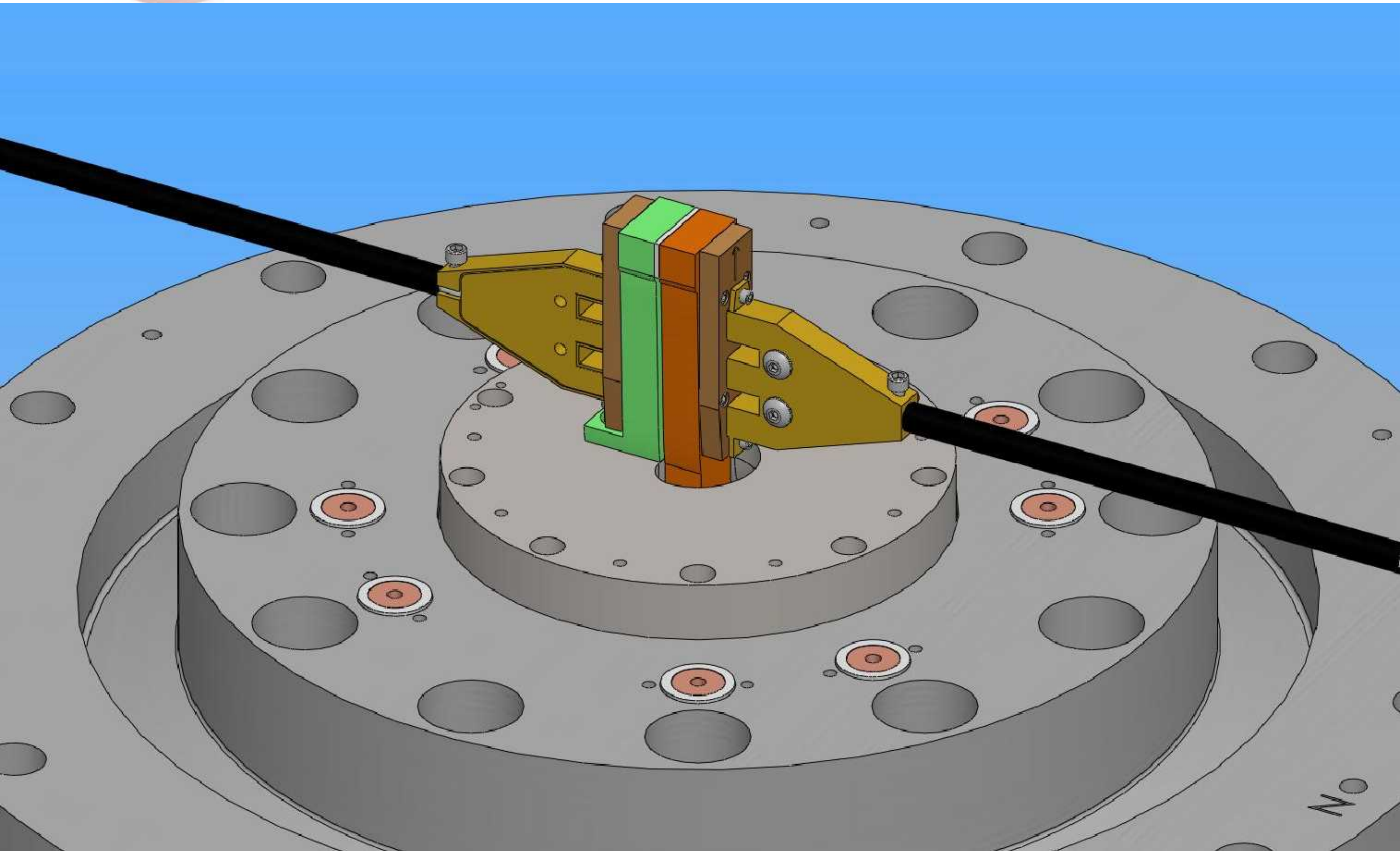


22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

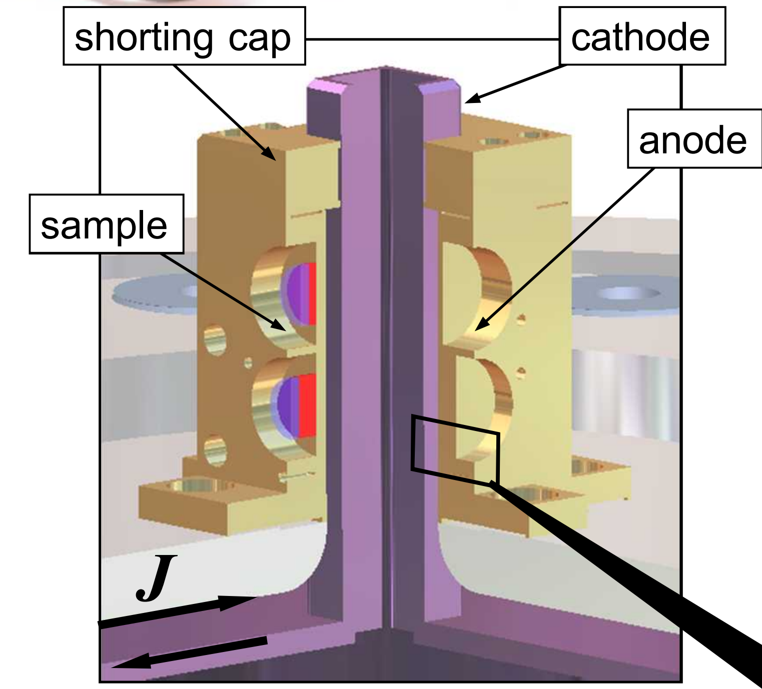
Typical coaxial load for multi-Mbar shock compression experiments on Z



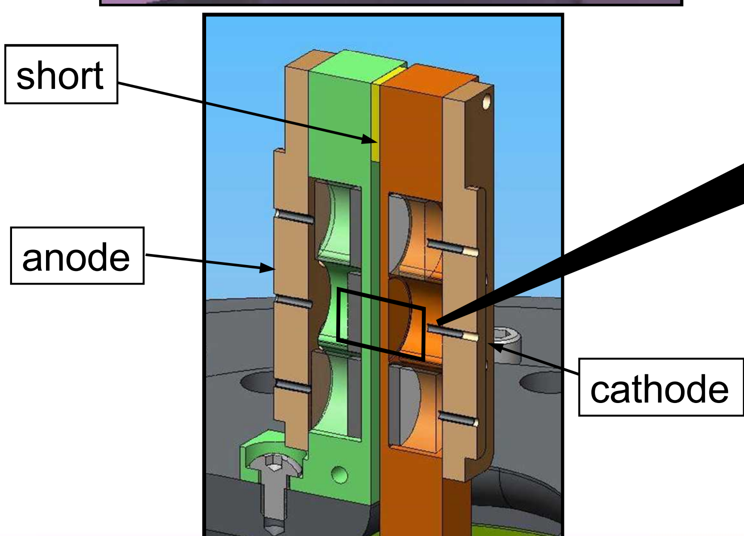
Typical stripline load for multi-Mbar ramp compression experiments on Z

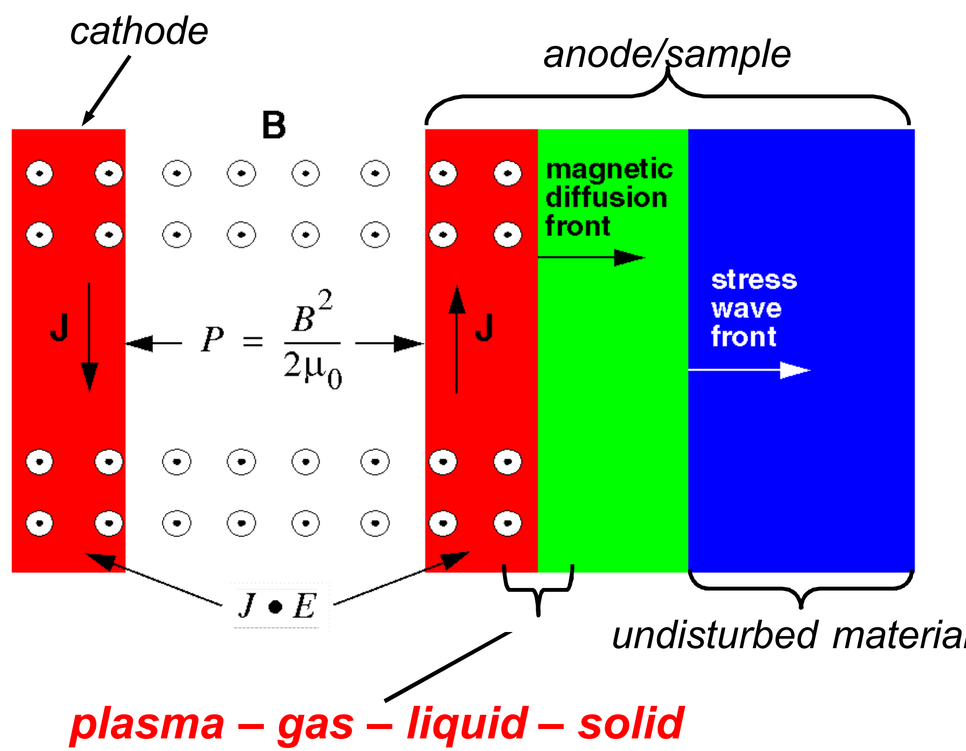


Magnetic compression on Z produces smooth ramp loading to ultra-high pressures



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

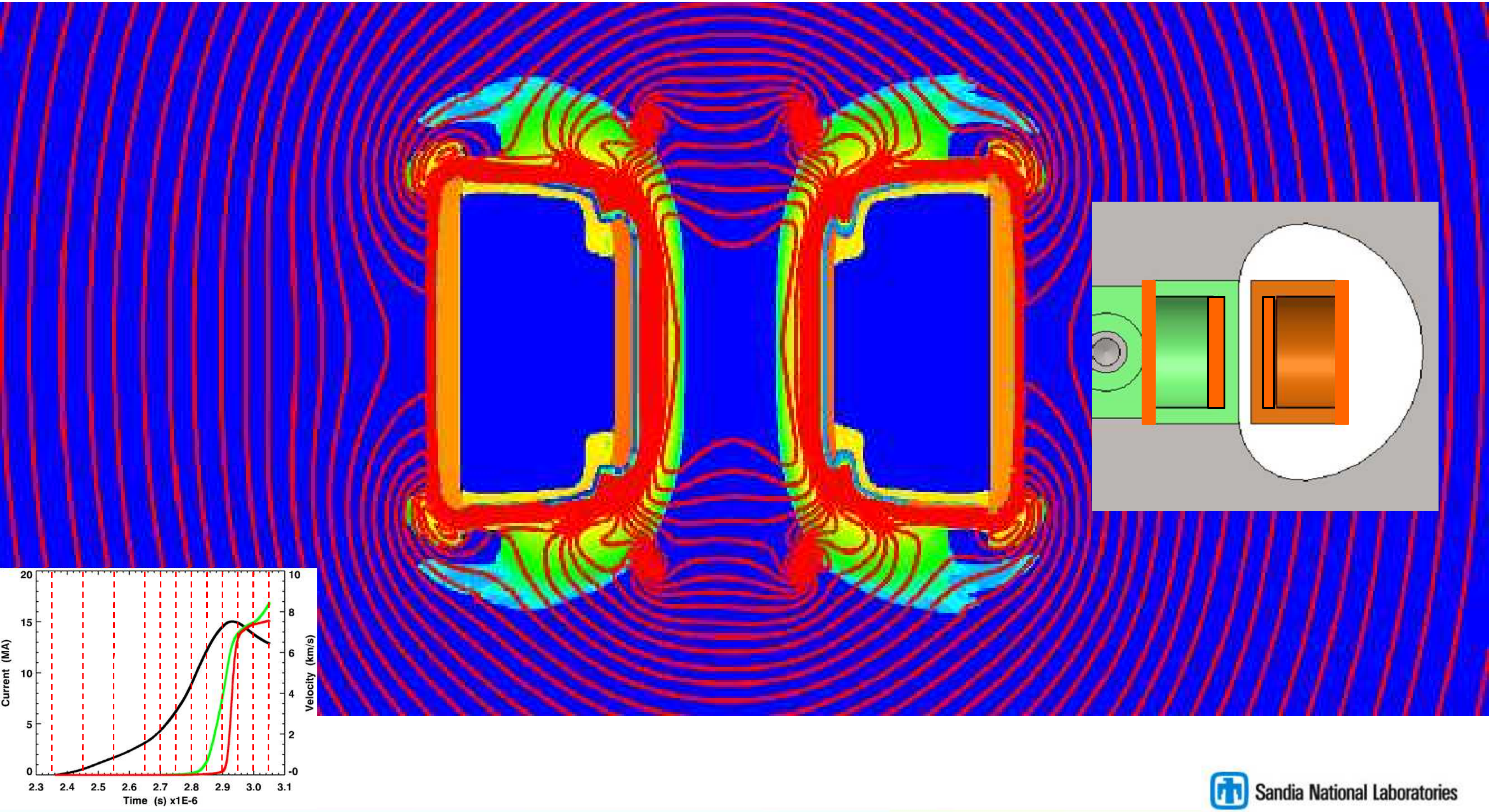




Fully self-consistent, 2-D MHD simulations required to accurately predict experimental load performance

10 mm wide stripline

t = 690 ns



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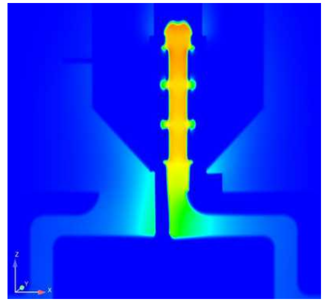
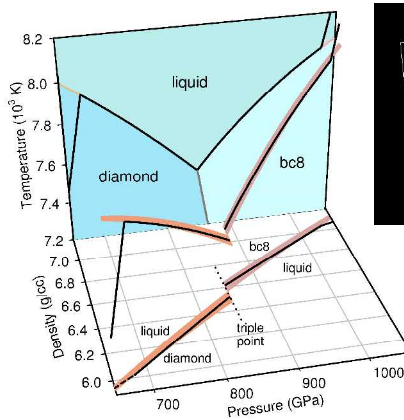
Success requires integration of theoretical, computational, and experimental capabilities

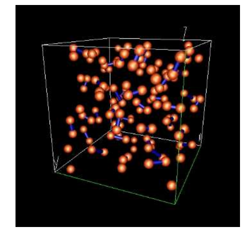
ALEGRA ...
The Shock and Multiphysics Family of Codes

DAKOTA

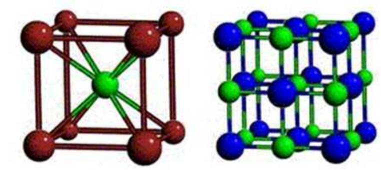


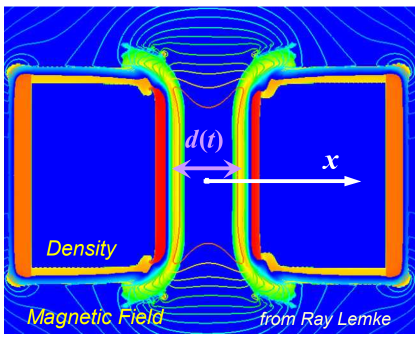
$$\sigma_{\mathbf{k}}(\omega)=\frac{2\pi e^2\hbar^2}{3m^2\omega\Omega}\sum_{\alpha=1}^{3}\sum_{j=1}^{N}\sum_{i=1}^{N}\left(F(\varepsilon_{i,\mathbf{k}})-F(\varepsilon_{j,\mathbf{k}})\right)\left|\left\langle\Psi_{j,\mathbf{k}}\left|\nabla_\alpha\right|\Psi_{i,\mathbf{k}}\right\rangle\right|^2\delta(\varepsilon_{j,\mathbf{k}}-\varepsilon_{i,\mathbf{k}}-\hbar\omeg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

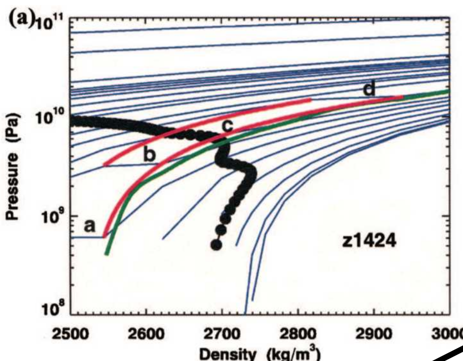


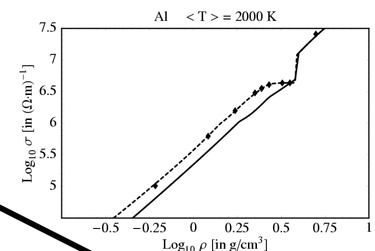


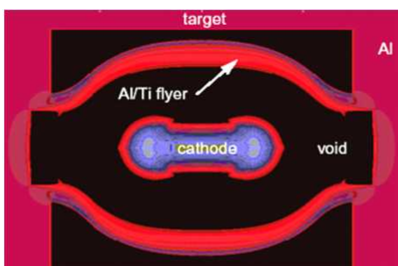
Vienna Ab-initio Simulation Package

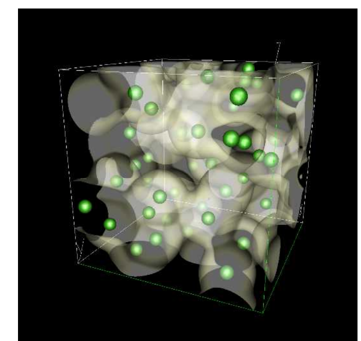


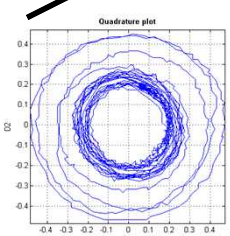


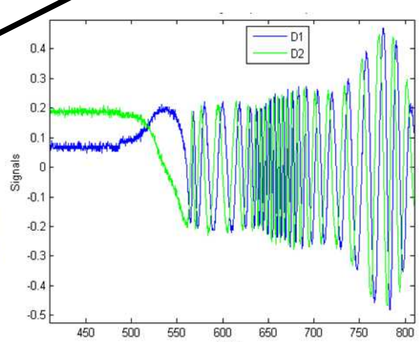


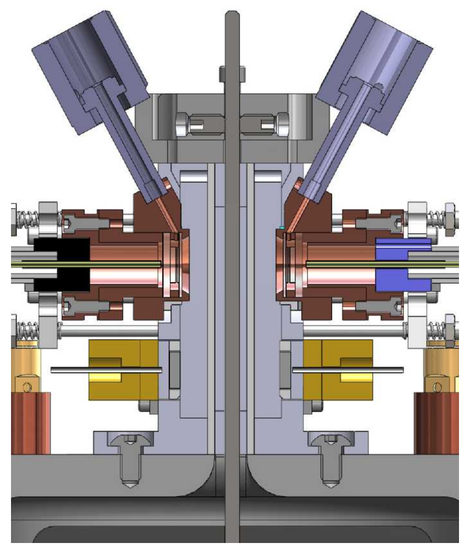


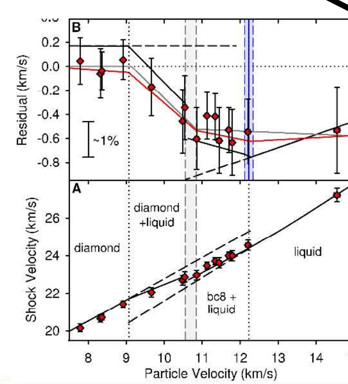


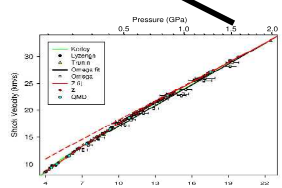












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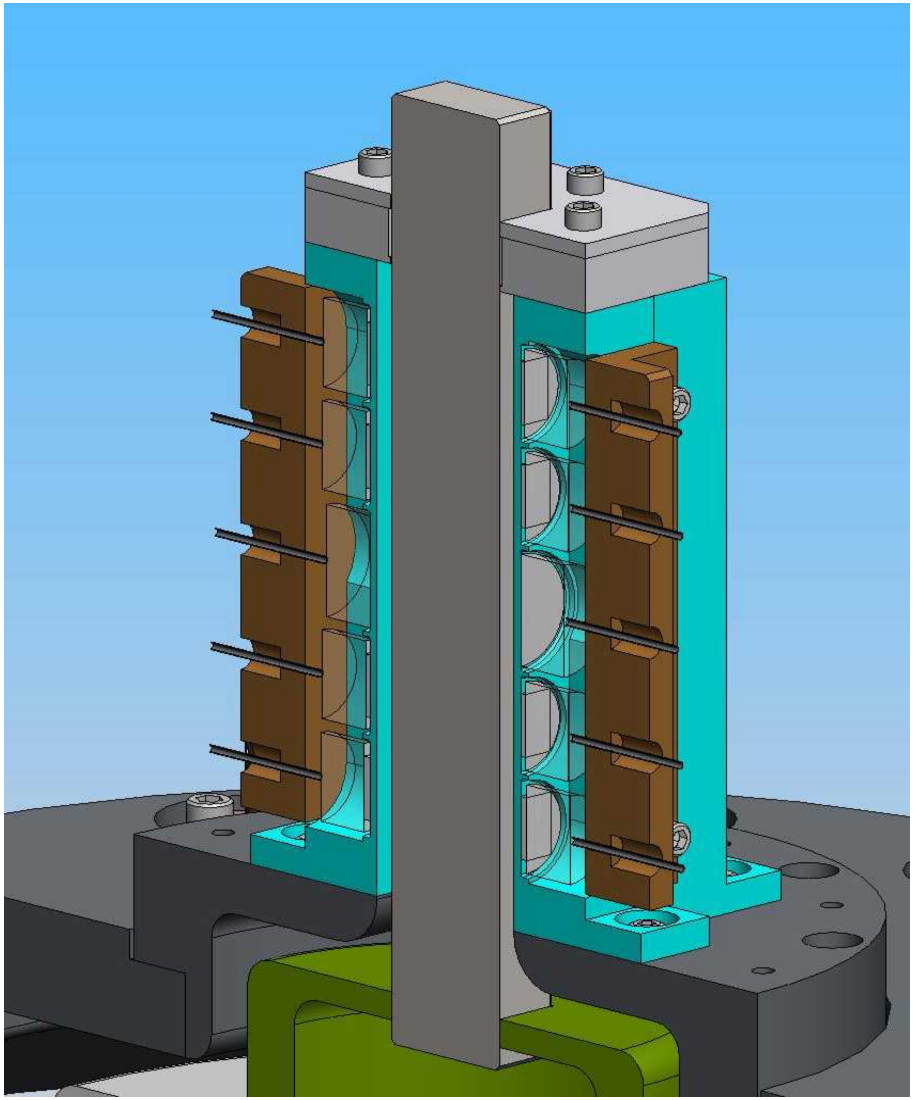
Outline

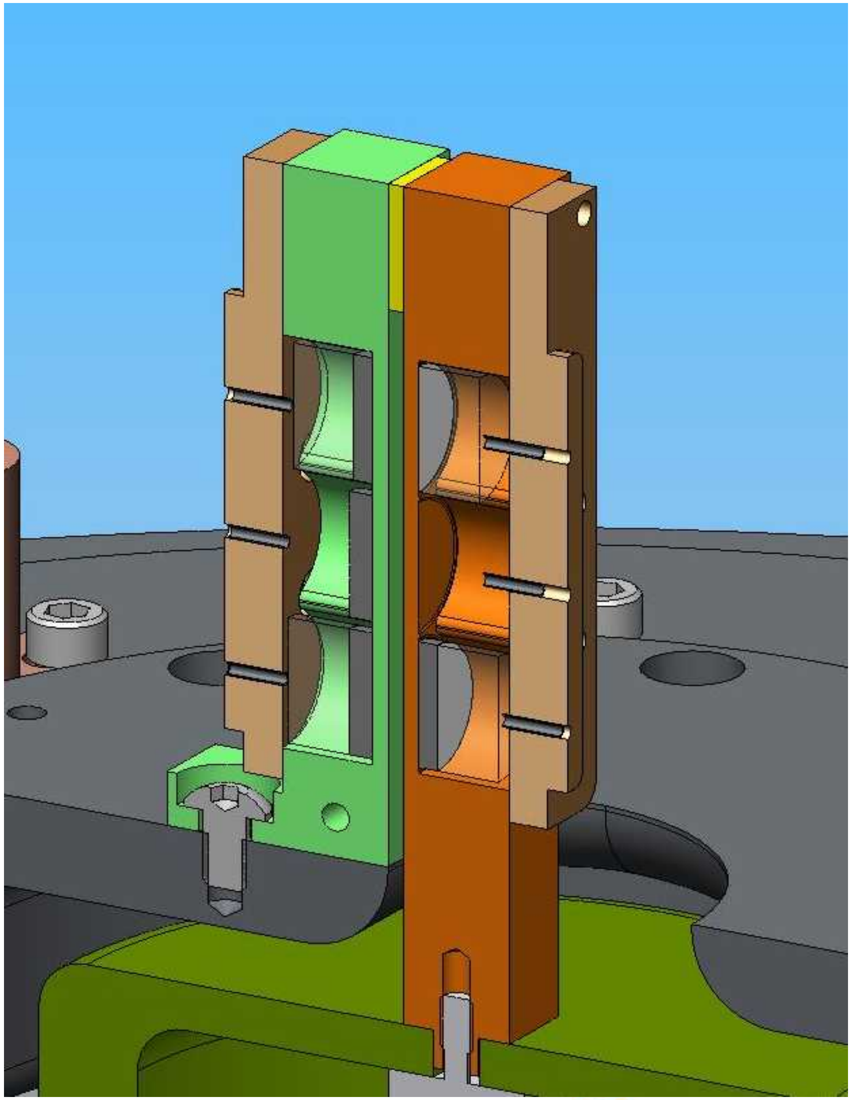
- High-Stress Isentropic compression platform
  - Tantalum: solid squeezed to two-fold compression
- High-Velocity plate-impact platform
  - Quartz: redefinition of a high pressure standard
- Examples of interplay between experiment and theory
  - Beryllium: evolution of the phase diagram
  - Melting of diamond: existence of a triple point along the Hugoniot
  - Water: support for a cooler Neptune core
- Future directions
  - Development of a double shock plate-impact platform
  - Cylindrical implosion technique for ramp compression

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

Co-axial



Stripline



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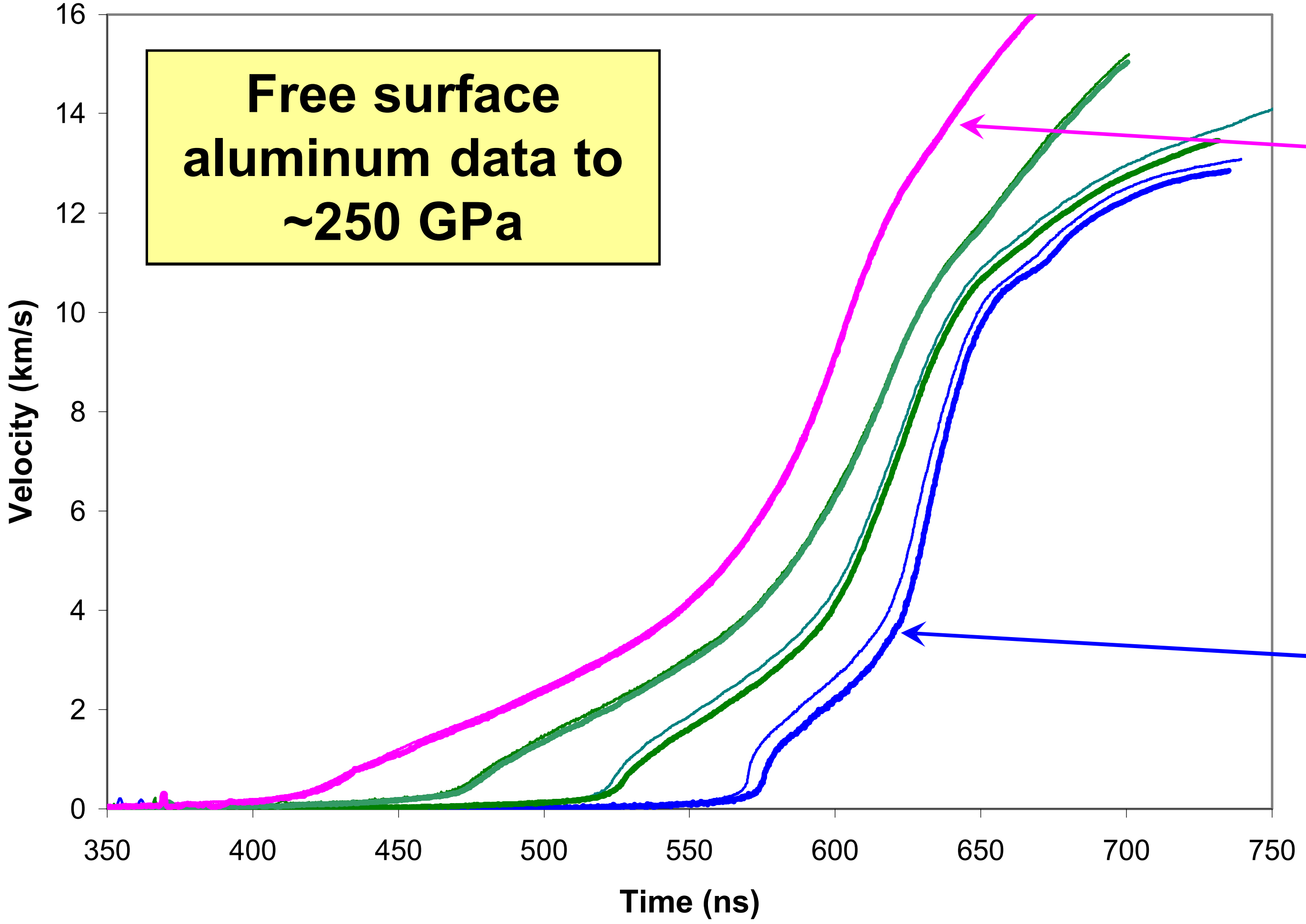
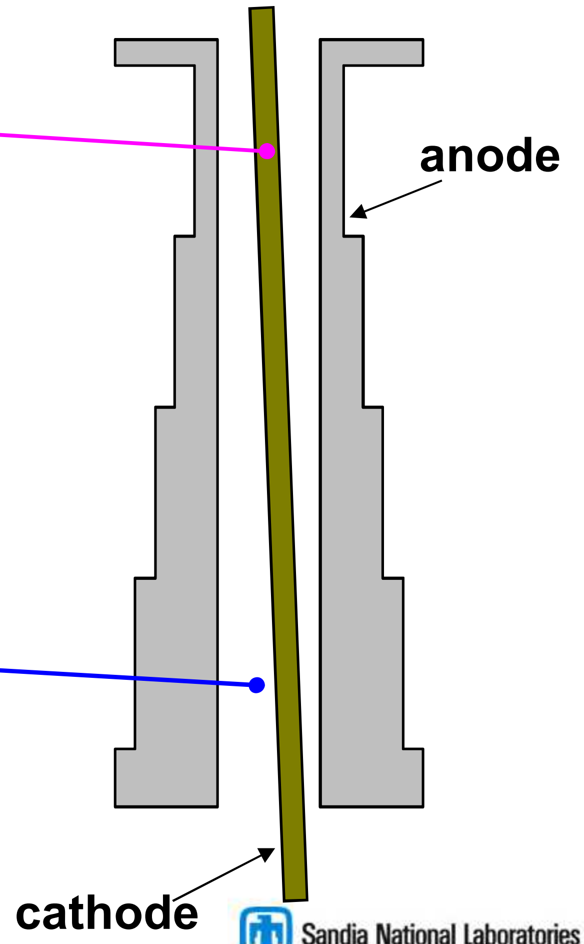
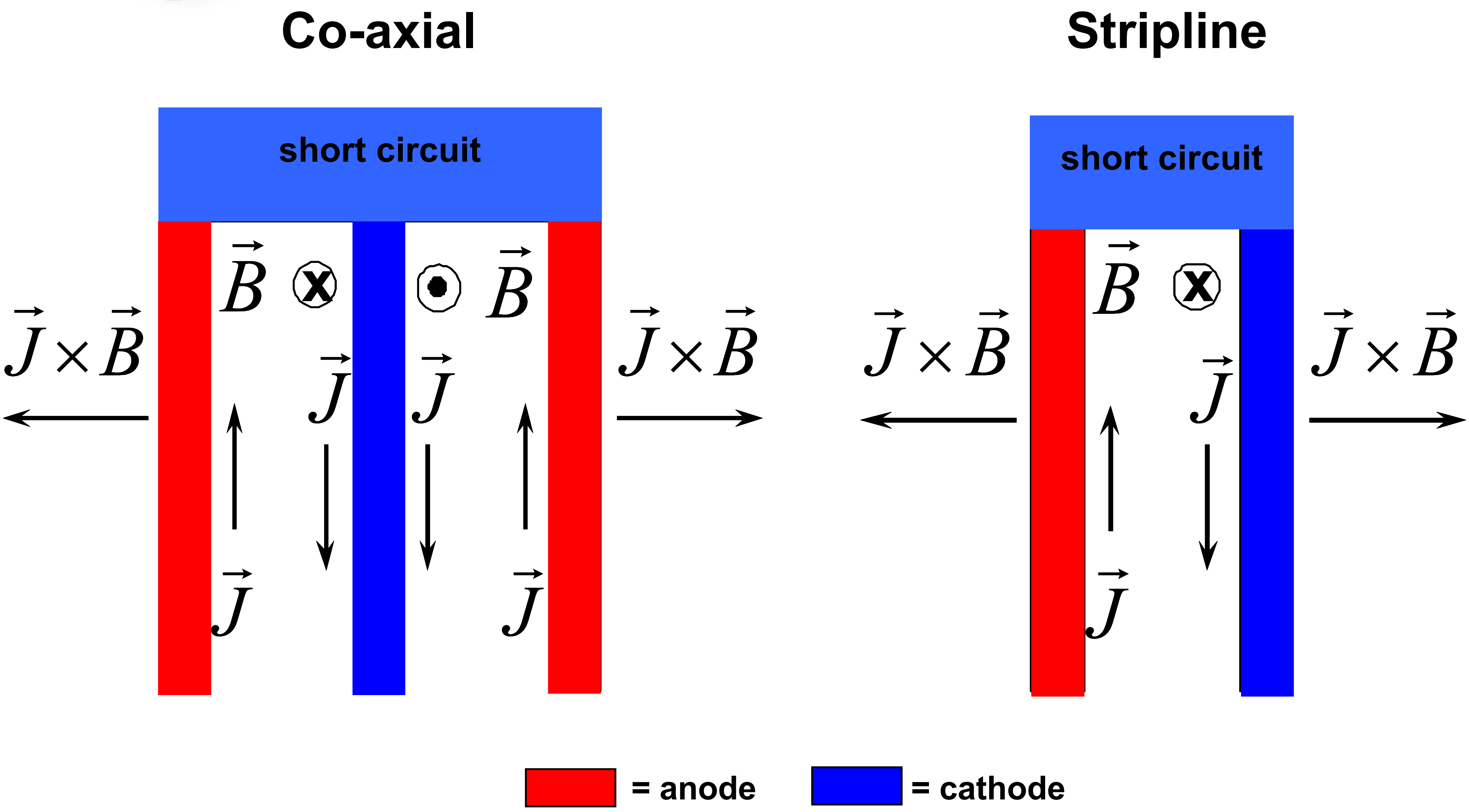
The coaxial design has some practical limitations for use in multi-Mbar ramp compression experiments

- 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

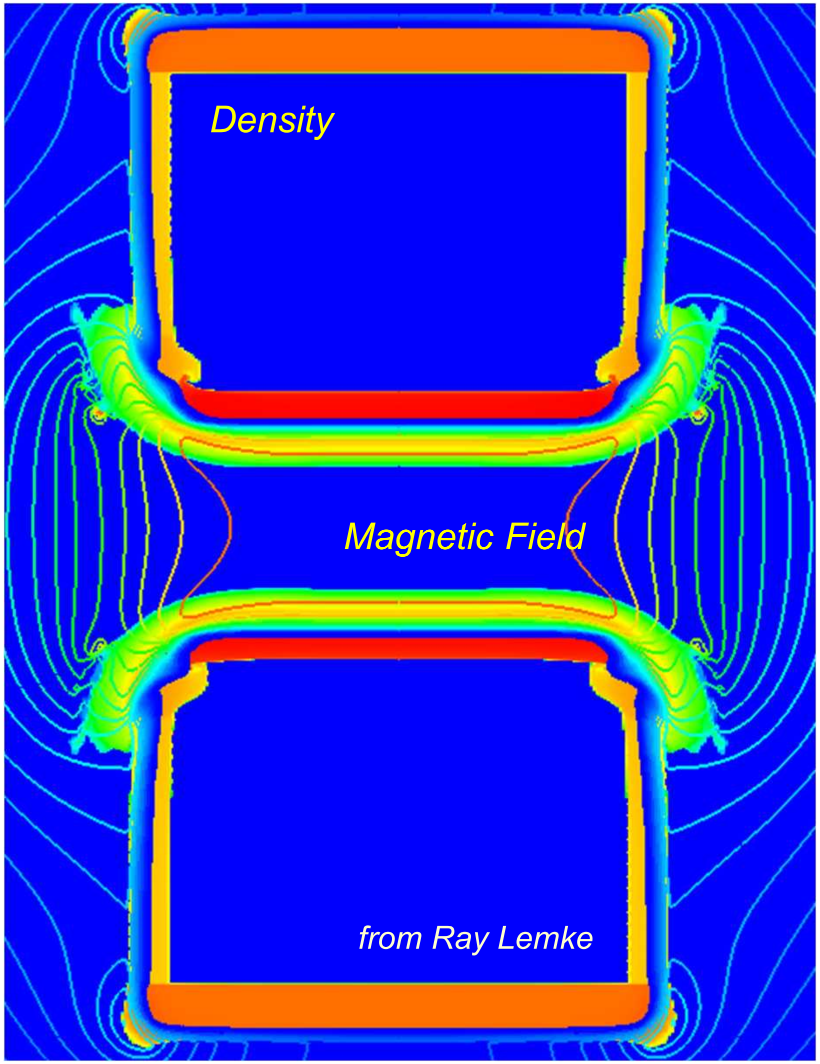




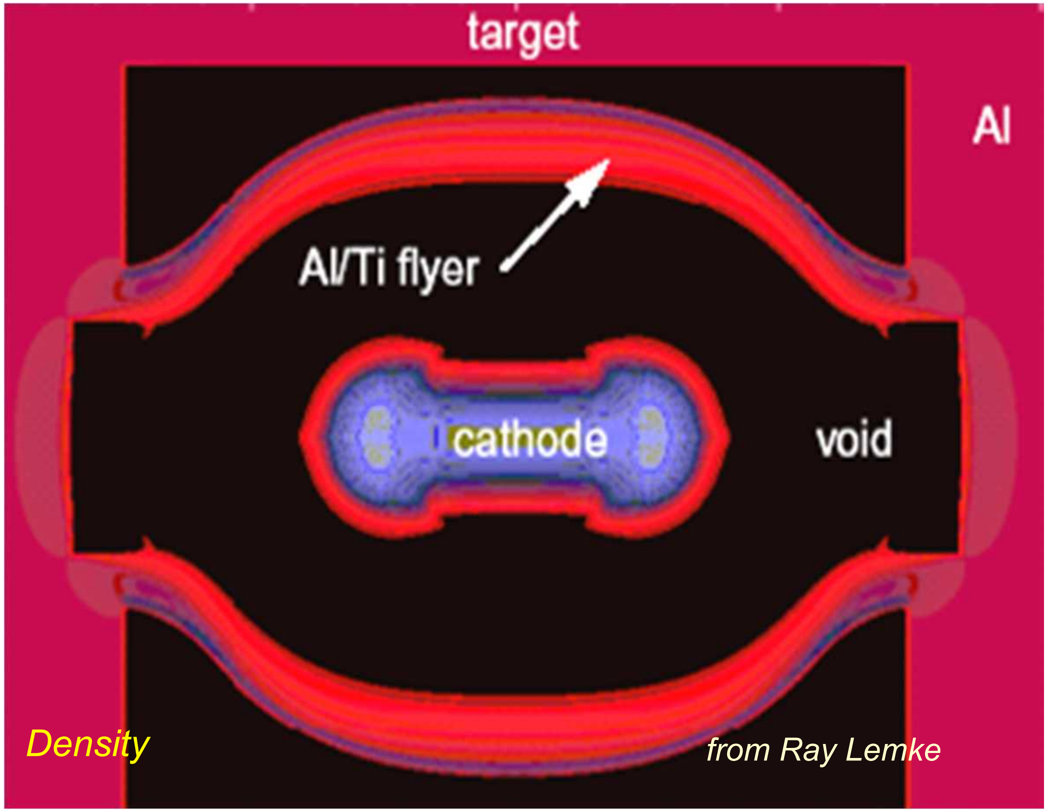
Stripline enables two samples to experience identical B-field, ensuring identical pressure histories



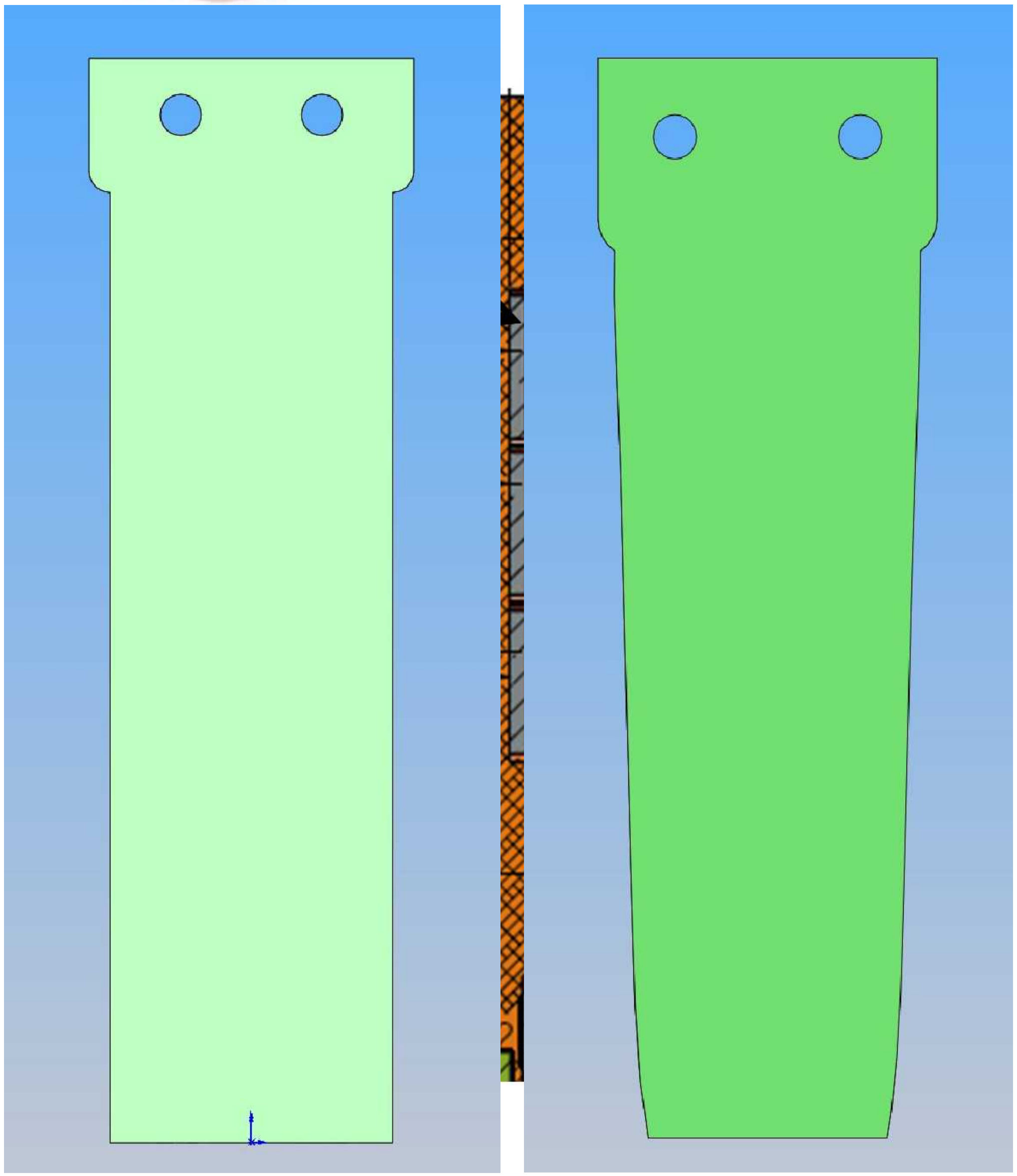
2D deformation effects are significantly reduced for the stripline compared to the coaxial geometry

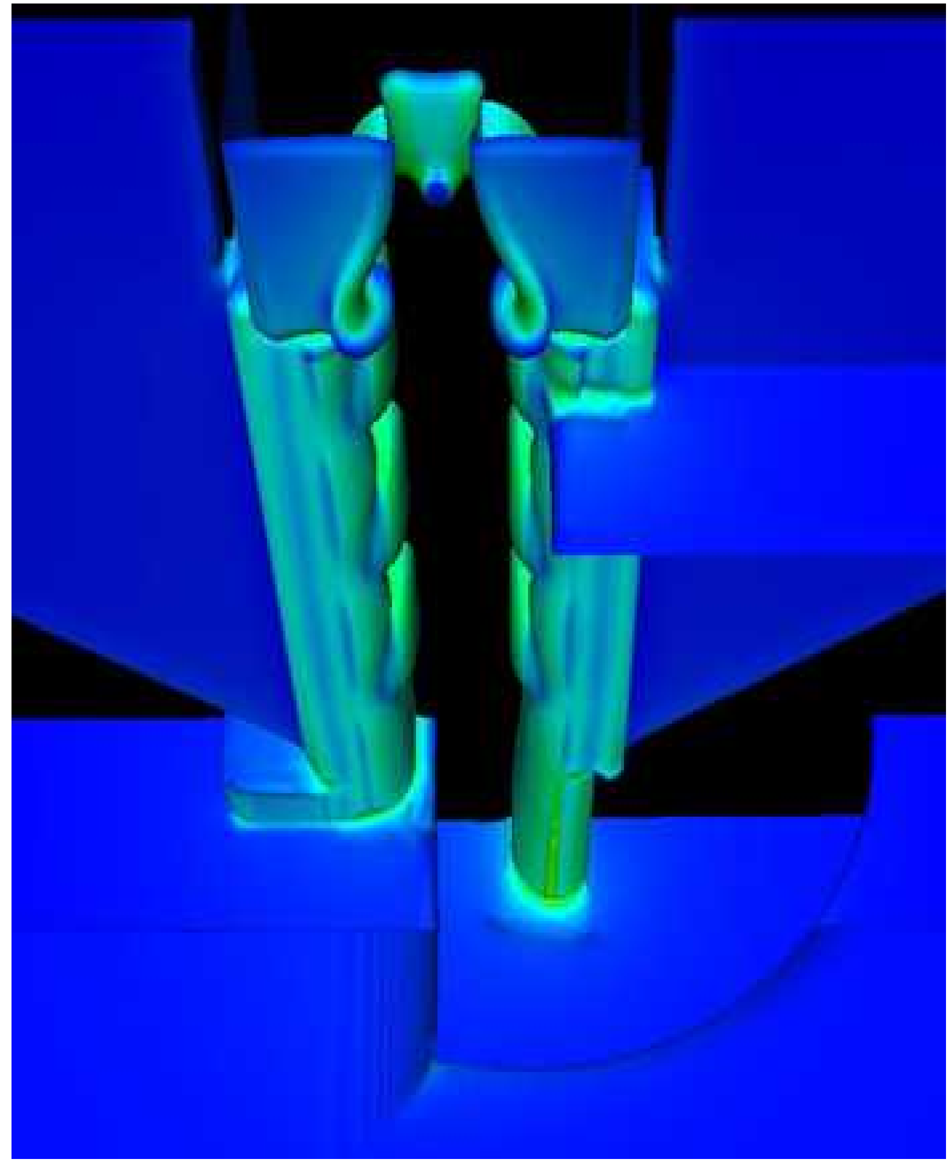


2D deformation effects are much more significant for coaxial geometry. Stripline geometry provides much better lateral uniformity



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





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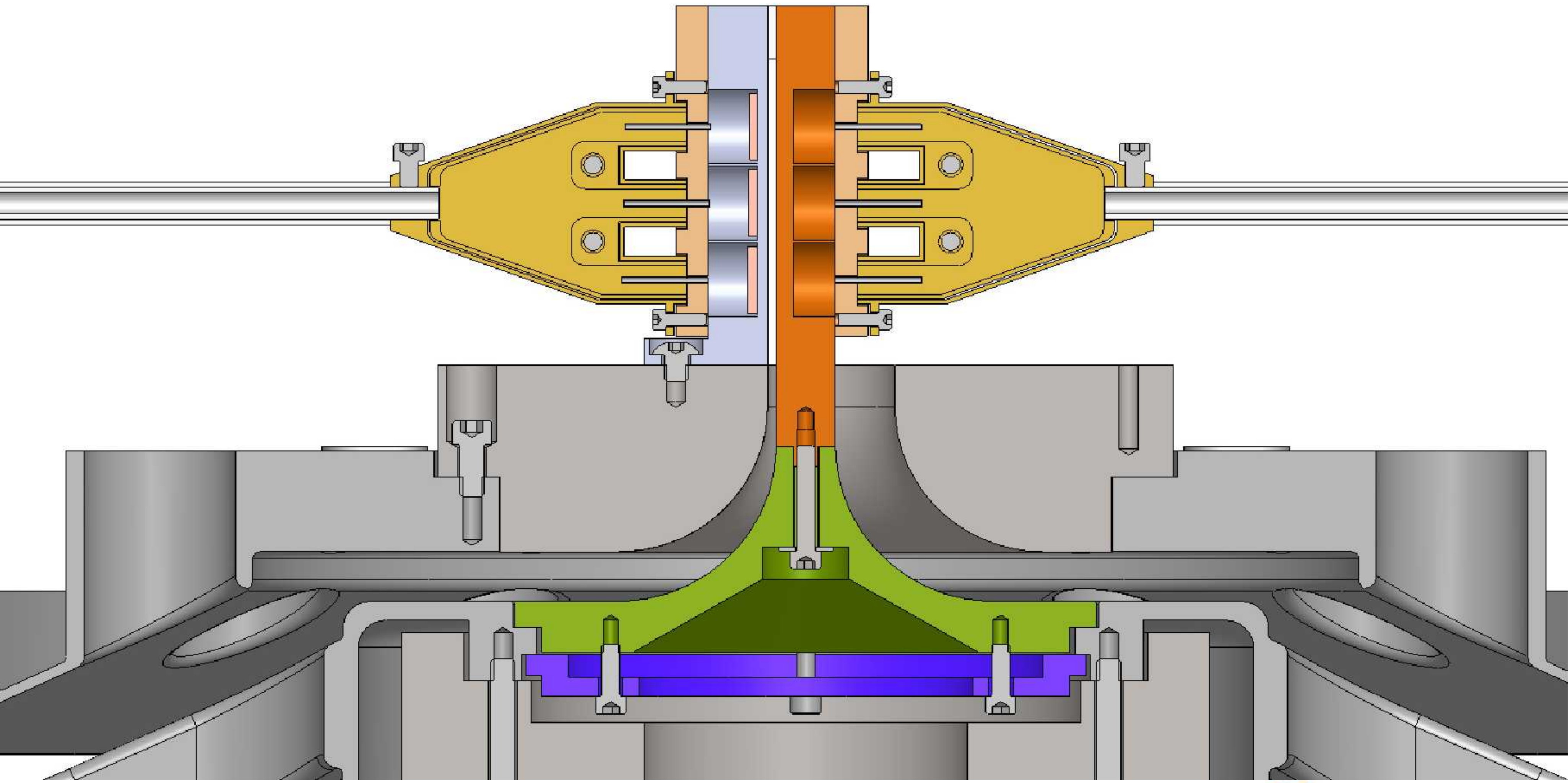
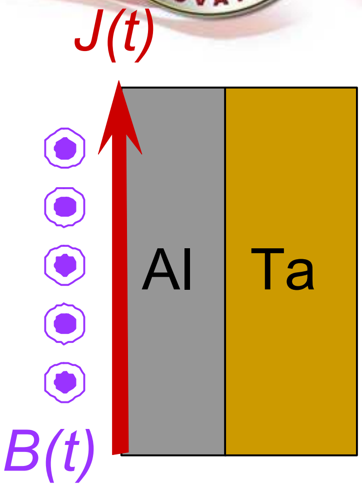
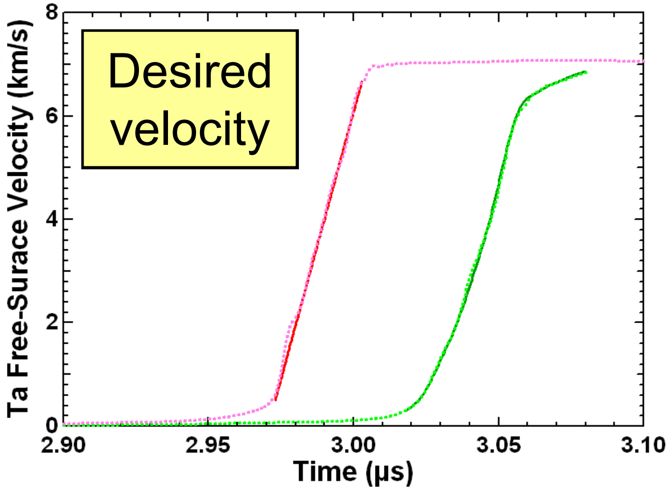
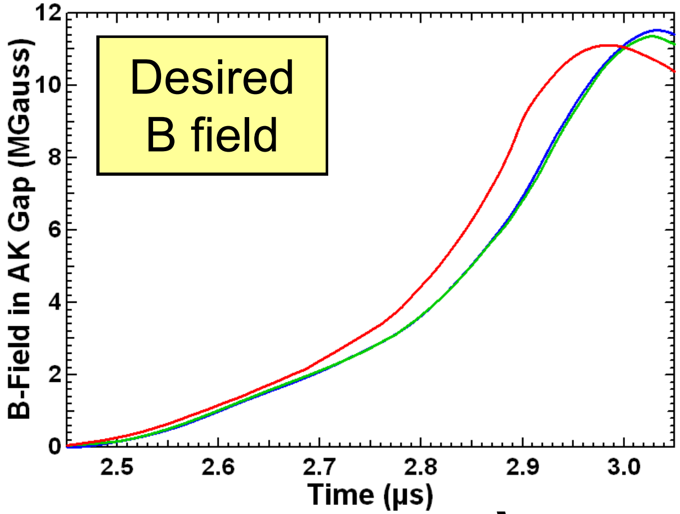
Remaining experimental definition includes electrode and sample thicknesses, and pulseshape

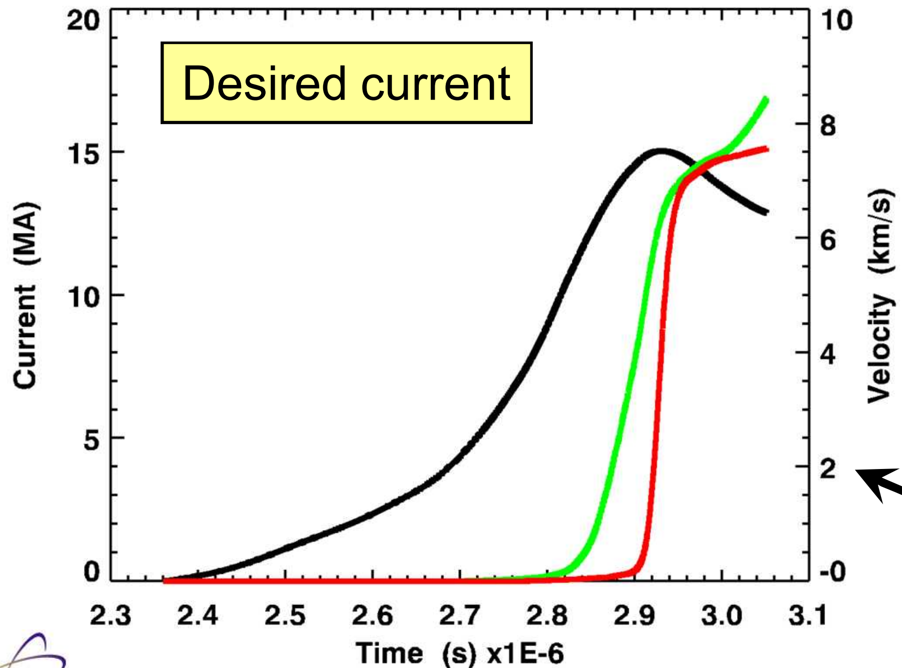


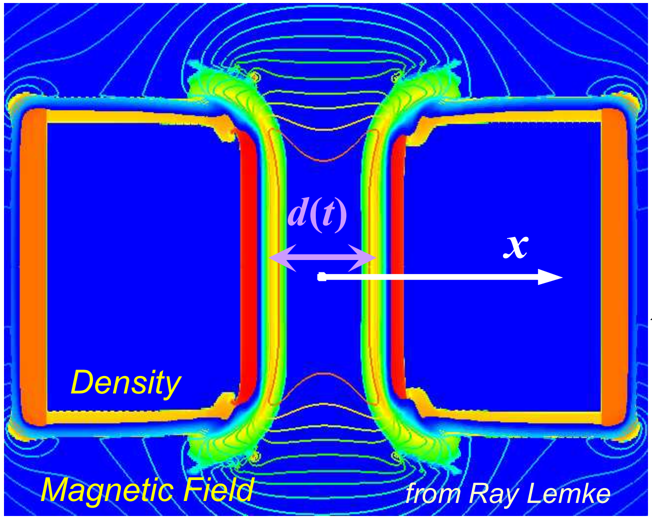
Design issues are handled through several iterative 1-D and 2-D MHD simulations











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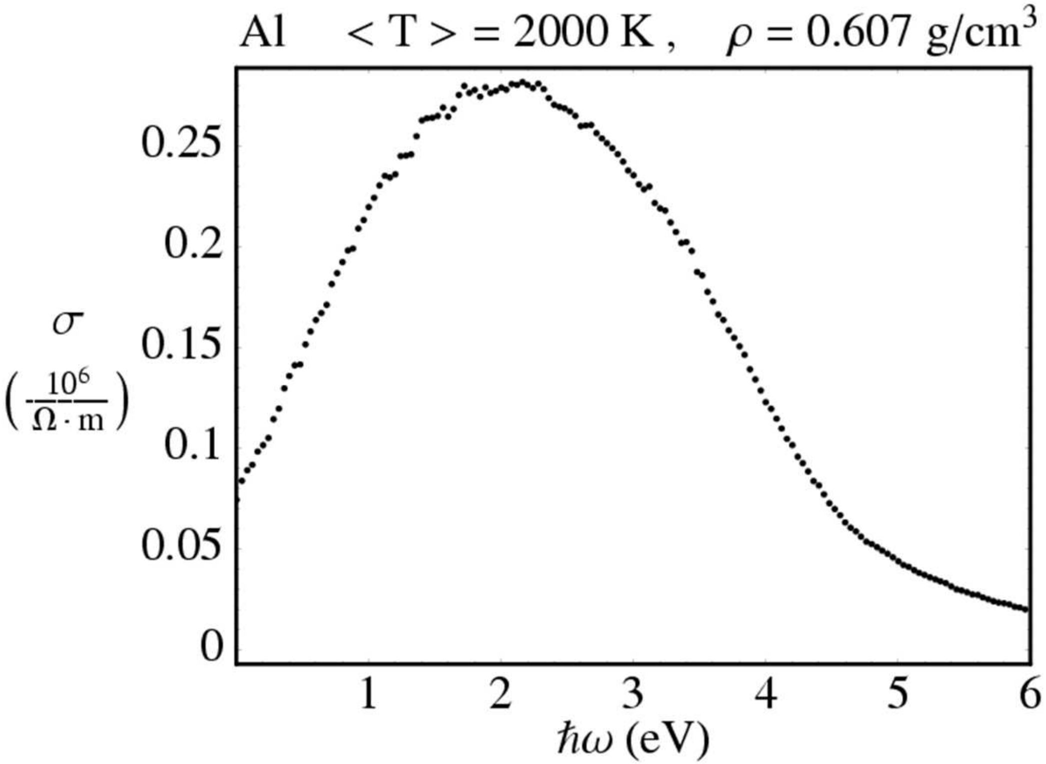
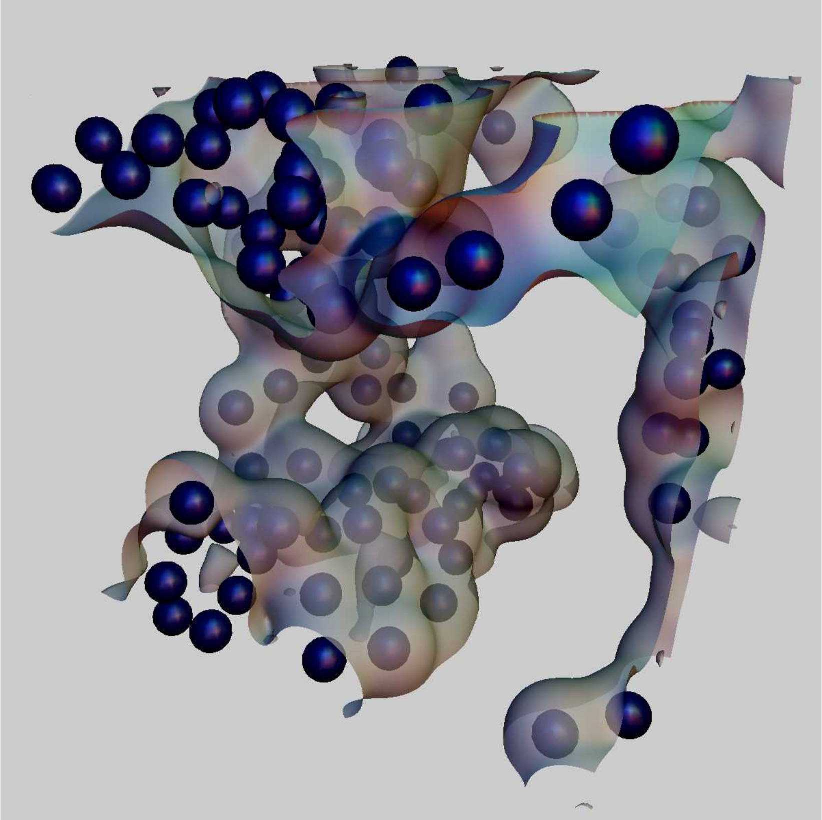
An improved aluminum conductivity model was found to be necessary for meaningful simulations



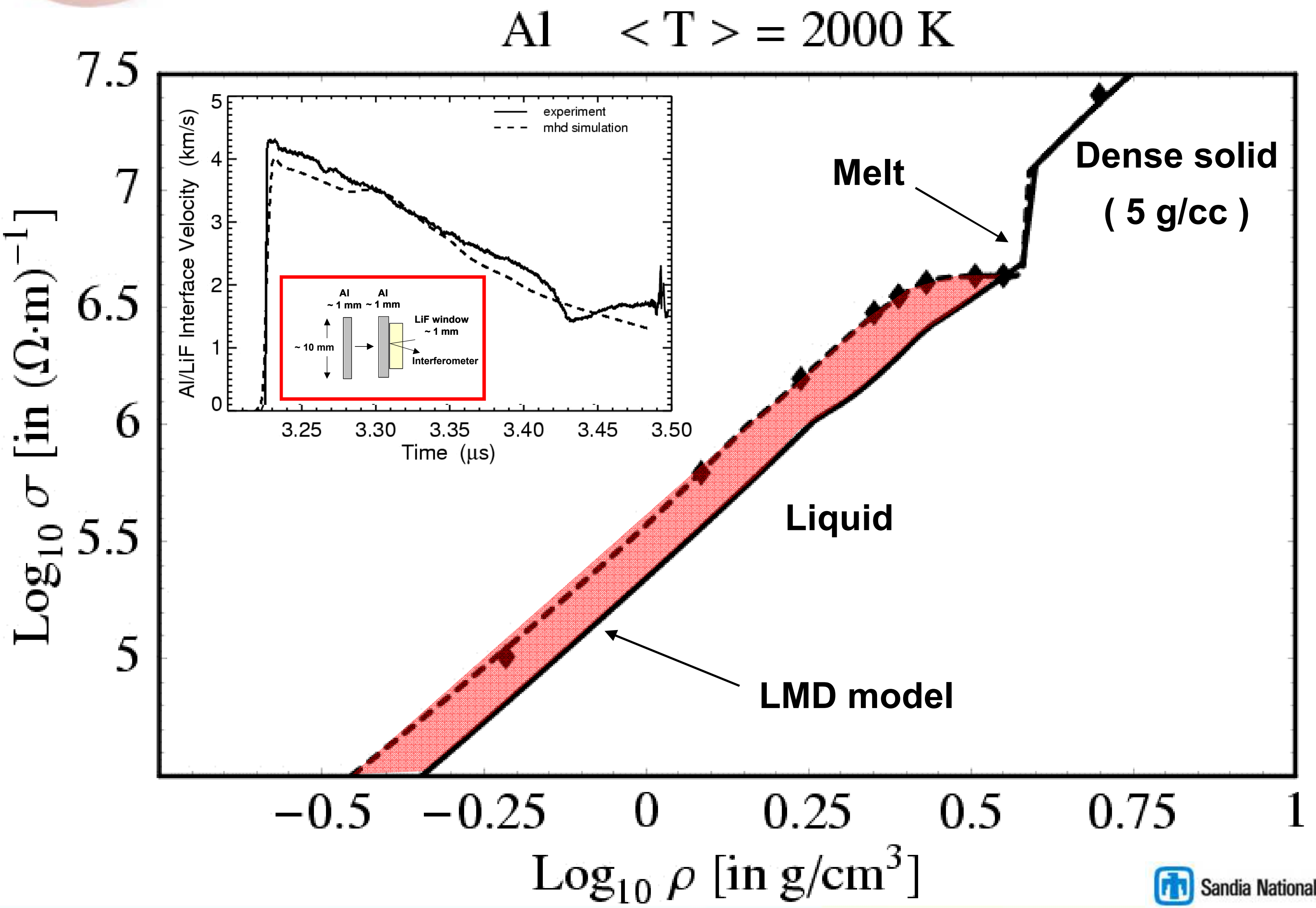
The dc conductivity has dropped by a factor of 25 for a factor of 4 drop in density



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

Conductivity calculations were performed over a broad temperature and density regime

QMD conductivity model significantly improved agreement between experiment and simulation



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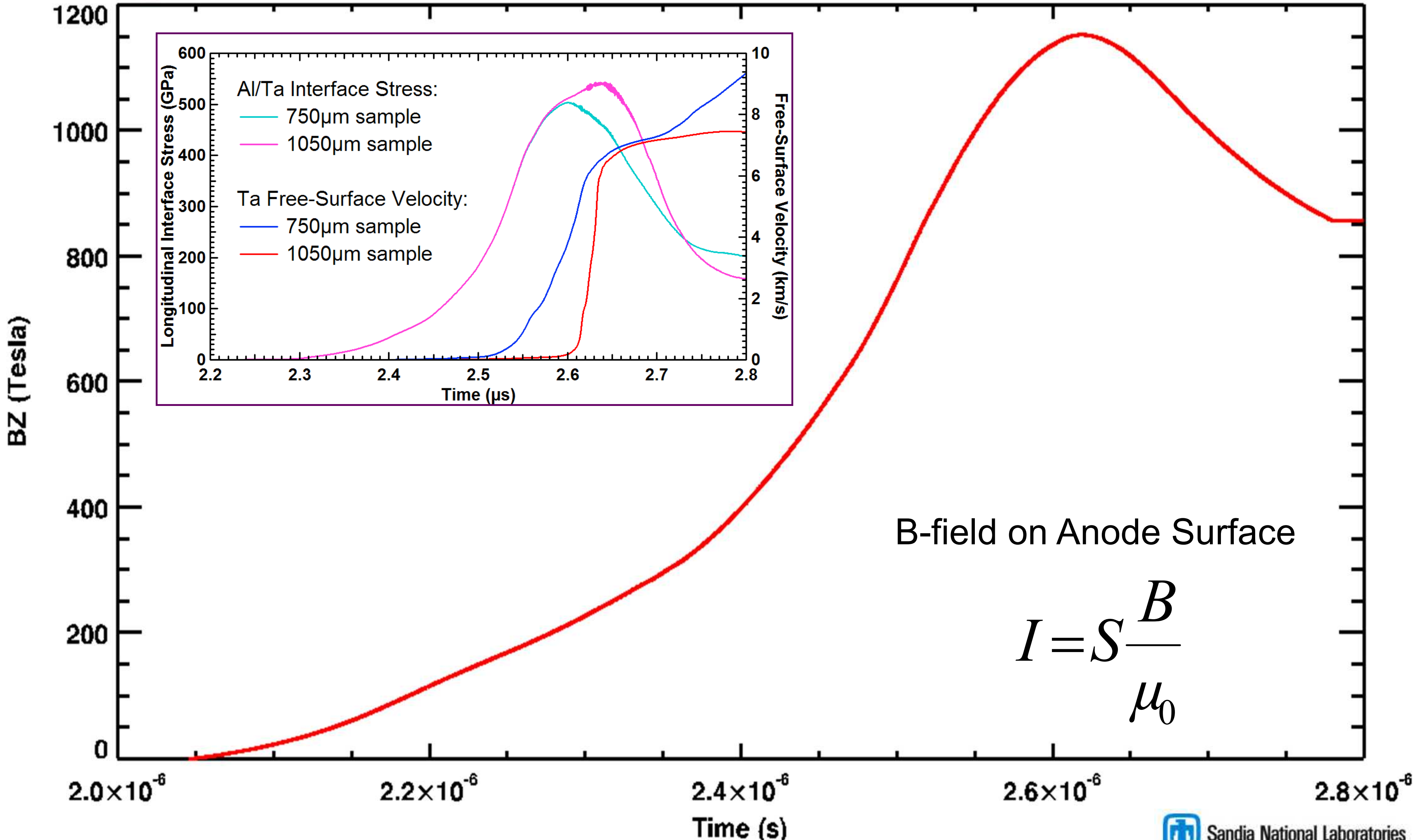
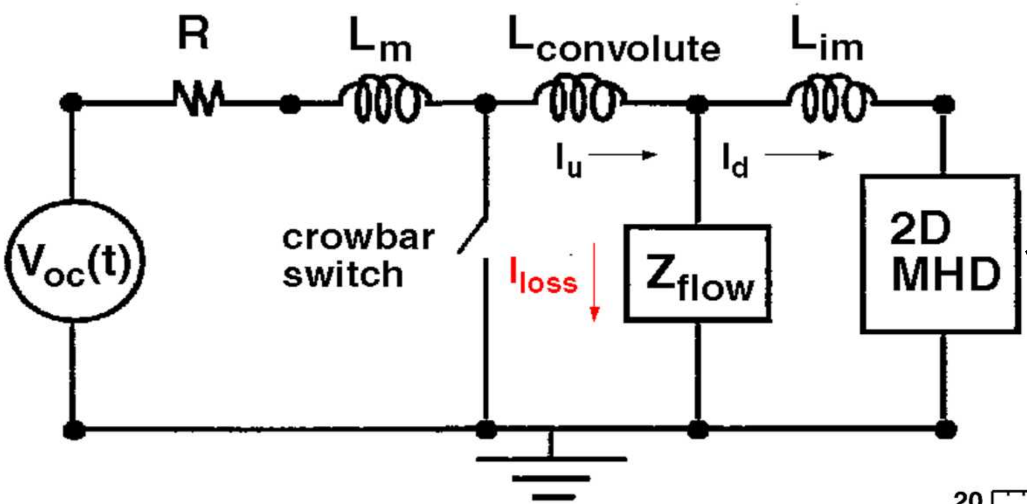
1D MHD provides B-field needed on the anode surface and evaluation of shock and reverberation



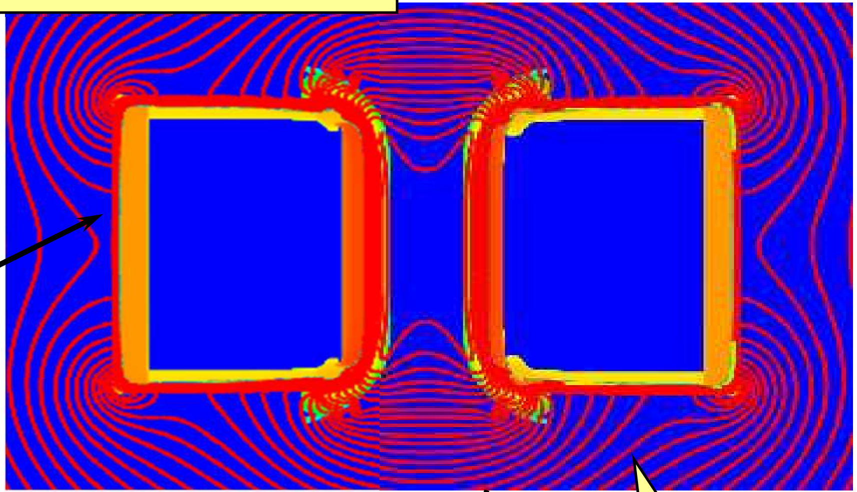
$$I = S\frac{B}{\mu_0}$$

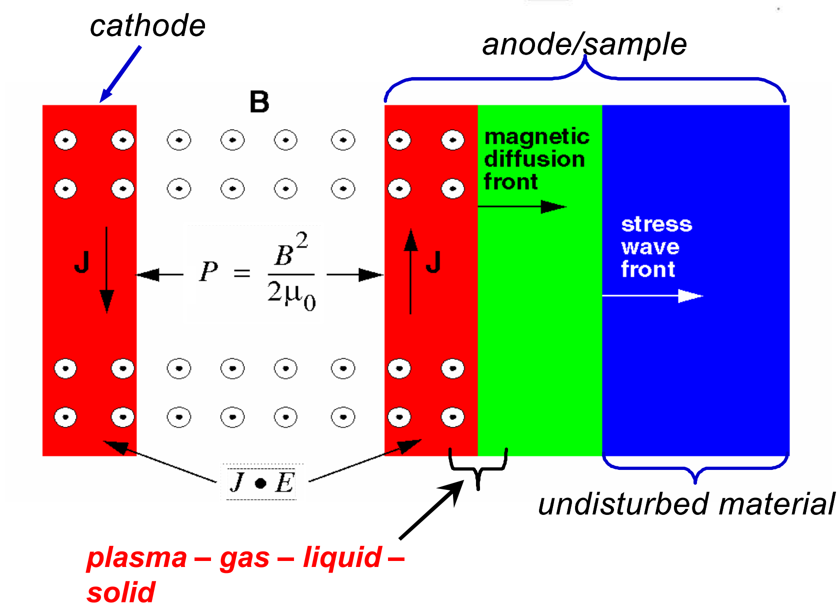
Accurate determination of 2D effects requires the use of a self-consistent circuit description of Z

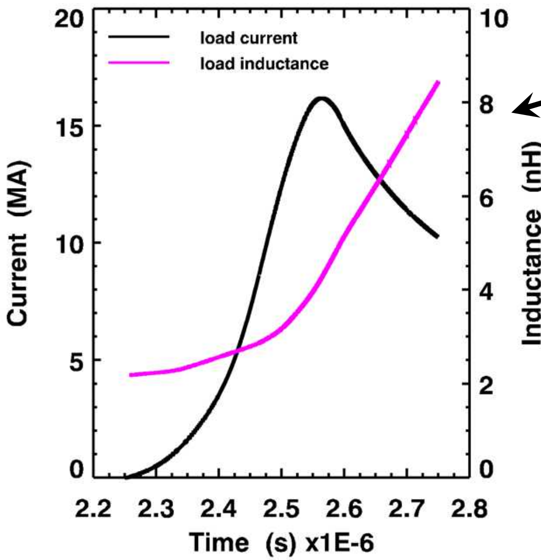
Z circuit for 2D MHD simulation



2D MHD geometry



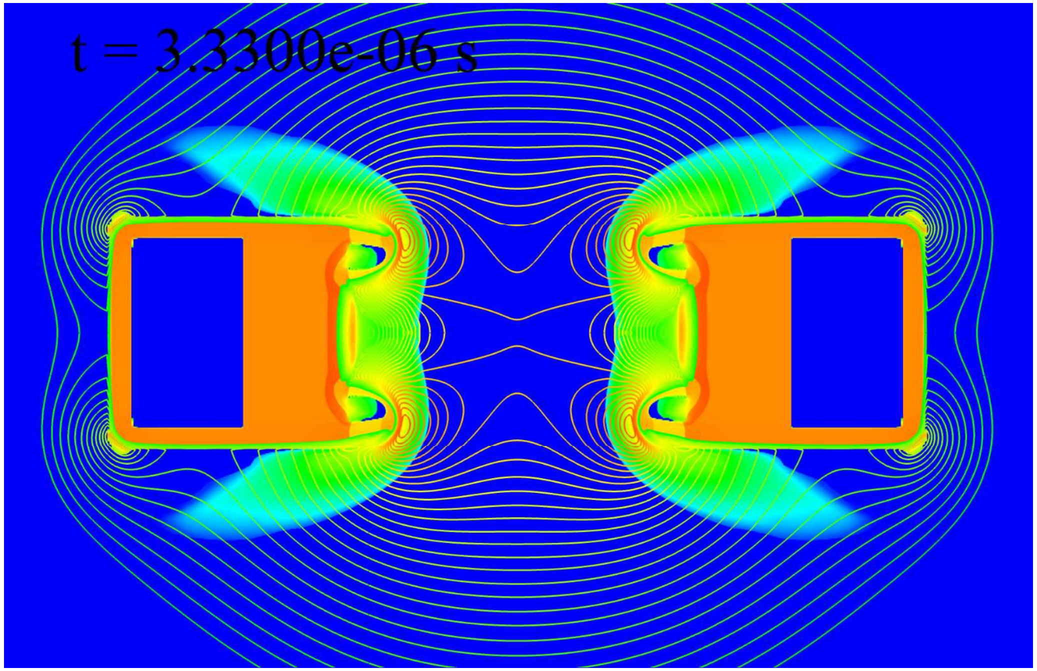


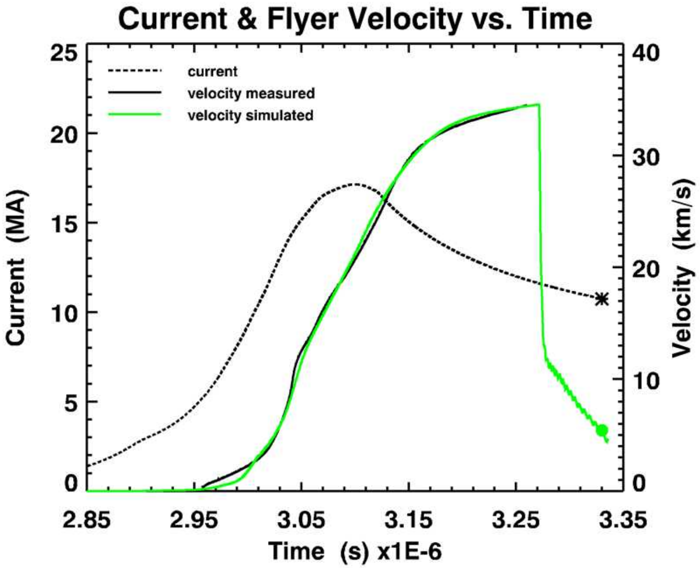


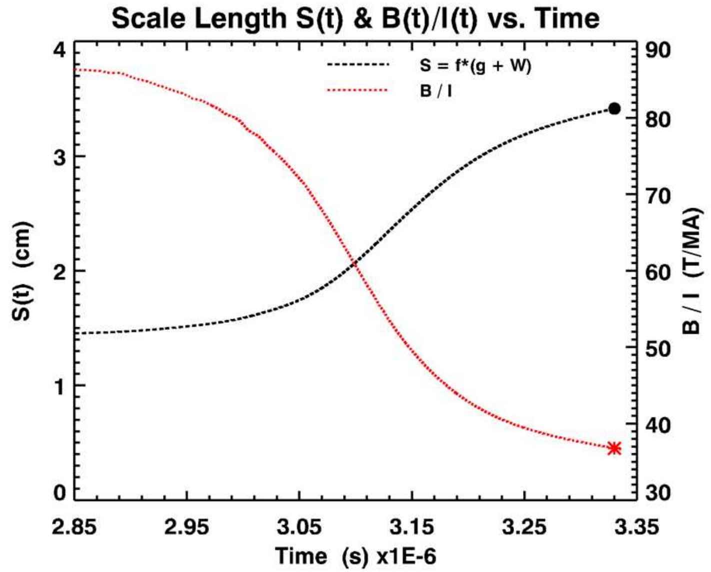
Length in 3D handled by circuit-MHD coupling algorithm

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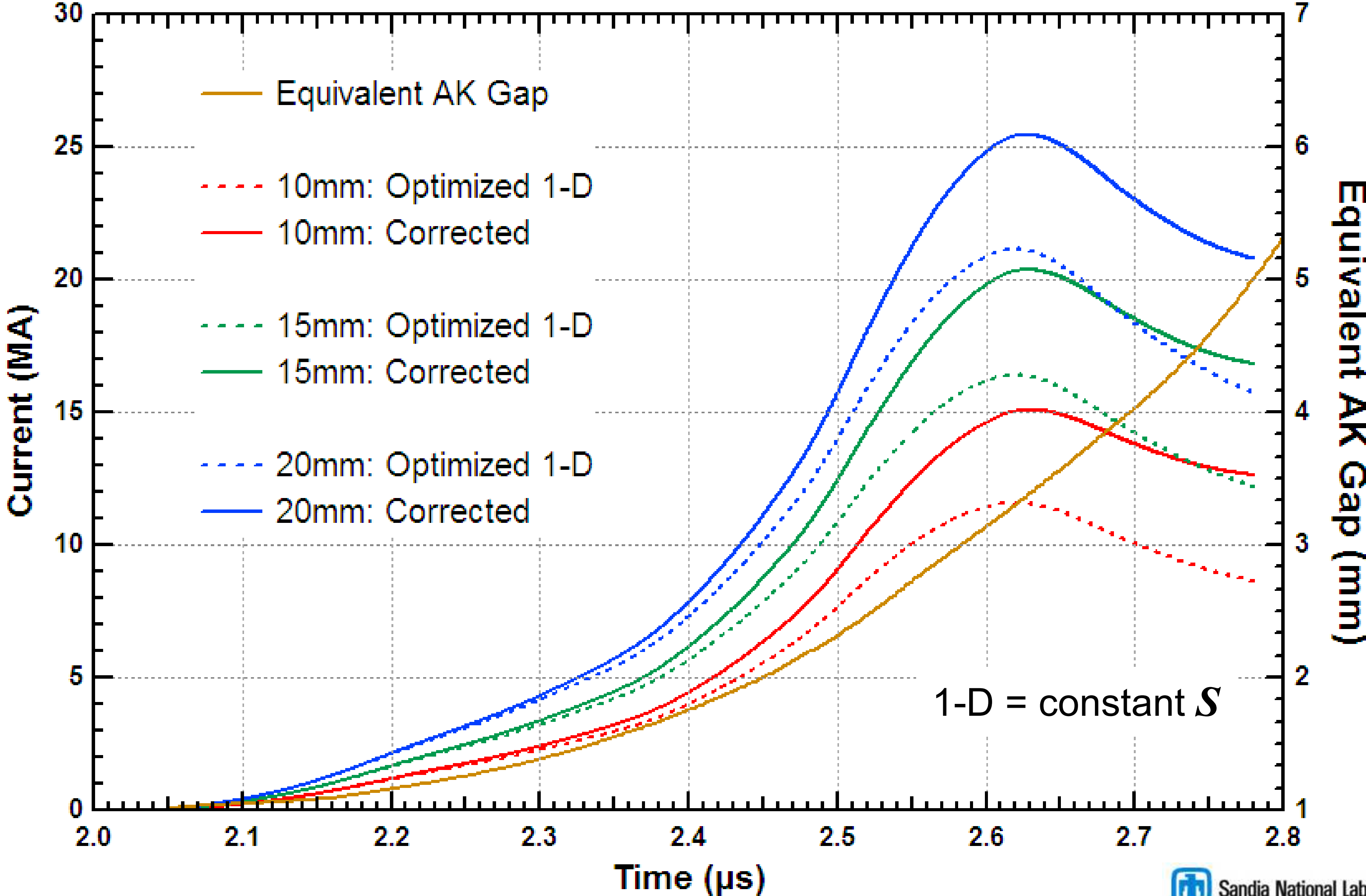
2D simulations and loss models provide the target current needed to drive the experimental load



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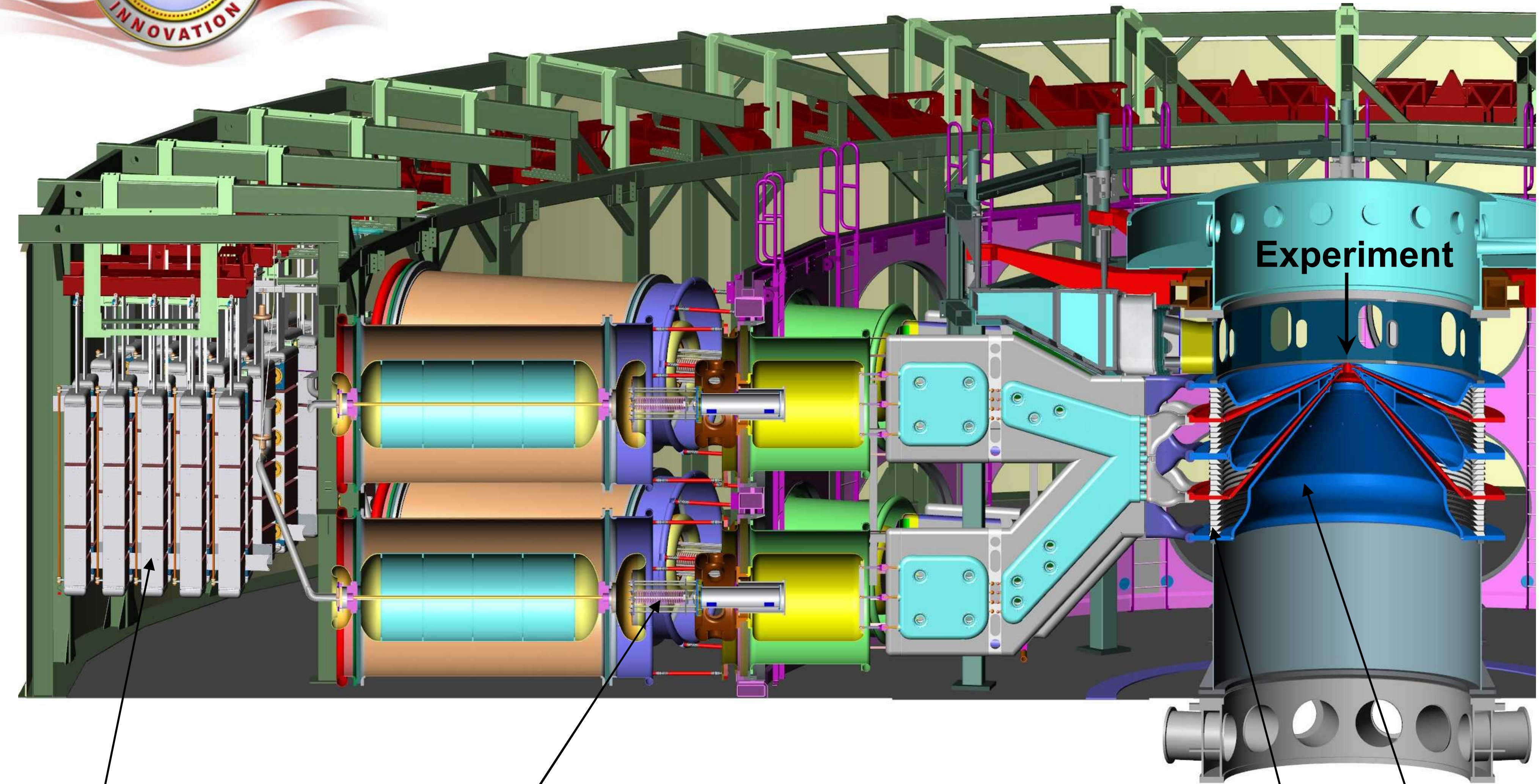
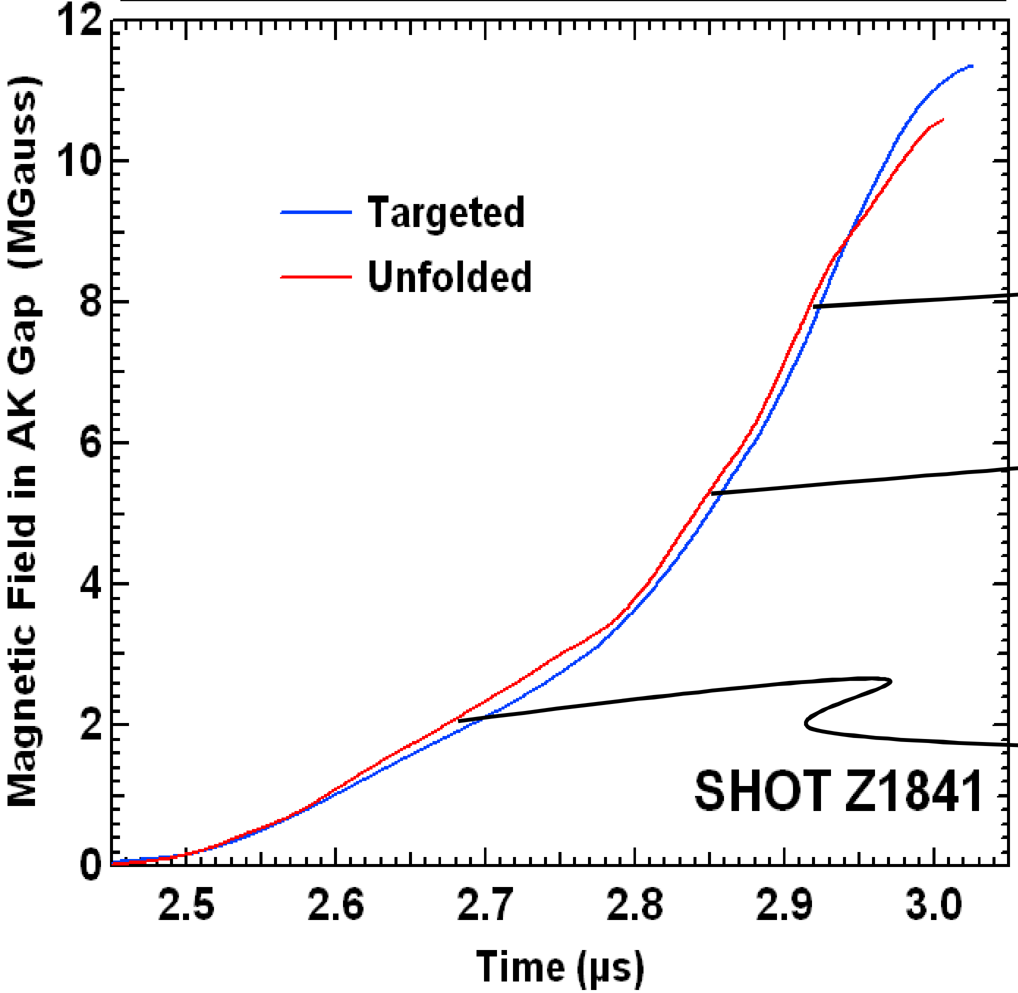
Independently triggerable gas switches provide the variability necessary for pulse shaping



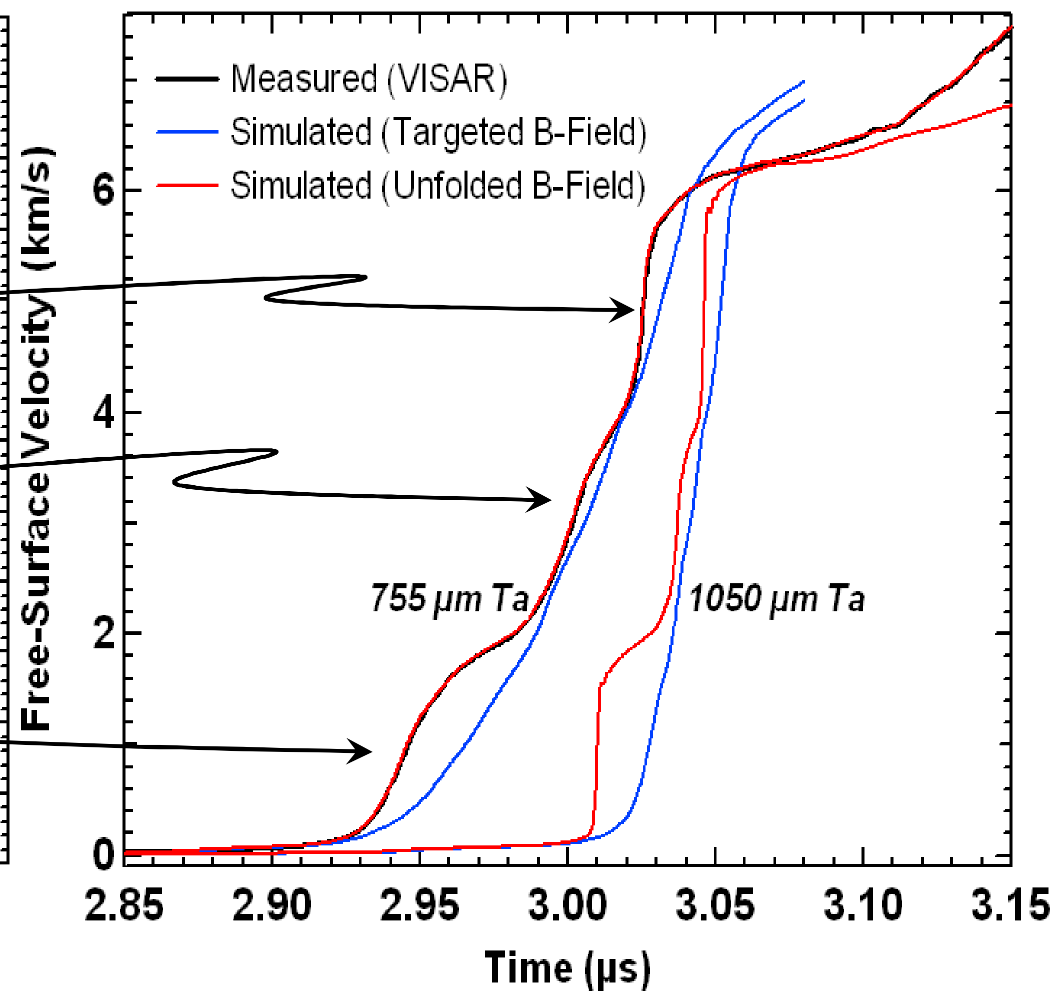
18 independently triggerable groups of 2 transmission lines

The Bertha circuit model provides an accurate prediction of machine performance

Current comparison



Wave profile comparison



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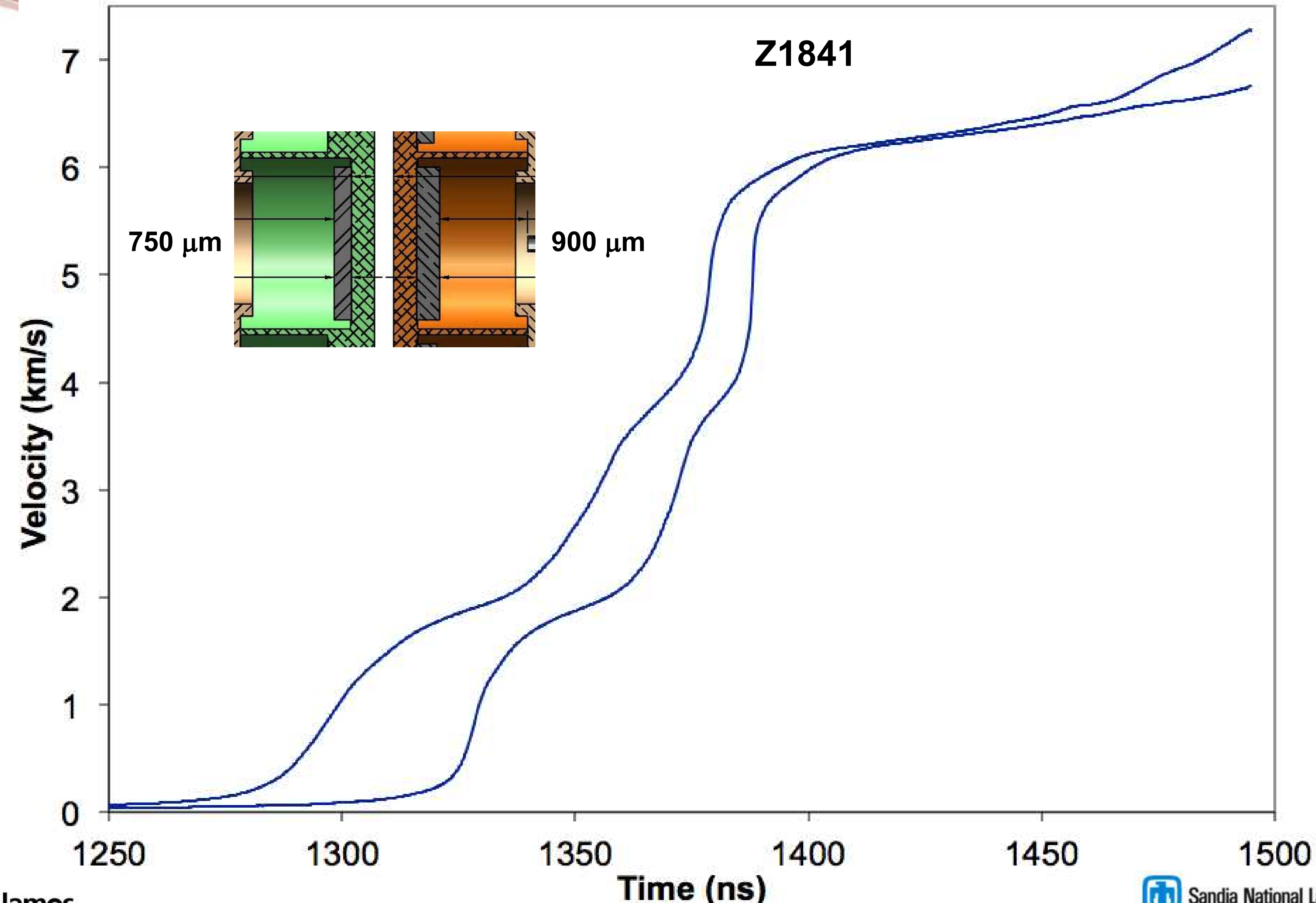
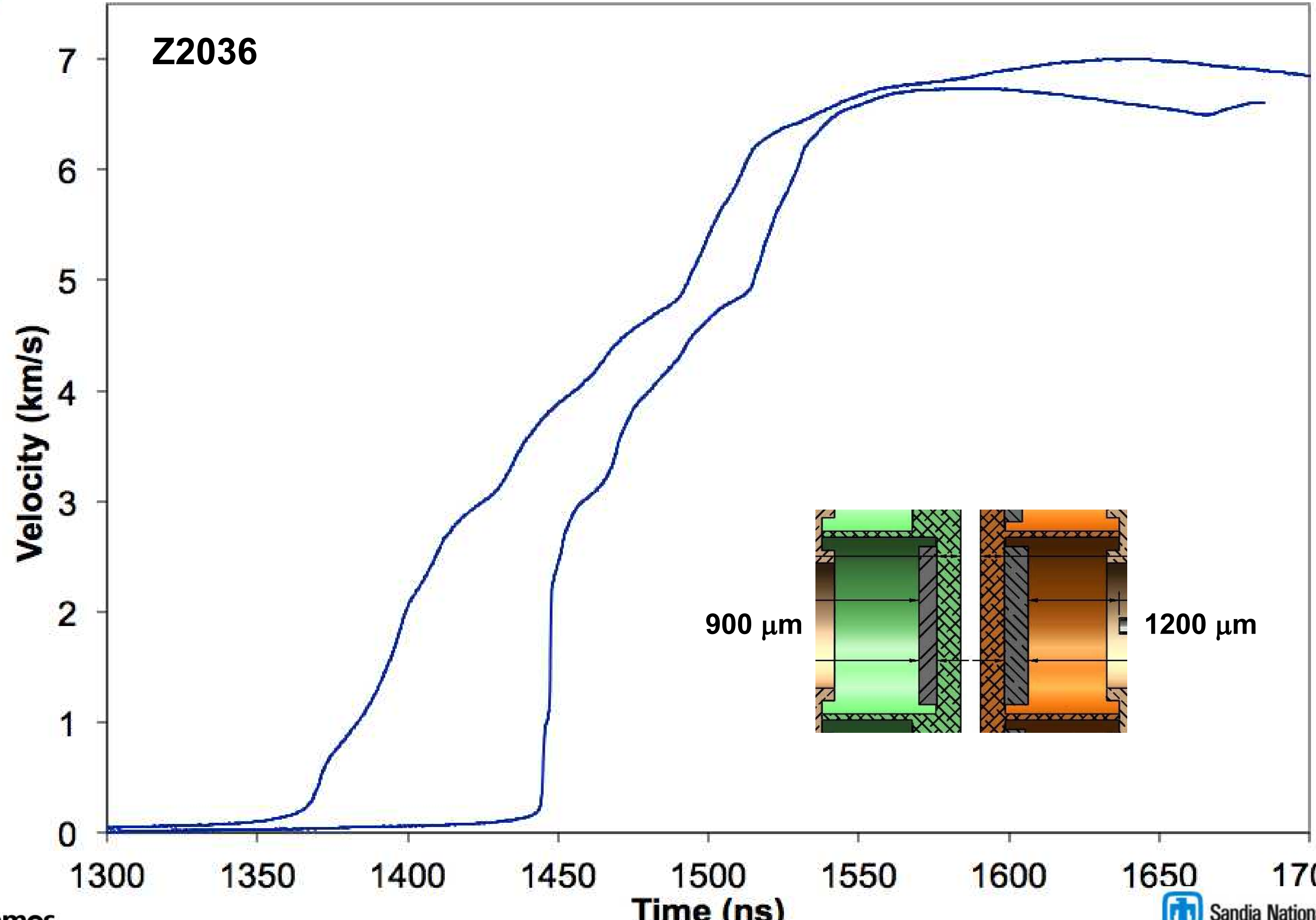
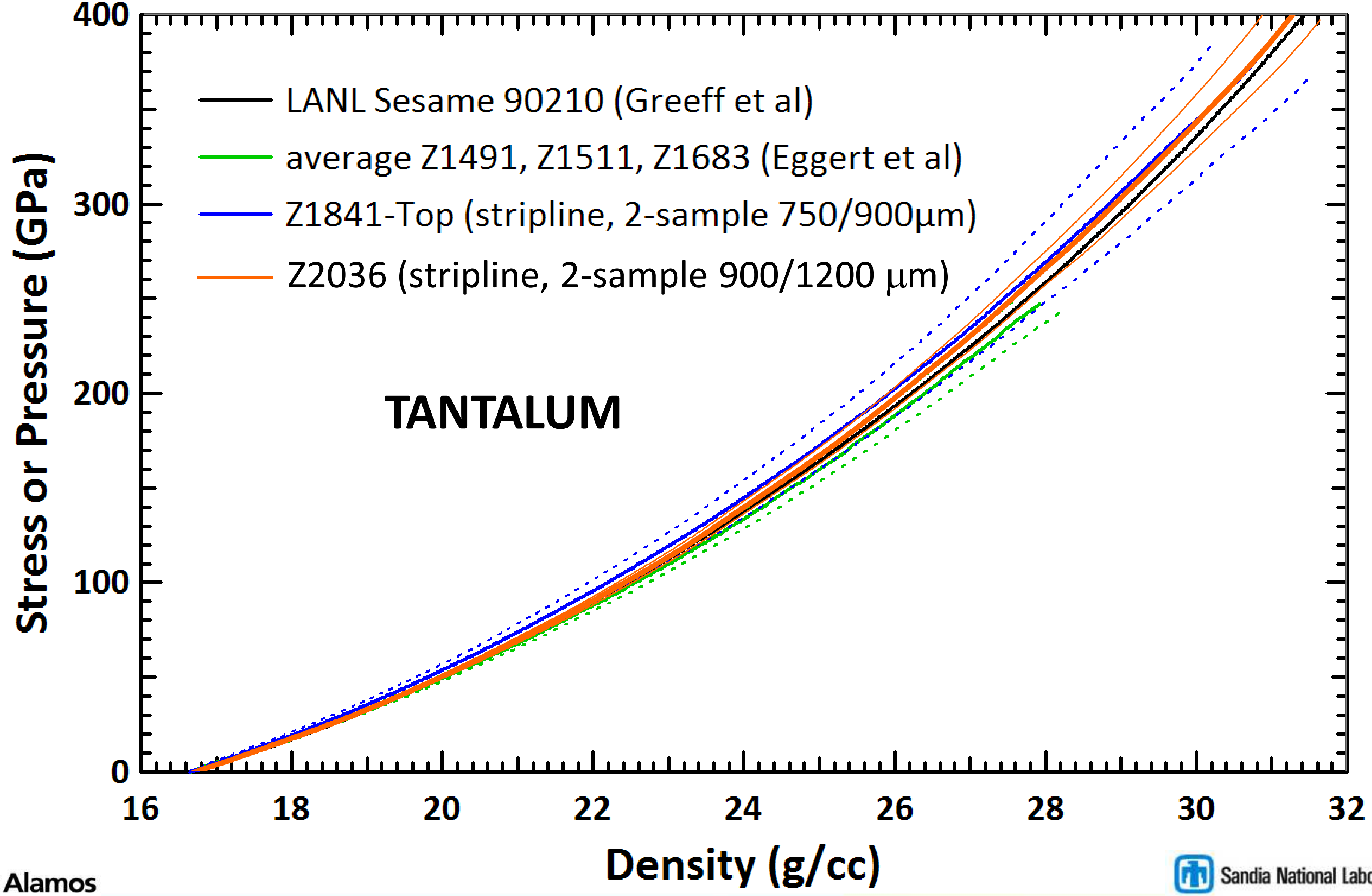
Recent ramp compression data have enable extraction of the Ta isentrope to over 400 GPa



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



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



Los Alamos

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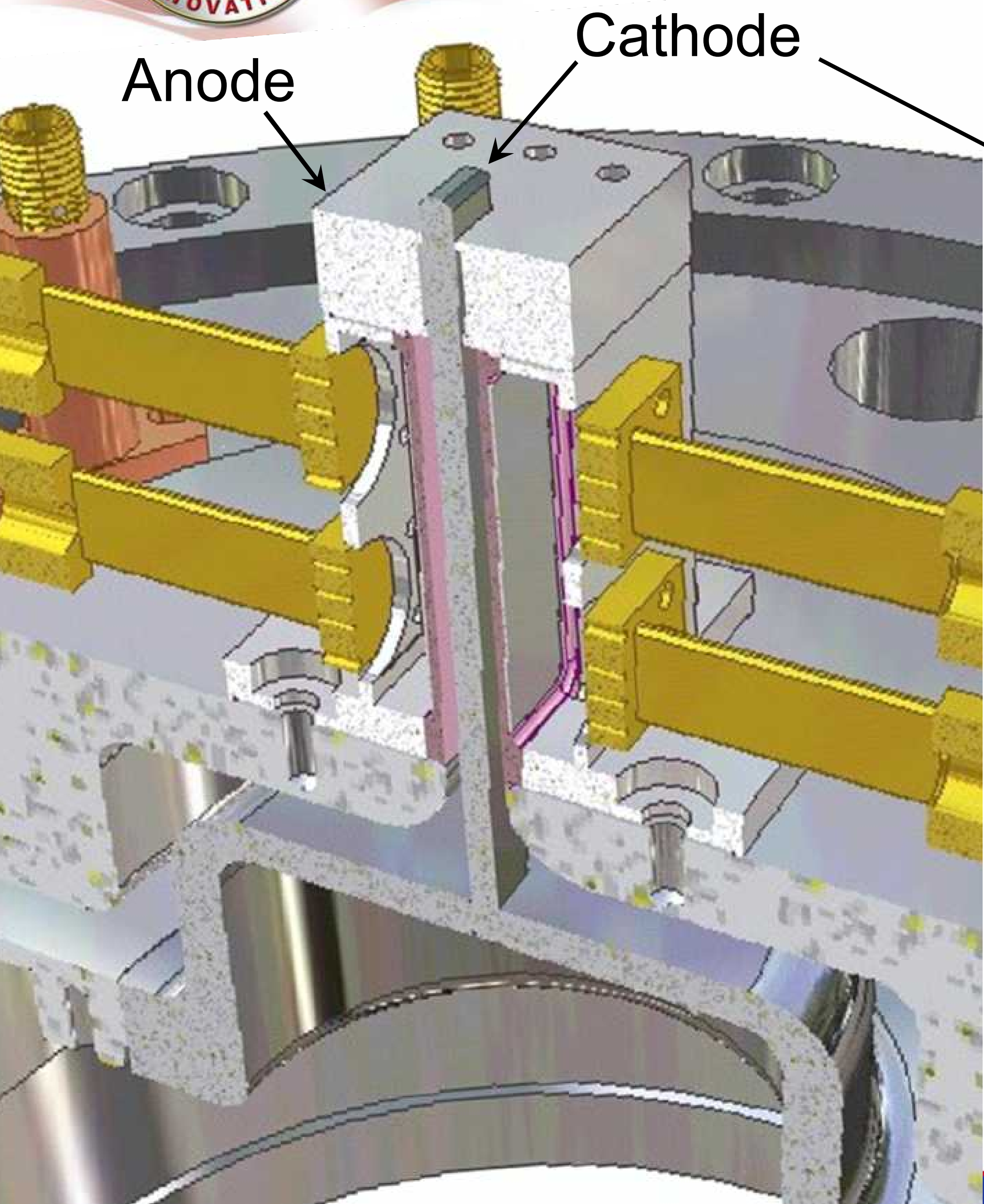
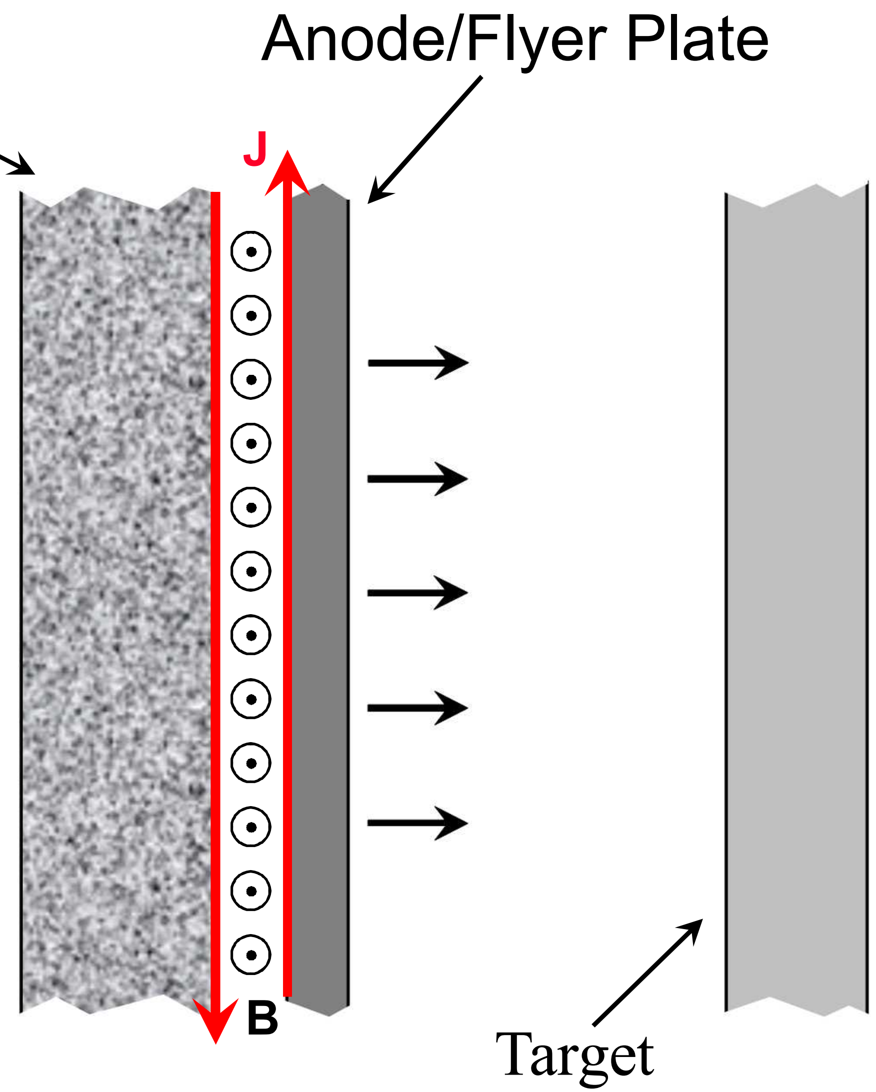
Outline

- High-Stress Isentropic compression platform
  - Tantalum: solid squeezed to two-fold compression
- High-Velocity plate-impact platform
  - Quartz: redefinition of a high pressure standard
- Examples of interplay between experiment and theory
  - Beryllium: evolution of the phase diagram
  - Melting of diamond: existence of a triple point along the Hugoniot
  - Water: support for a cooler Neptune core
- Future directions
  - Development of a double shock plate-impact platform
  - Cylindrical implosion technique for ramp compression

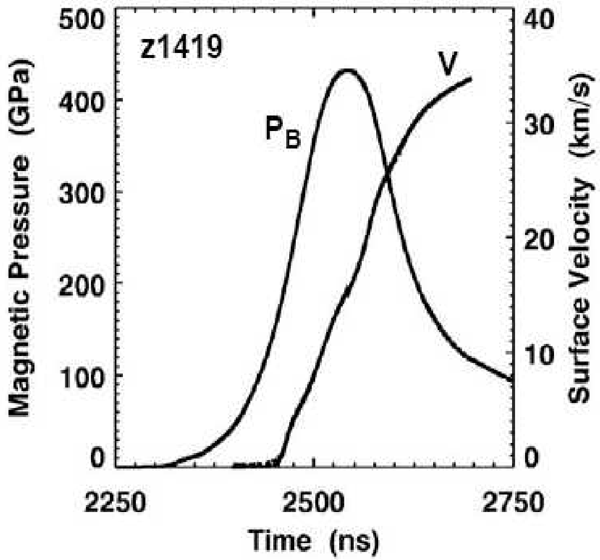
With proper pulse shape and design the anode can be launched as an effective high-velocity flyer plate

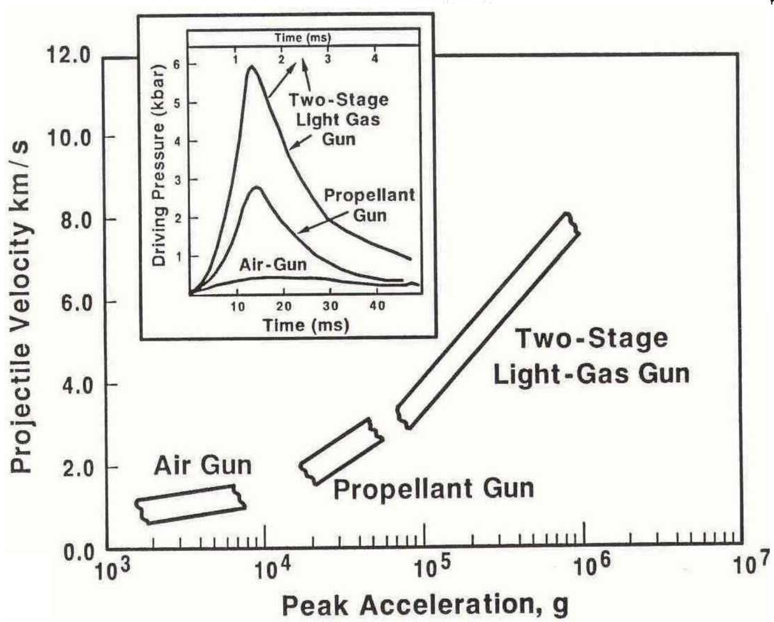


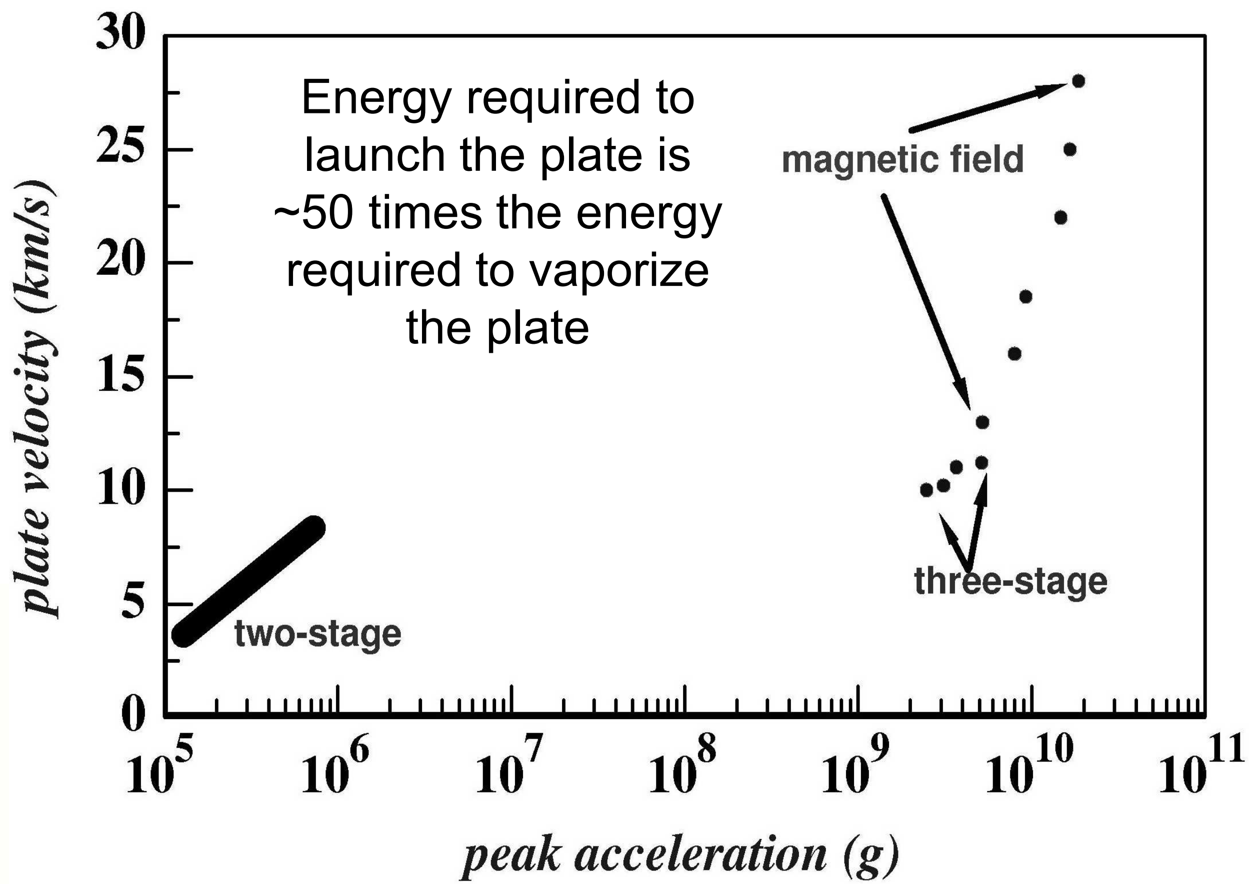


Lemke, et al., J. Appl. Phys. 98, 073530 (2005)

Magnetic pressure provides an impulse to "gently" accelerate the flyer plate to ultra-high velocities



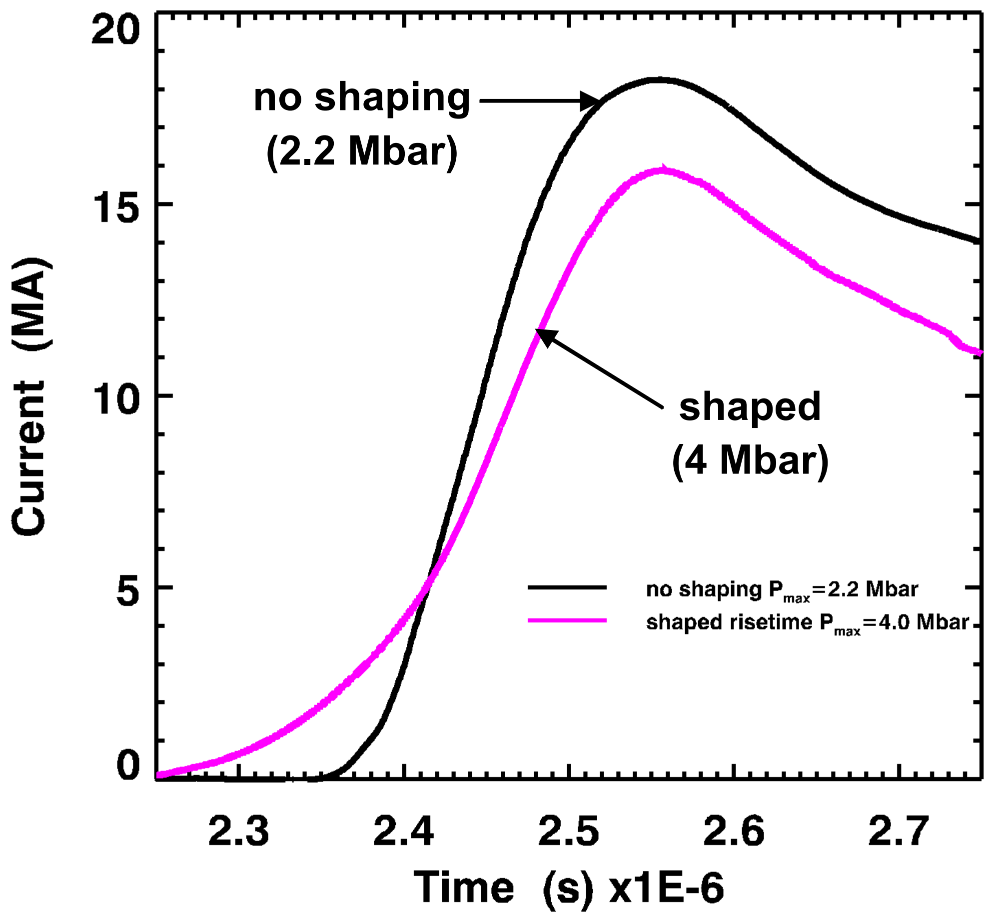




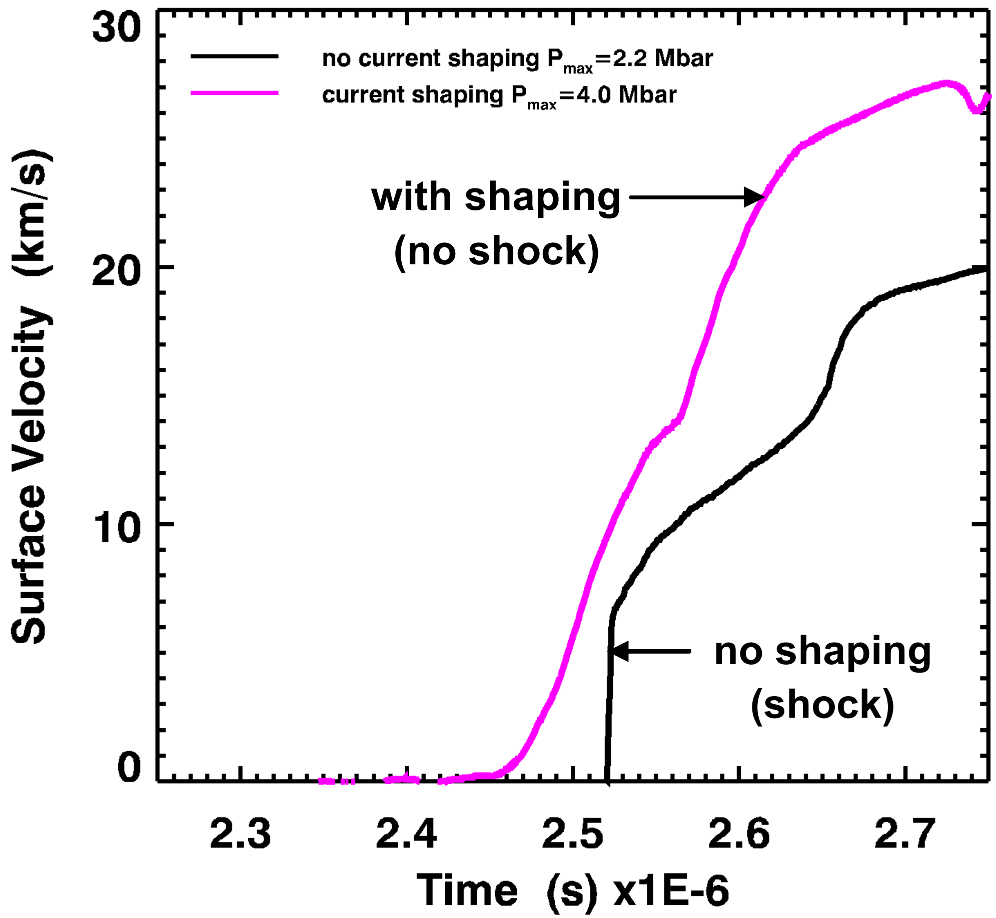
Peak pressures approaching 6 Mbar and peak accelerations of 10^{10} g used in launching of the flyer plate – must control energy deposition

Pulse shaping is critical to ensure shockless acceleration and therefore solid density flyer plate

Measured load current



Measured flyer velocity



Energy sacrificed to shape current; B-field optimized with geometry.

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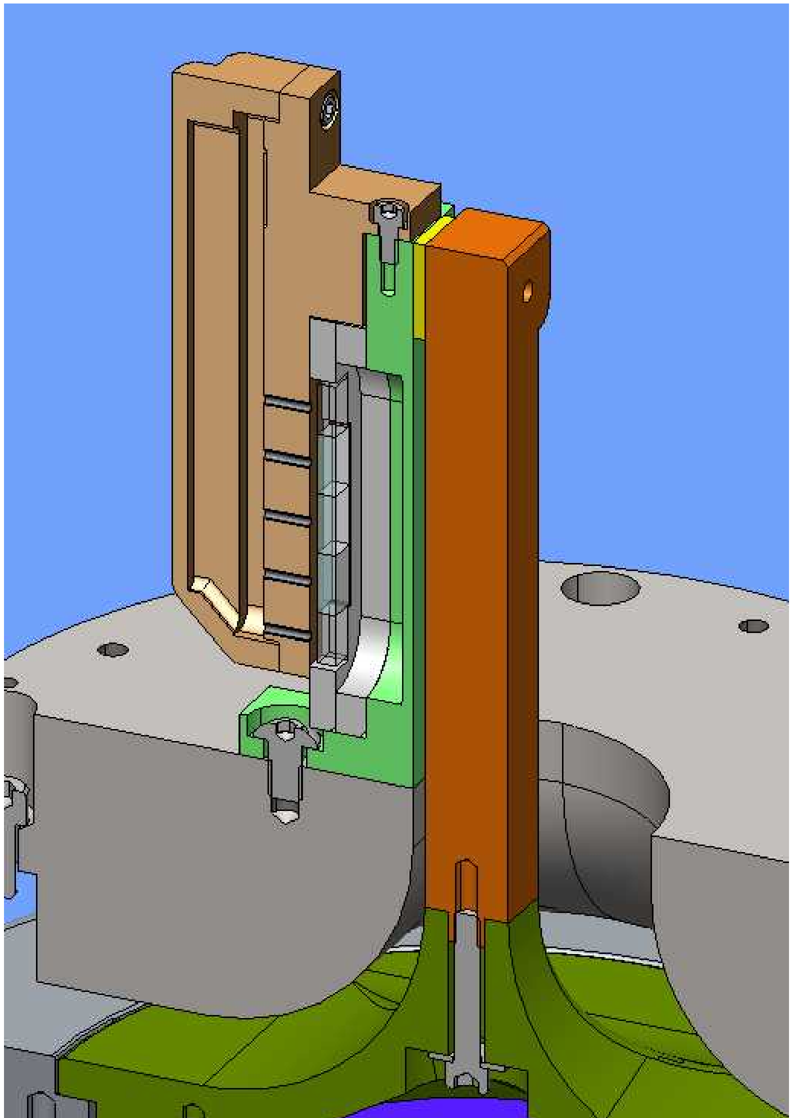
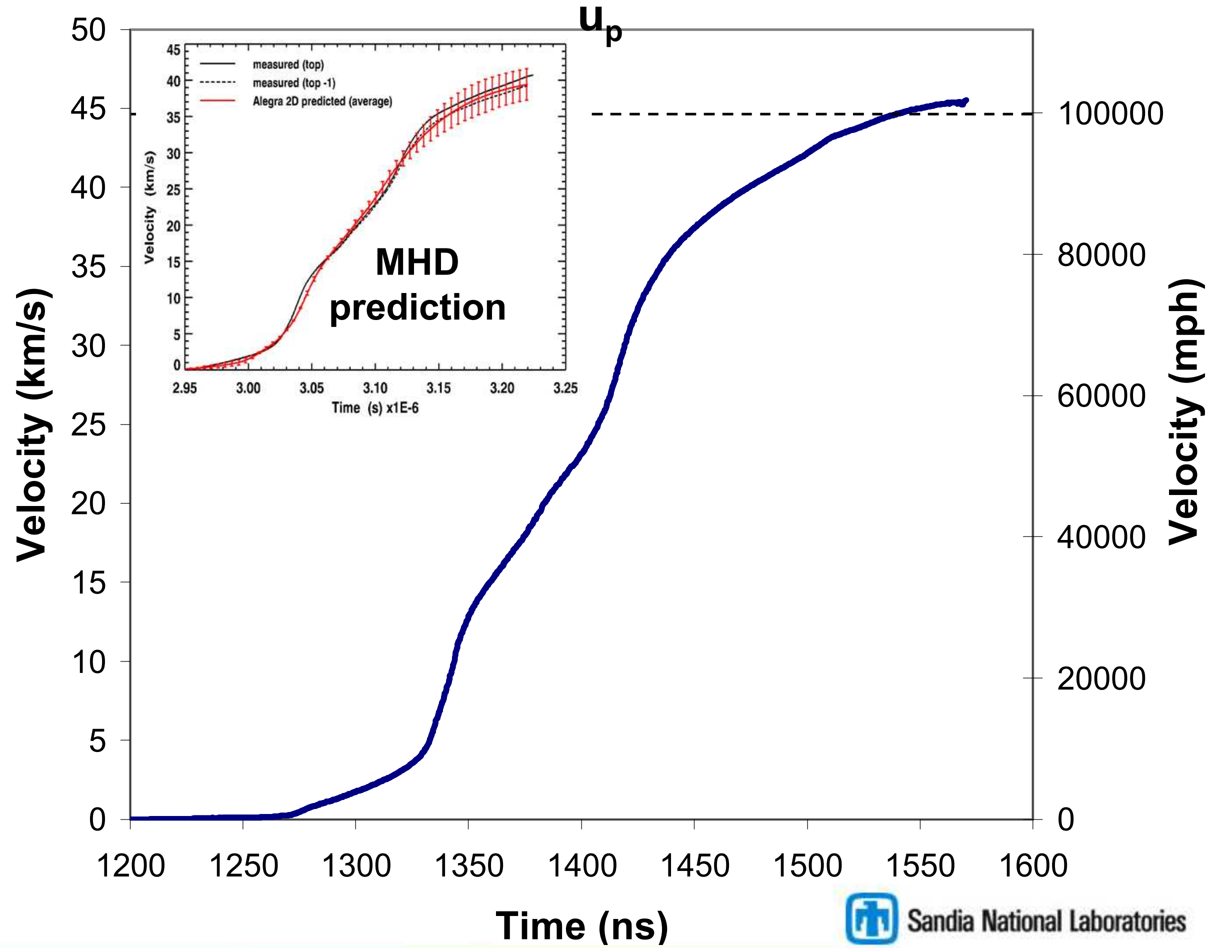
Lemke, et al., J. Appl. Phys. 98, 073530 (2005)

The stripline geometry has enabled flyer plate velocities to exceed 45 km/s (over 100,000 mph)

The flyer velocity on Z has now exceeded 45 km/s – impacts to 41 km/s have generated Hugoniot data for quartz and sapphire to 15.6 and 20.6 Mbar, respectively with ~1% or less uncertainty in U_s and u_p





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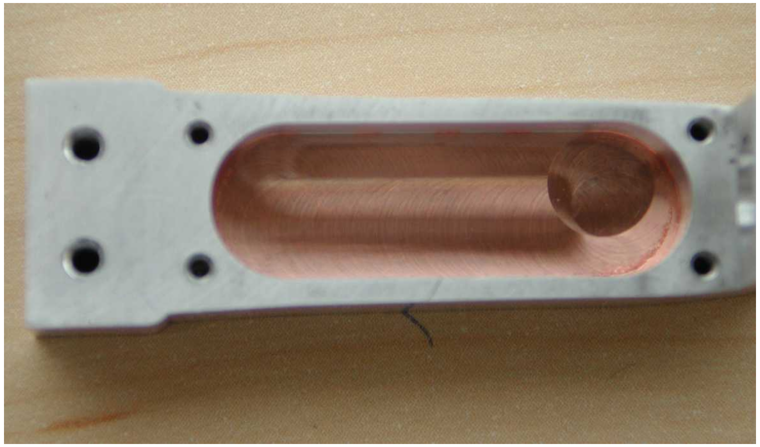
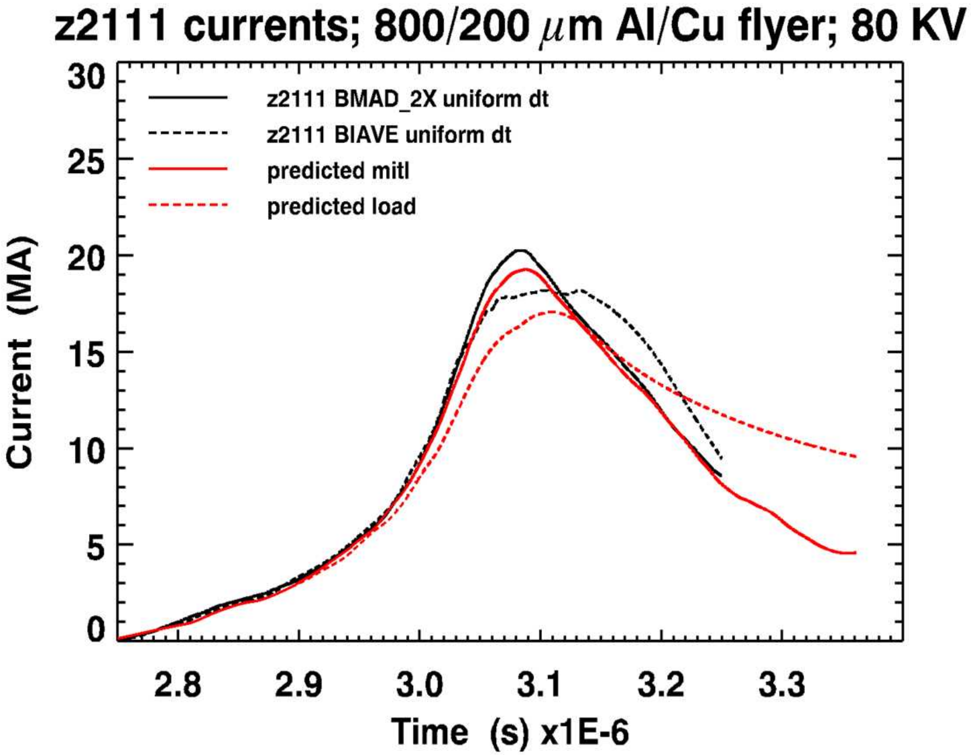
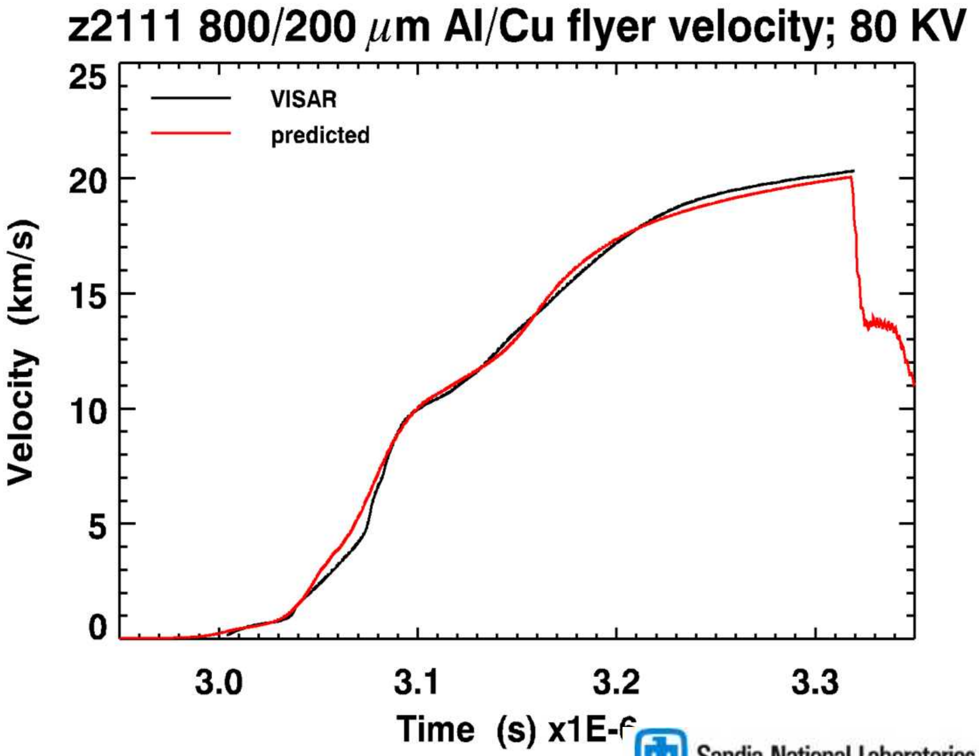
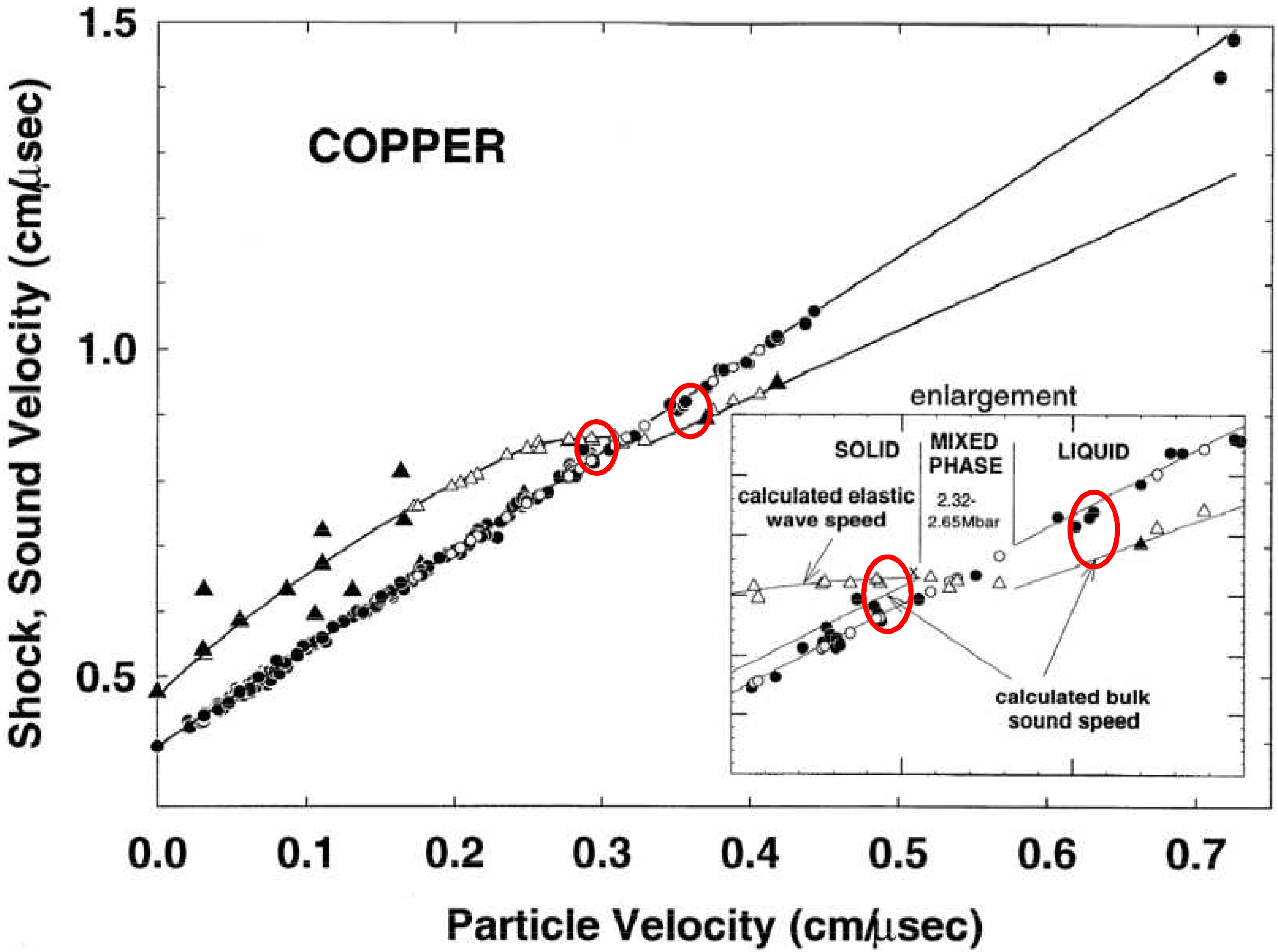
Composite al/cu flyer plates are also being used to provide a well defined loading/unloading





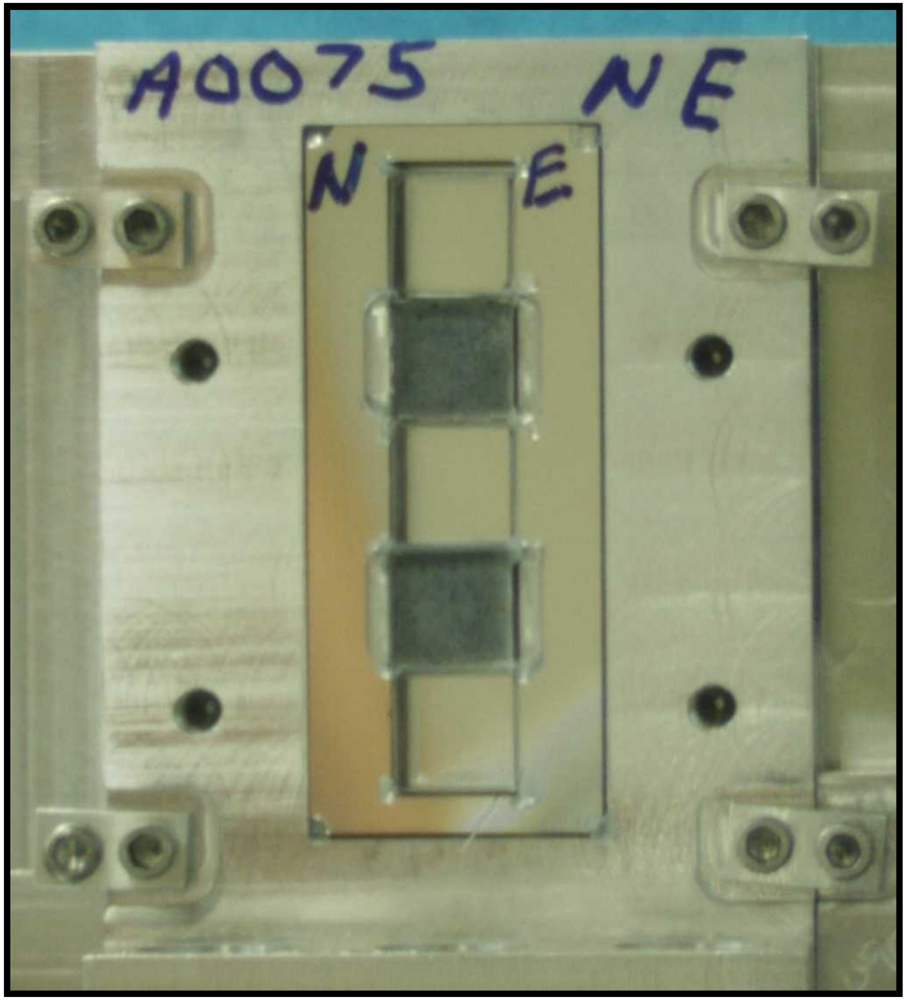


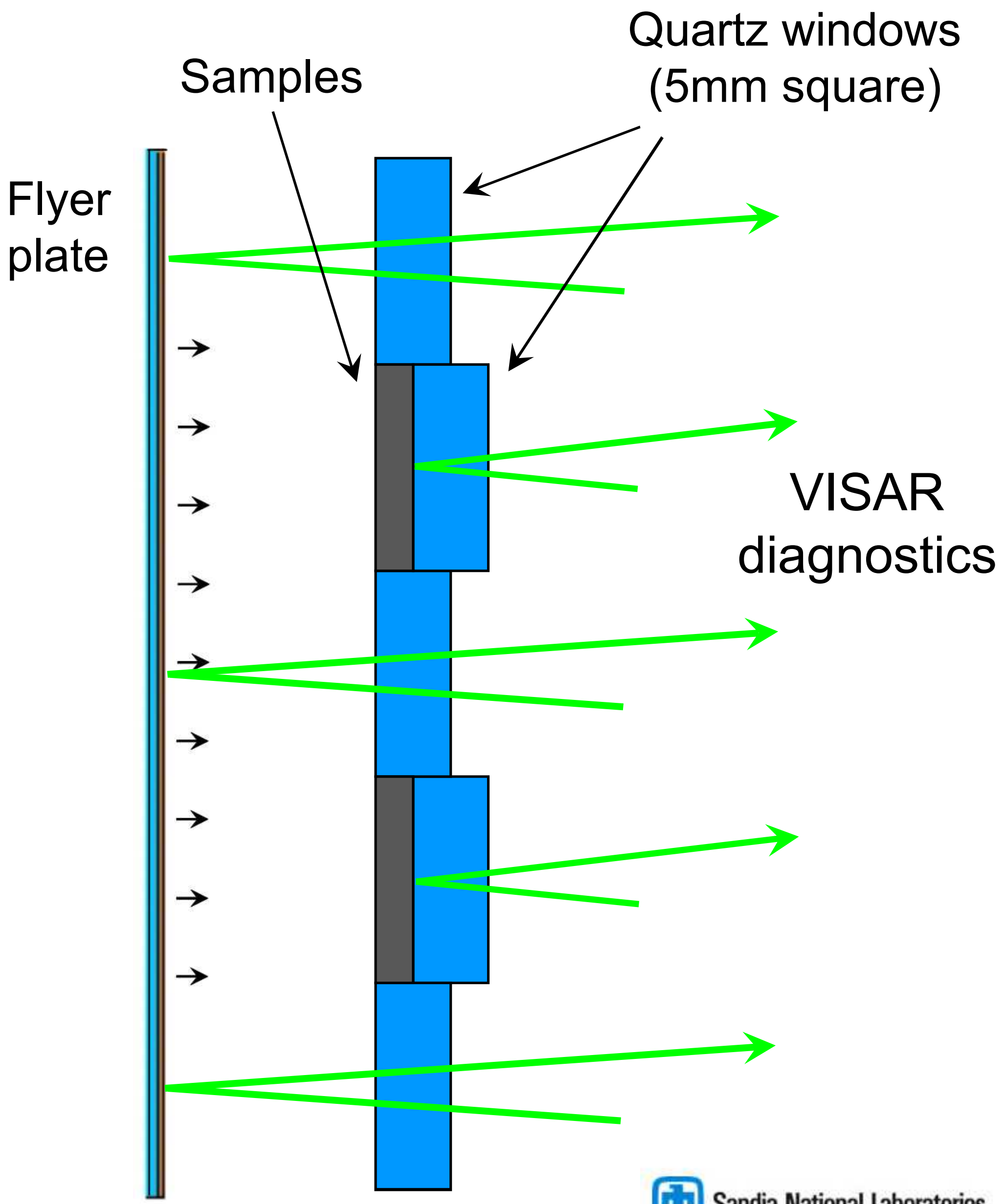
Improved diagnostics are enabling very high fidelity measurements that corroborate flyer plate integrity



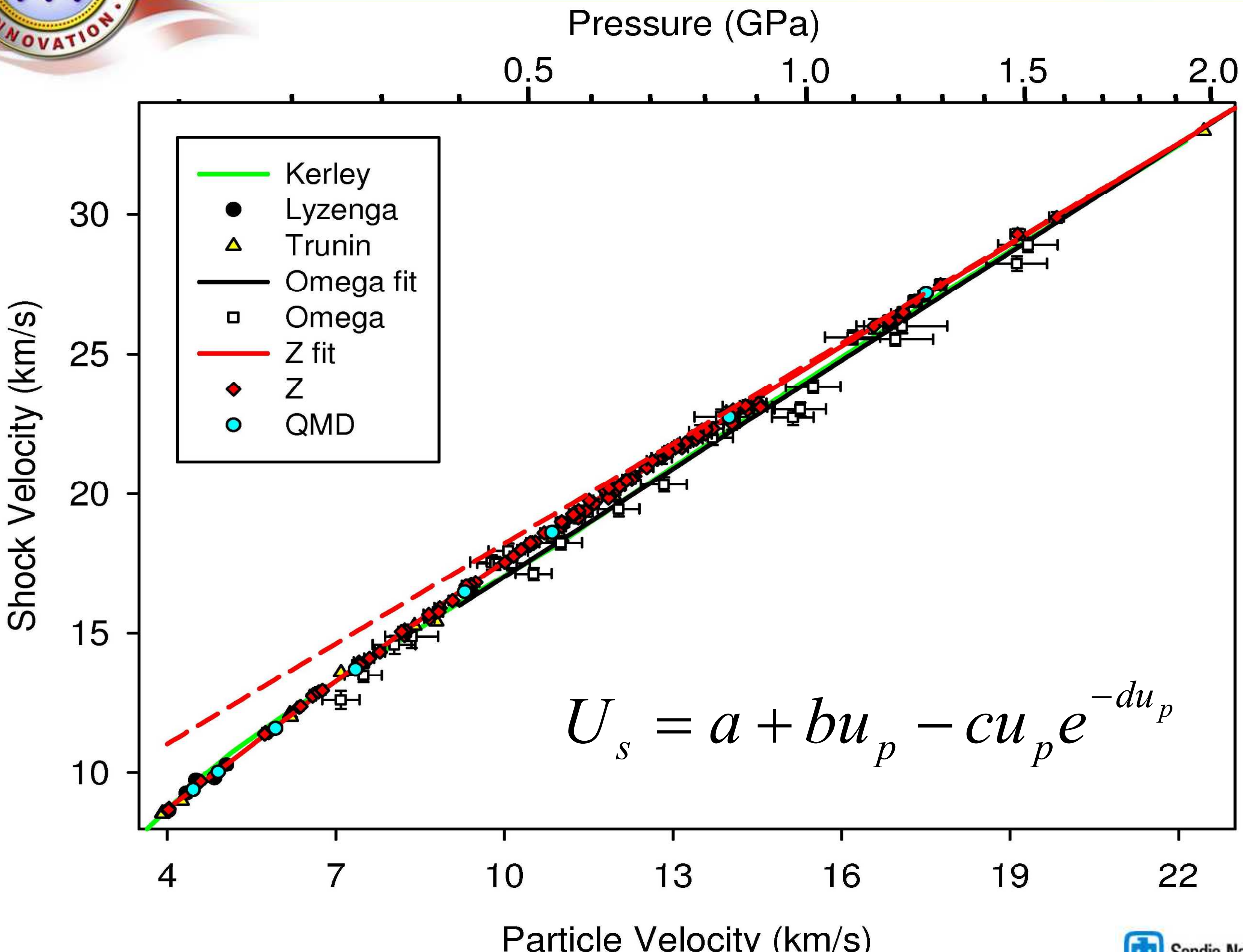
Quartz has been used as a transparent window enabling multiple flyer velocity measurements

Typical configuration





U_s-u_p Hugoniot for α-Quartz − over 200 points



$$U_s = a + bu_p - cu_p e^{-du_p}$$

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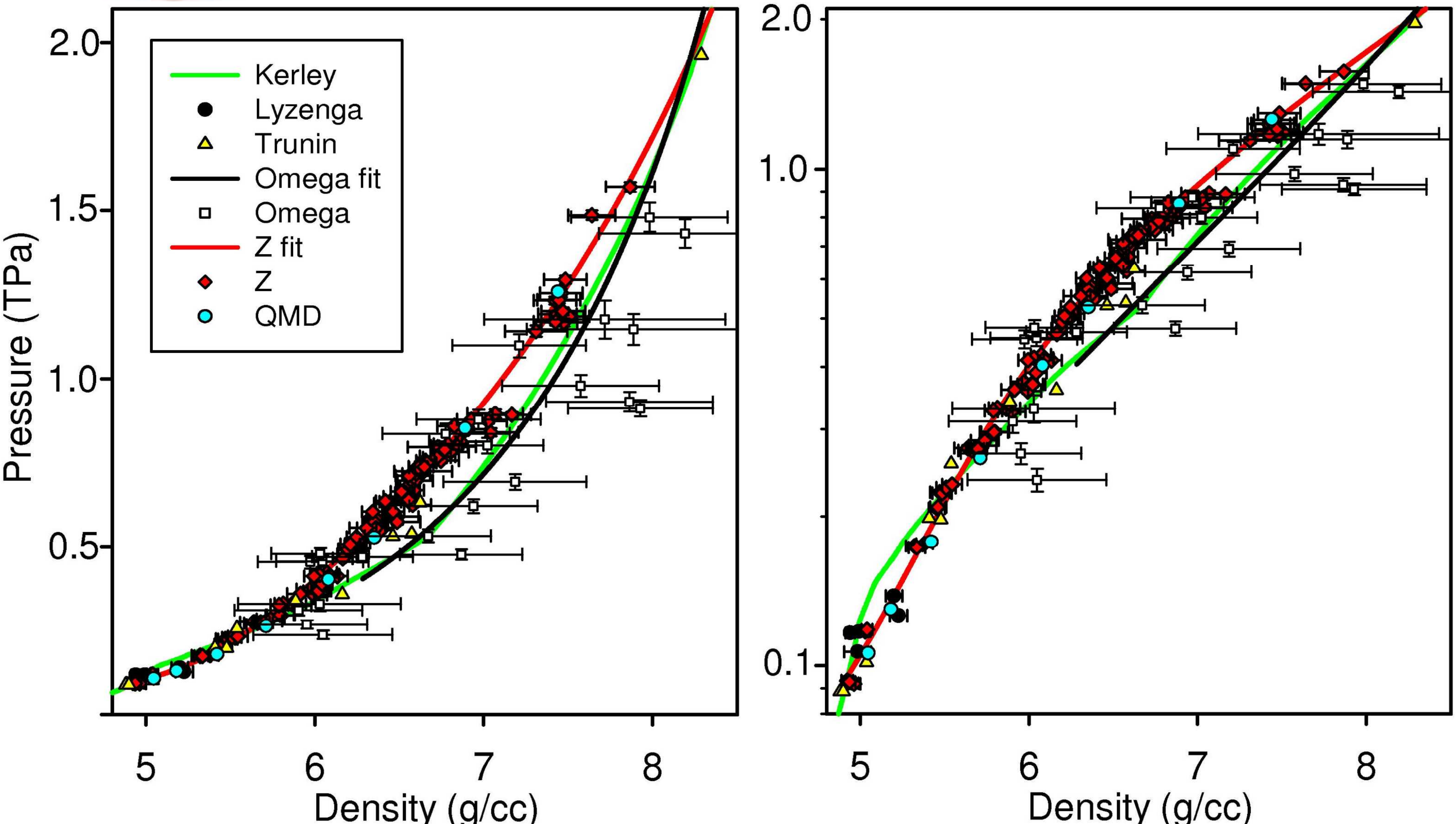
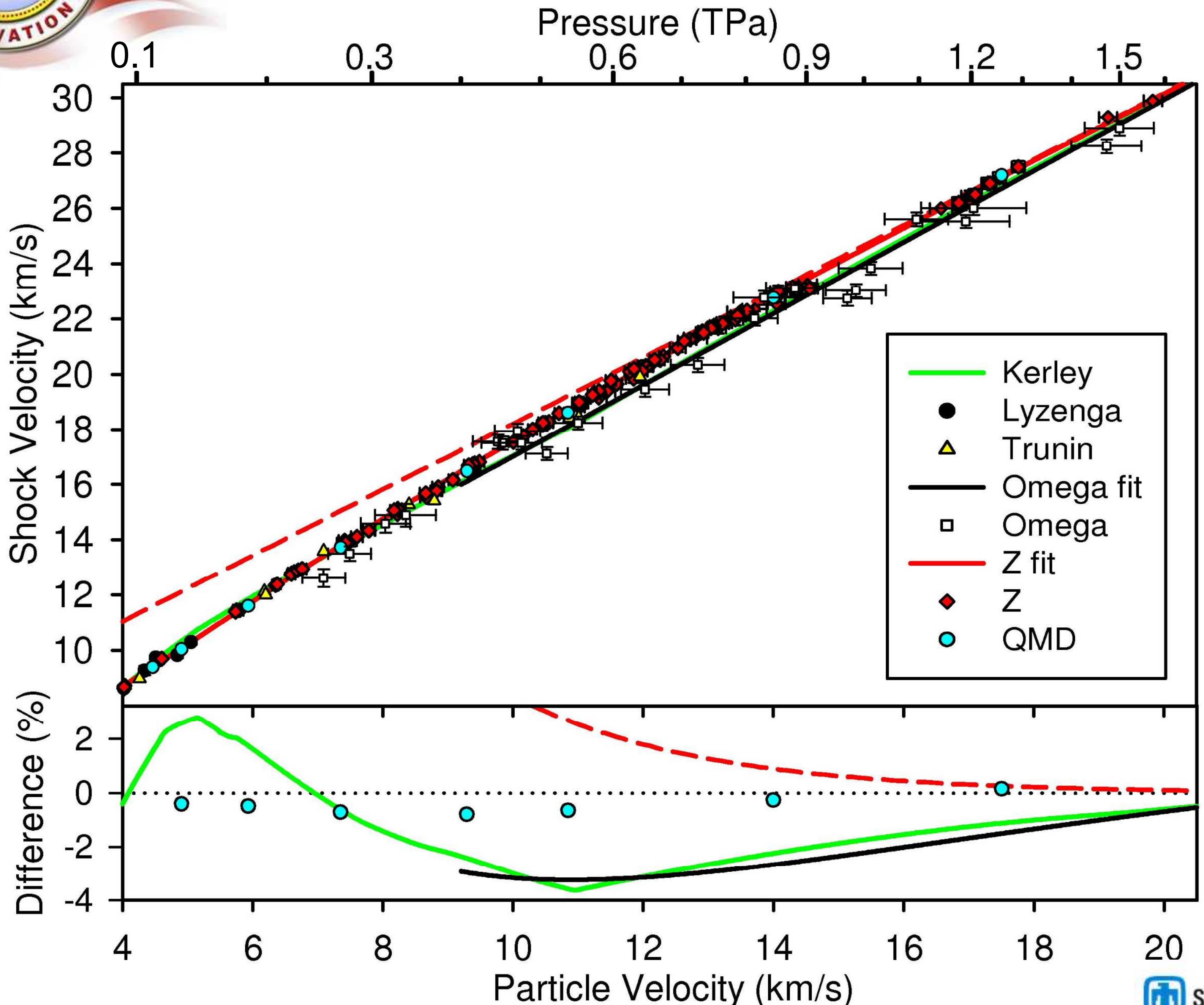
Pressure – density Hugoniot for α-Quartz



Knudson and Desjarlais, PRL 103, 225501 (2009)

U_s residuals with respect to the Z-fit indicate dissociative effects extend to ~10 Mbar pressure



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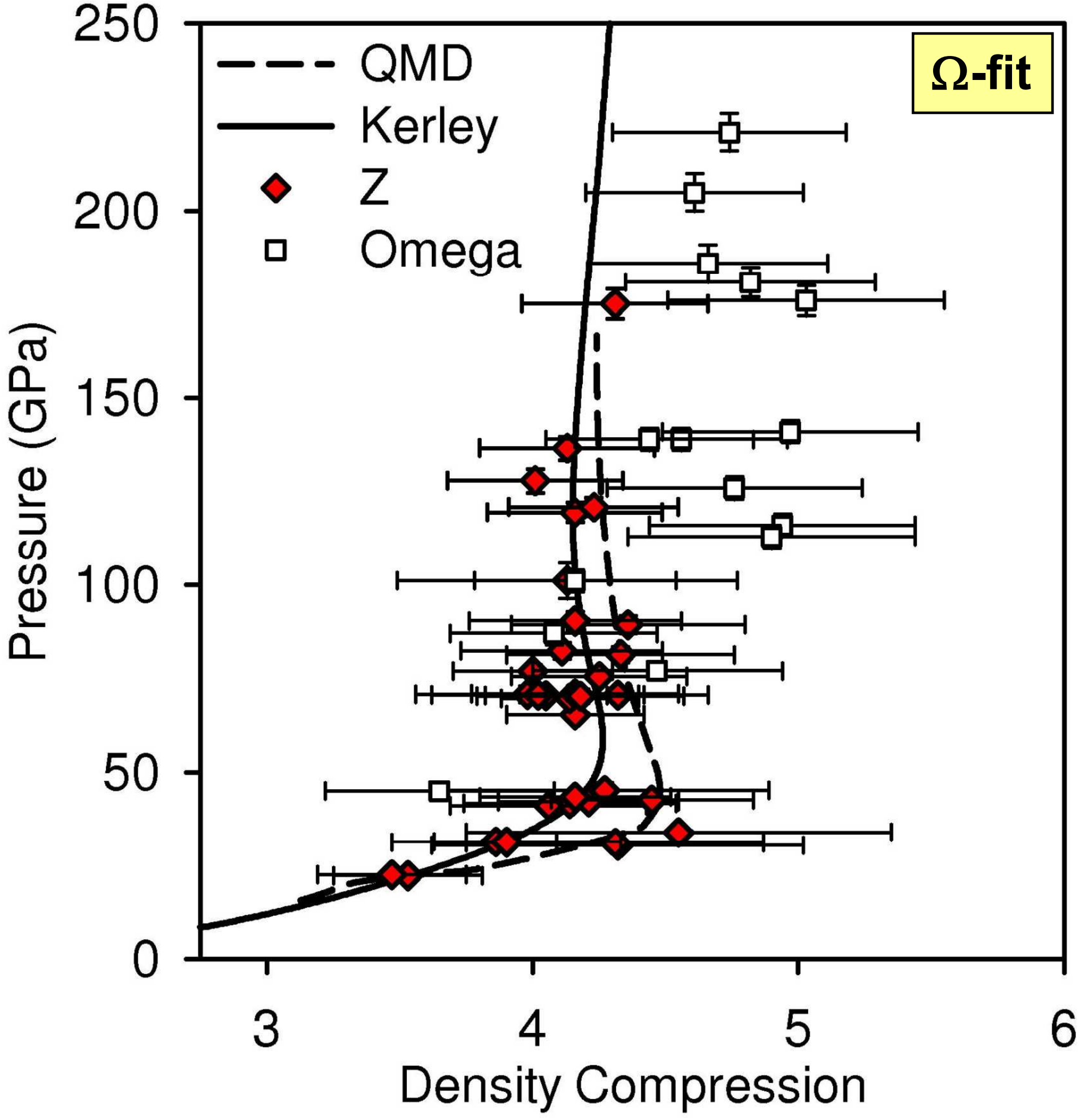
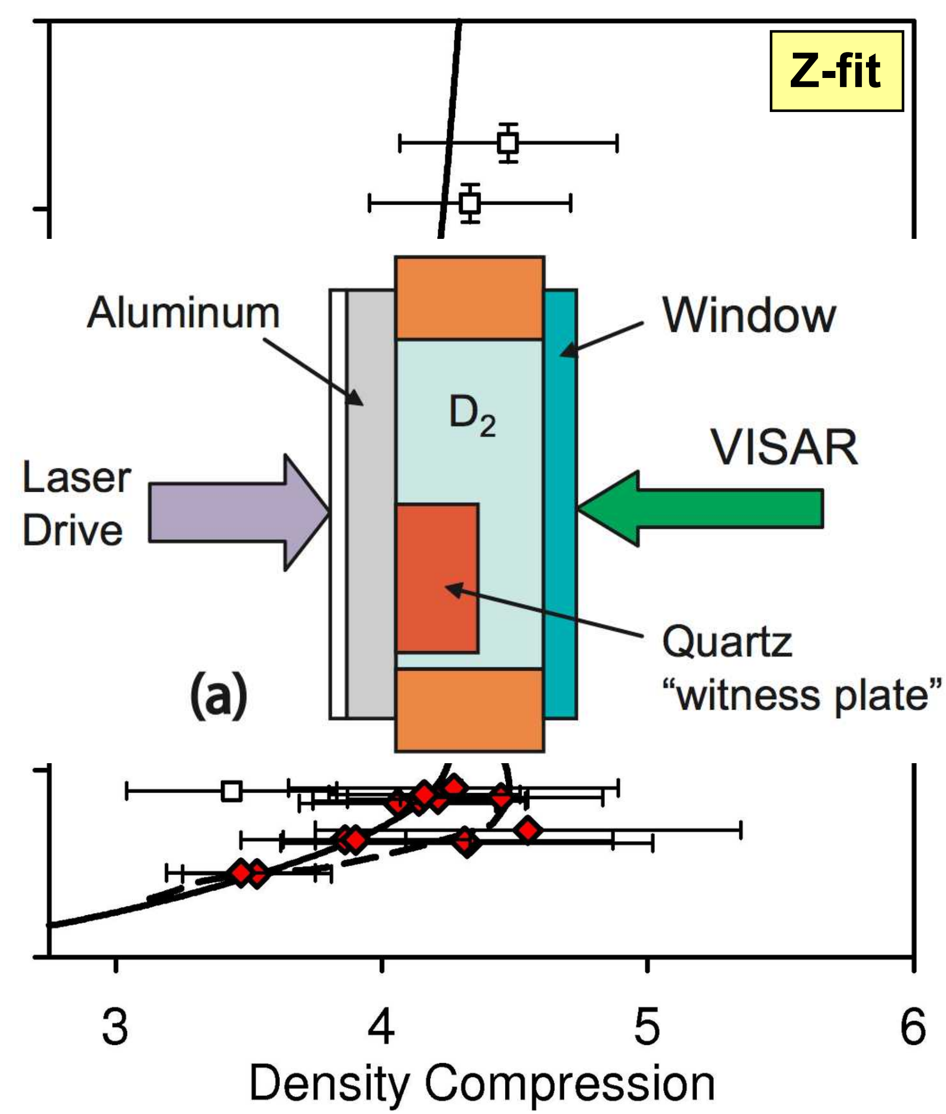
Recently published deuterium data becomes significantly stiffer upon reanalysis





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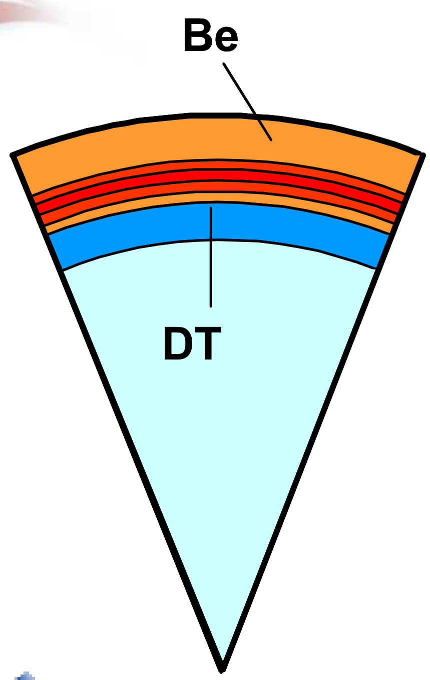
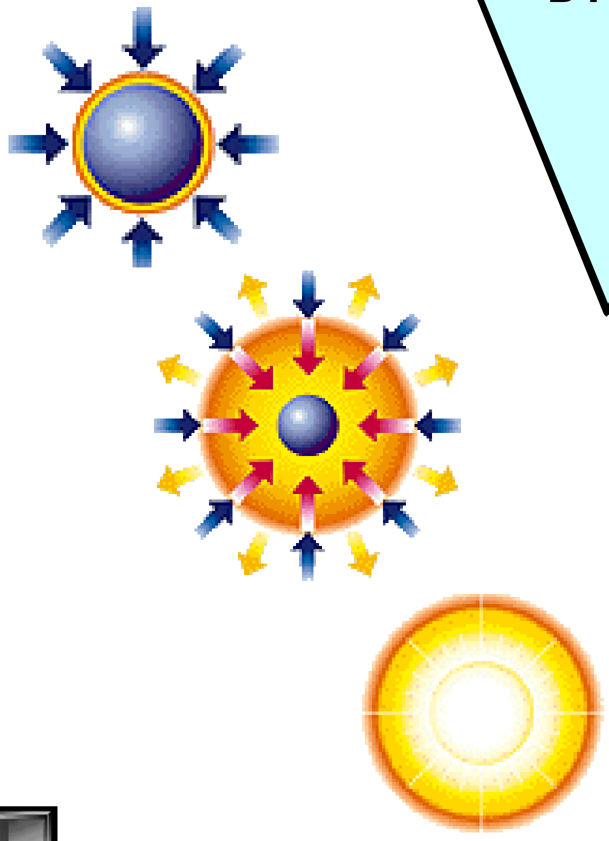
Beryllium and diamond melt studies performed in support of the National Ignition Campaign (NIC)

300 eV graded-doped Be design:

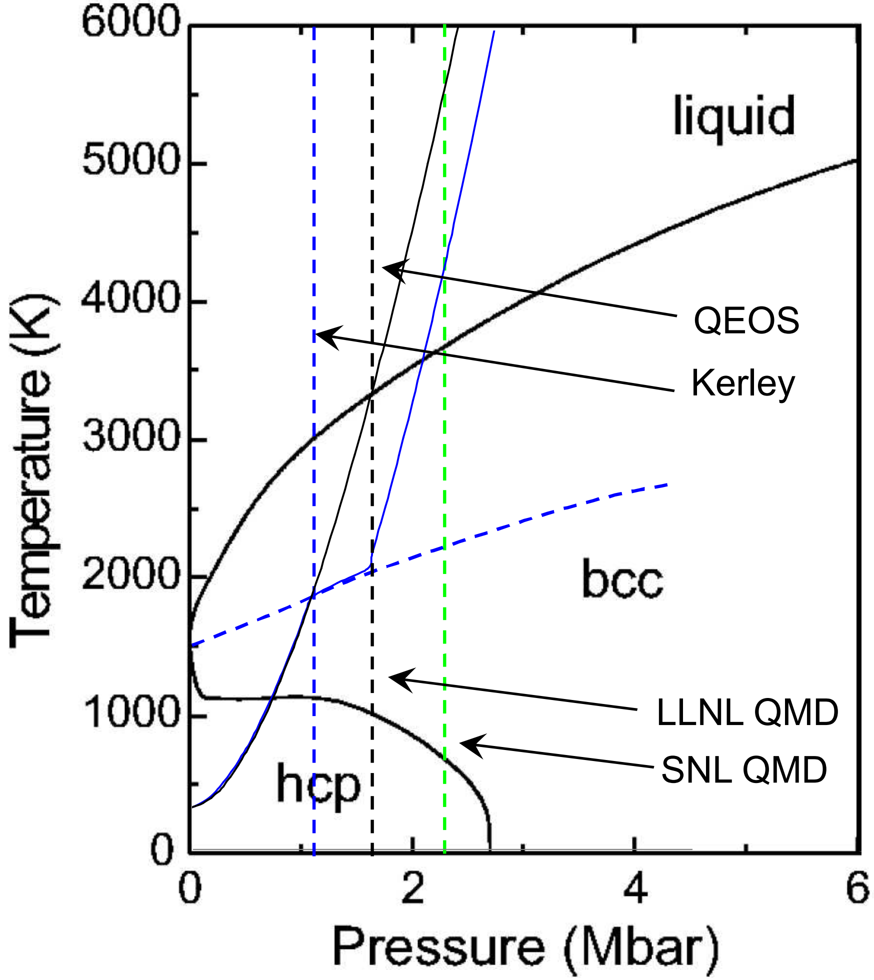




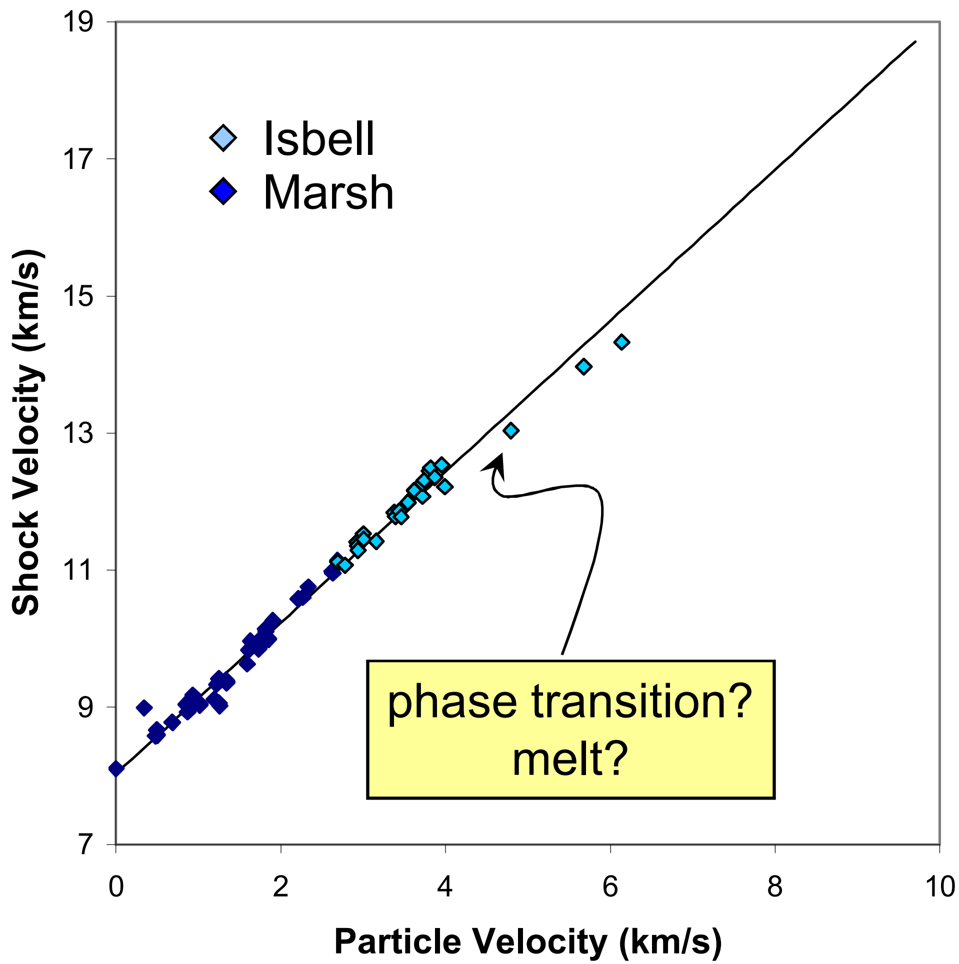
- Beryllium and diamond are being considered as ablator materials for ICF capsules
- Capsule implosion is an inherently unstable process
- Goal is to avoid any heterogeneities that may seed instability growth during implosion
  - Understanding the melt properties of the ablator material is critical
- CVD grown, polycrystalline diamond samples supplied through LLNL (both microcrystalline and nanocrystalline)
- Diamond studies resulted in a request for a delay in the shutdown for the Z upgrade

Previous scarcity of data for Be above ~95 Gpa and melt properties along Hugoniot poorly understood

Be Phase Diagram



Be Hugoniot



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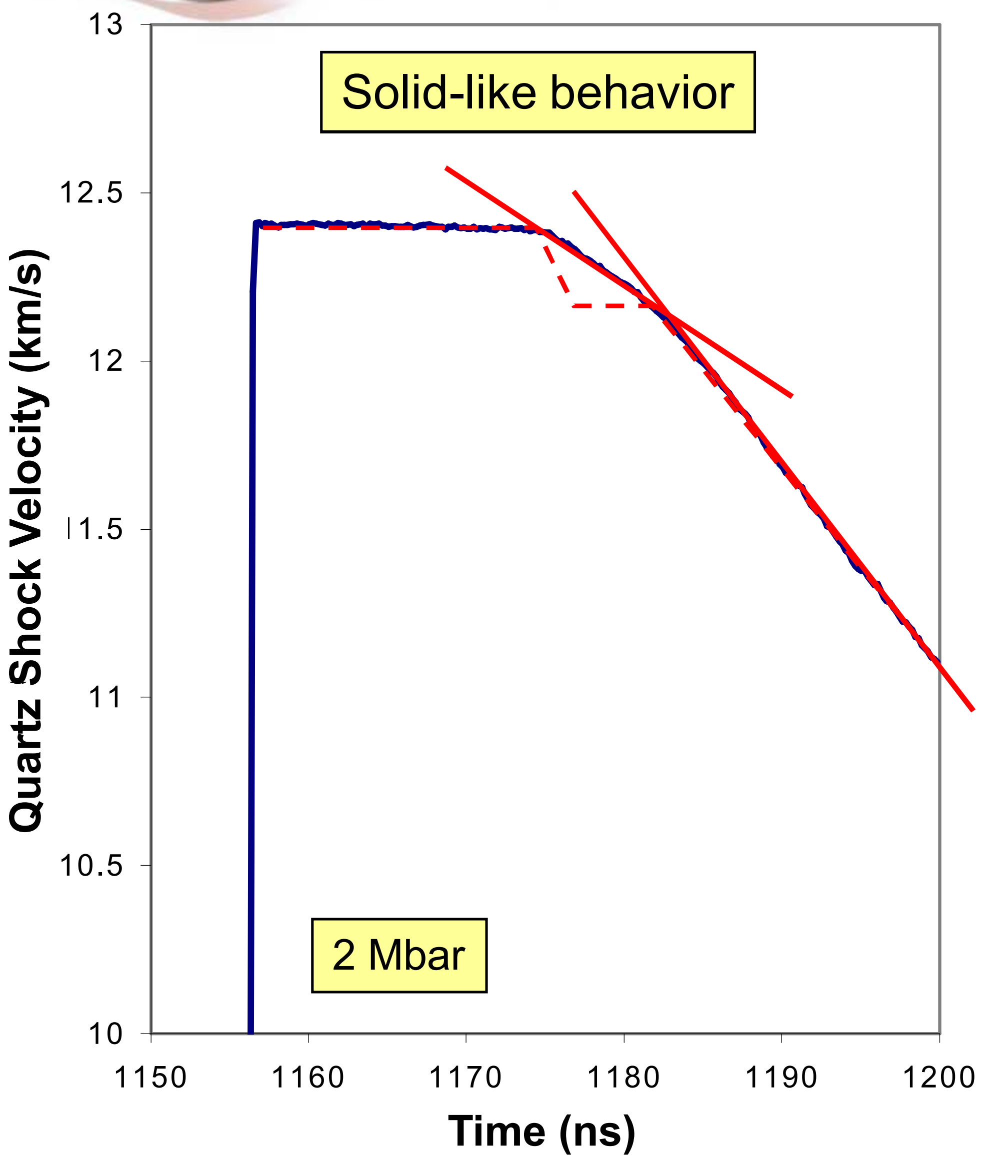
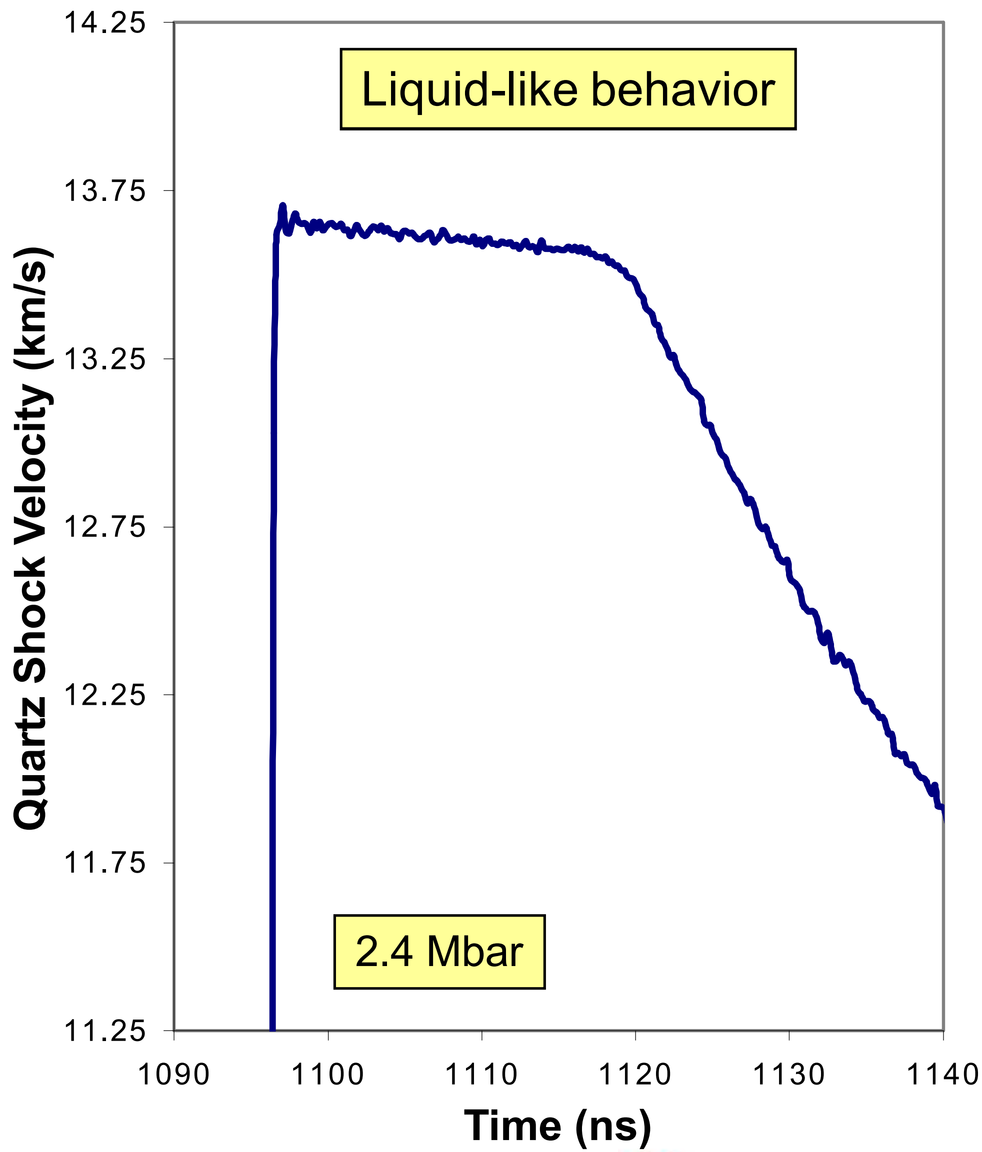
Experiments clearly show solid-like behavior at low stresses and a liquid-like behavior at higher stress





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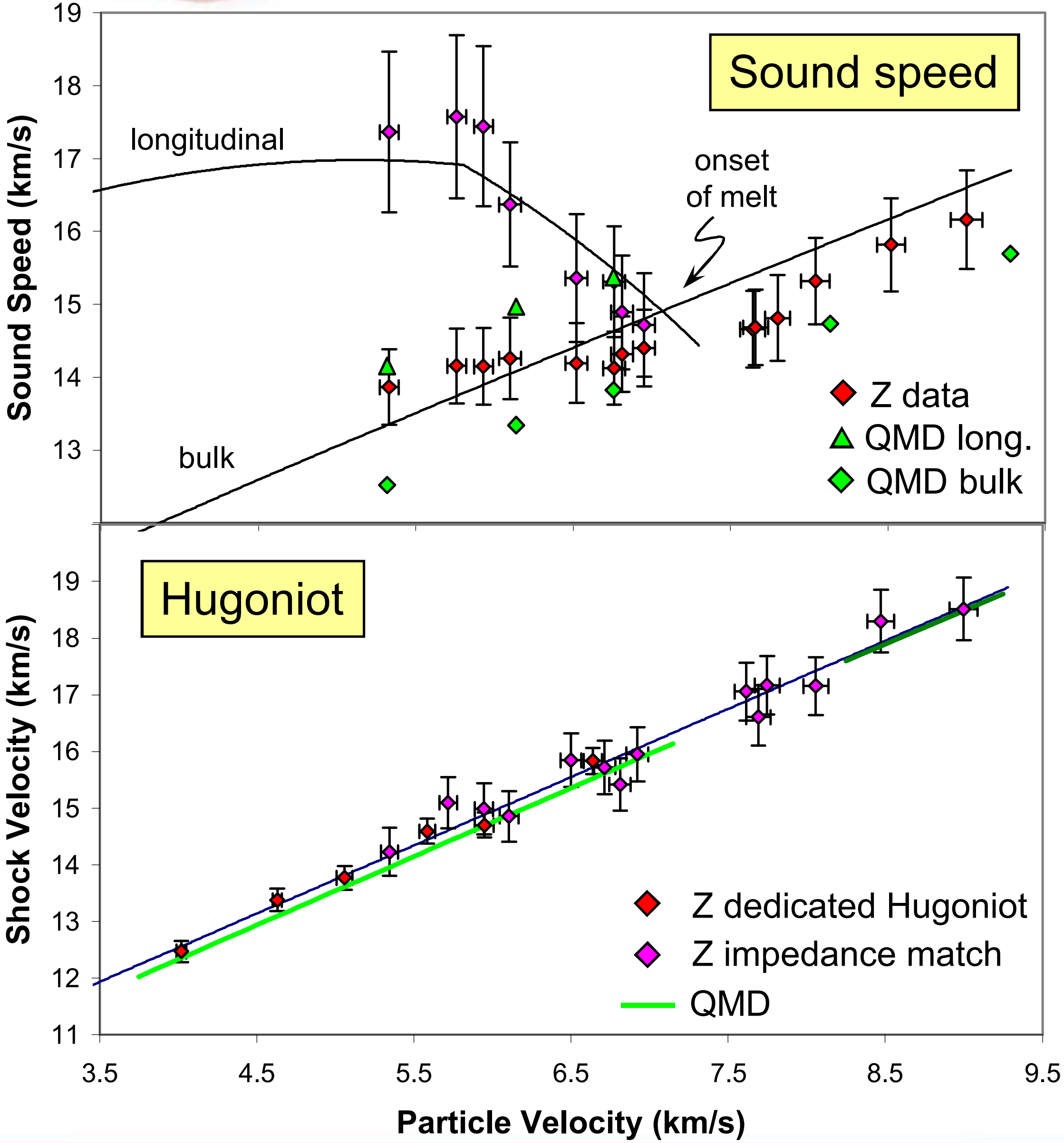
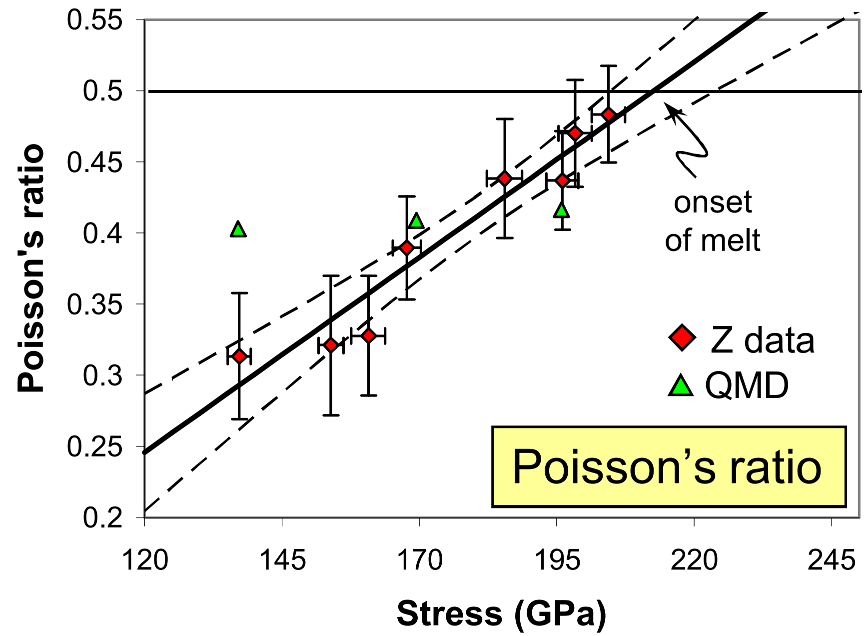
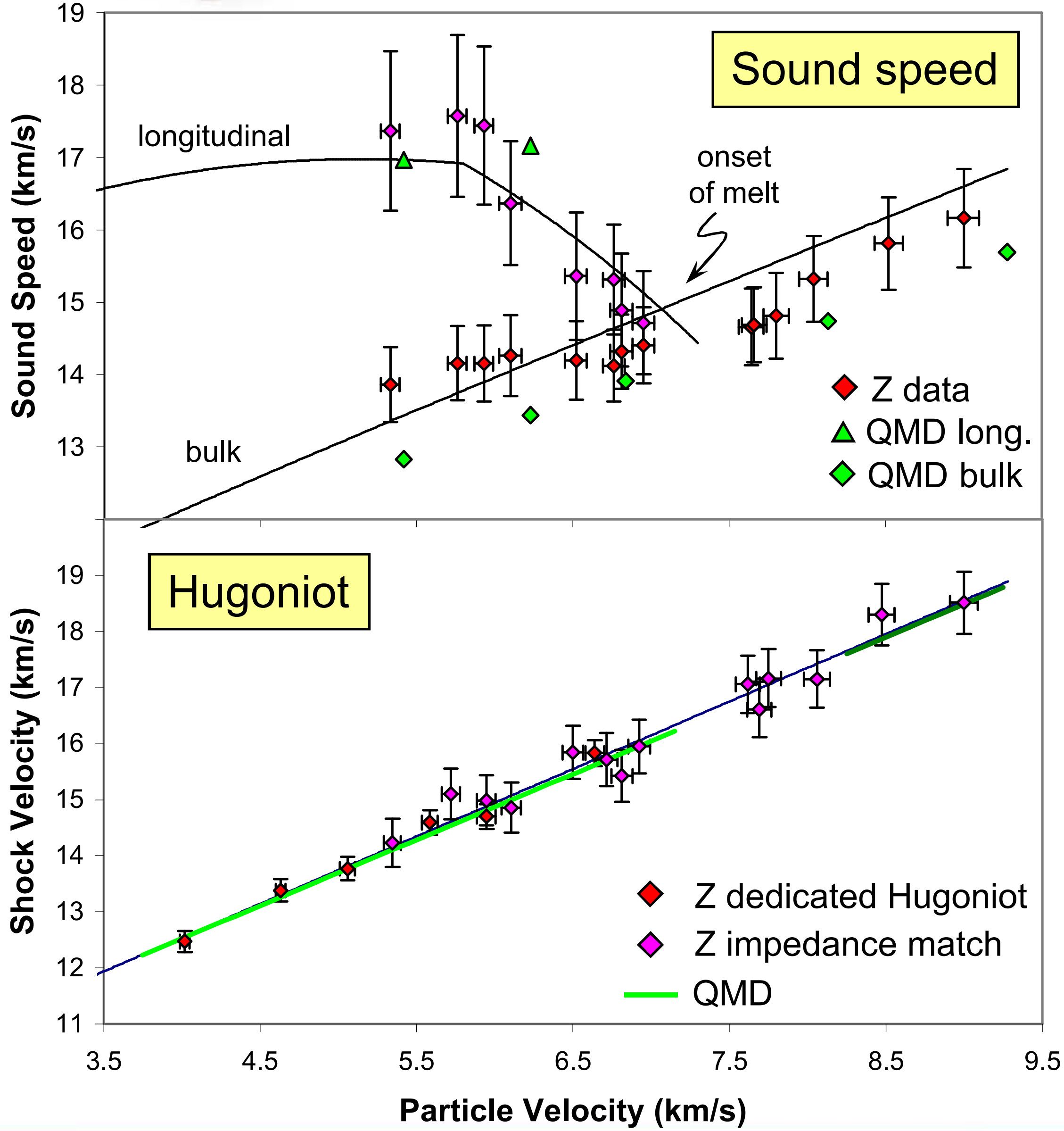
Comparison of Hugoniot and sound speed measurements with QMD calculations for bcc Be

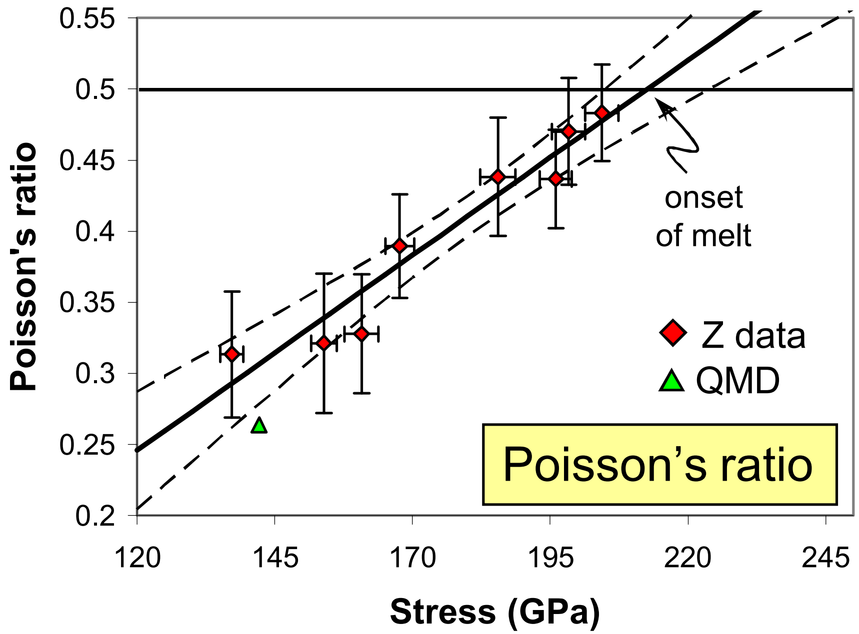




- QMD bcc Hugoniot appears systematically soft relative to experiment
- QMD bulk sound speed in decent agreement with experiment
- QMD longitudinal sound speed significantly low relative to experiment

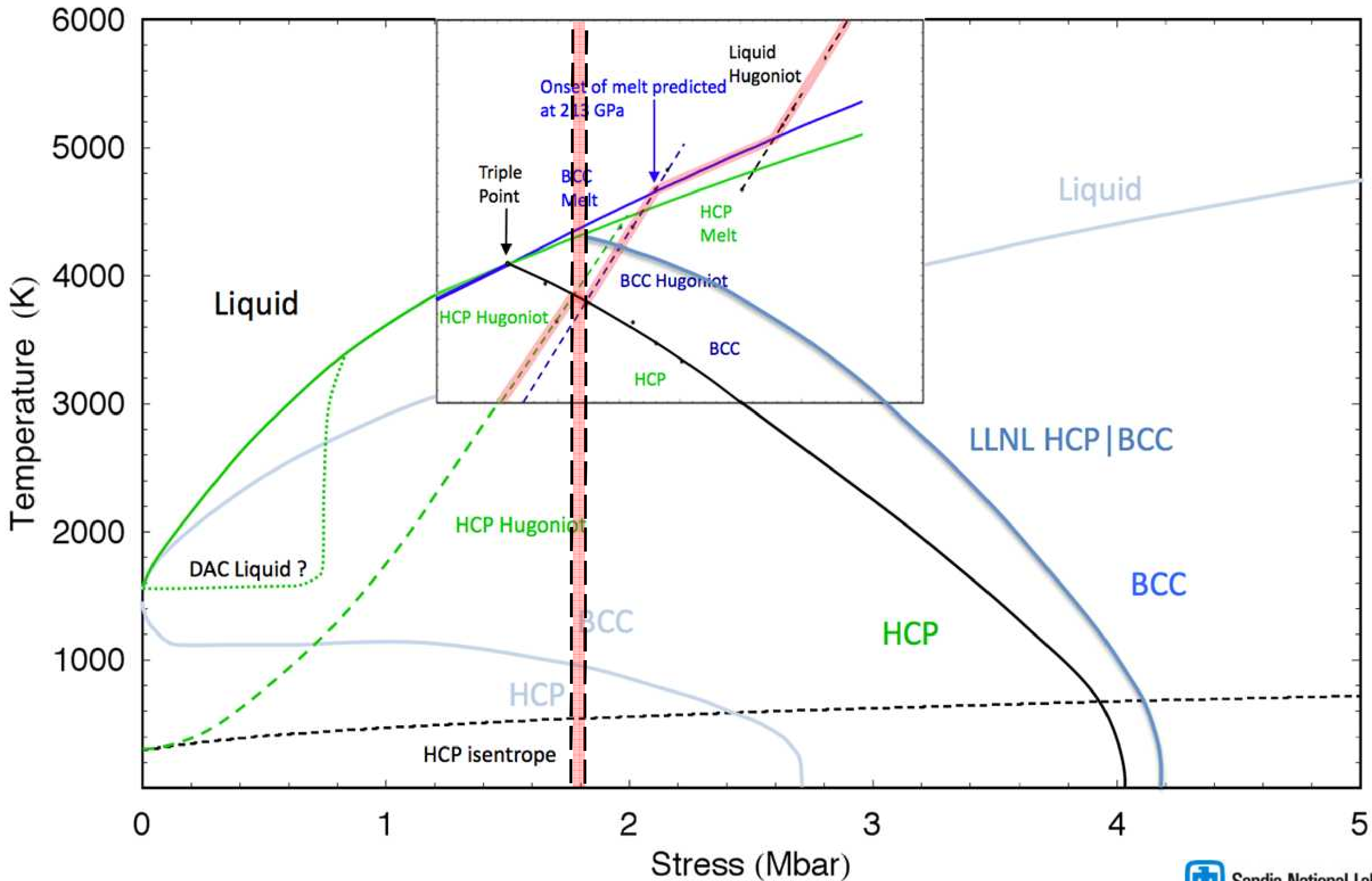
Comparison of Hugoniot and sound speed measurements with QMD calculations for hcp Be





- QMD hcp Hugoniot in better agreement with experiment
- QMD bulk sound speed in decent agreement with experiment
- QMD longitudinal sound speed in much better agreement with experiment

Further QMD study suggests a new picture for the phase diagram of Be and an hcp-bcc transition



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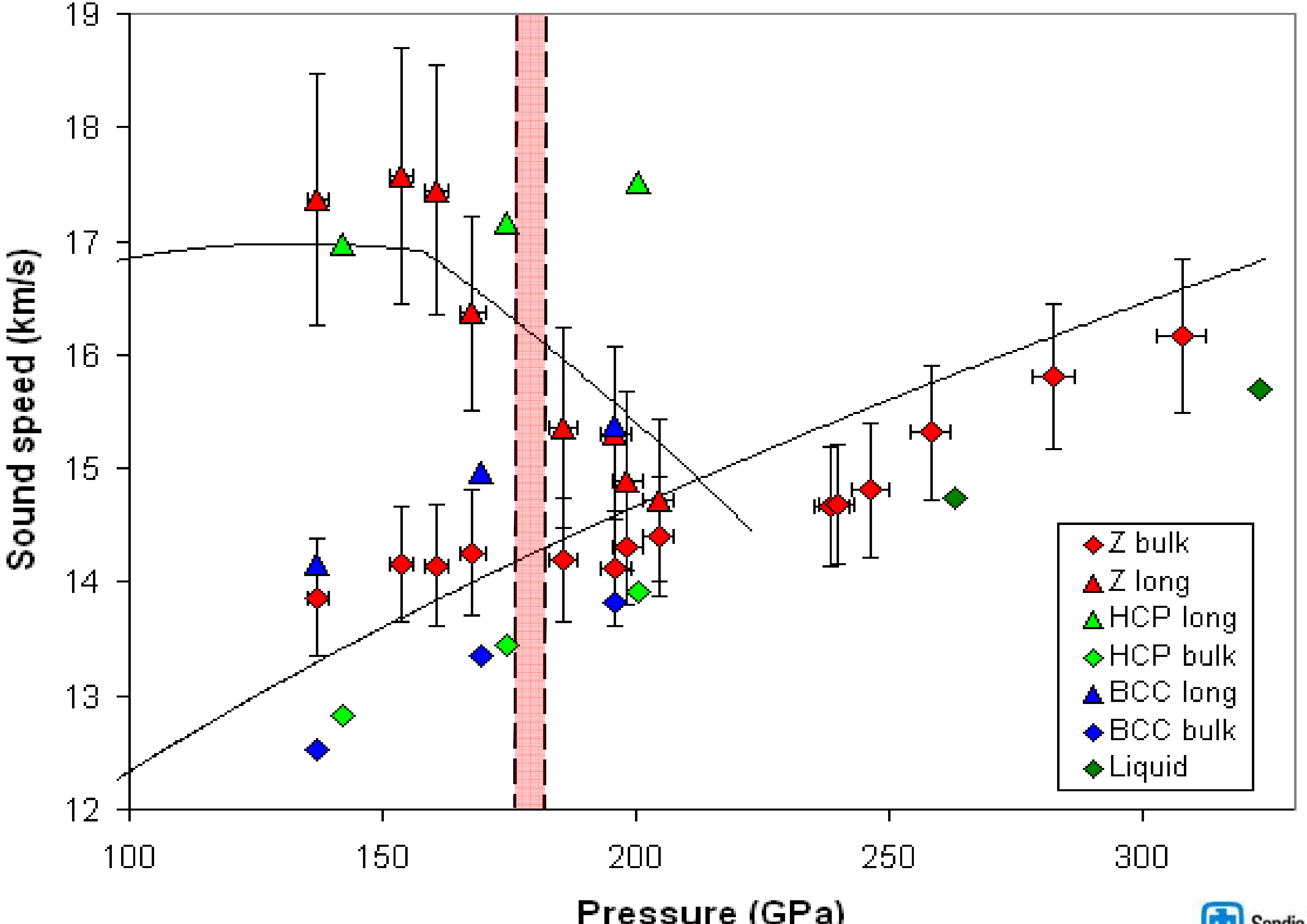
Z data is consistent with the prediction of an hcp-bcc transition just before melt on the Hugoniot



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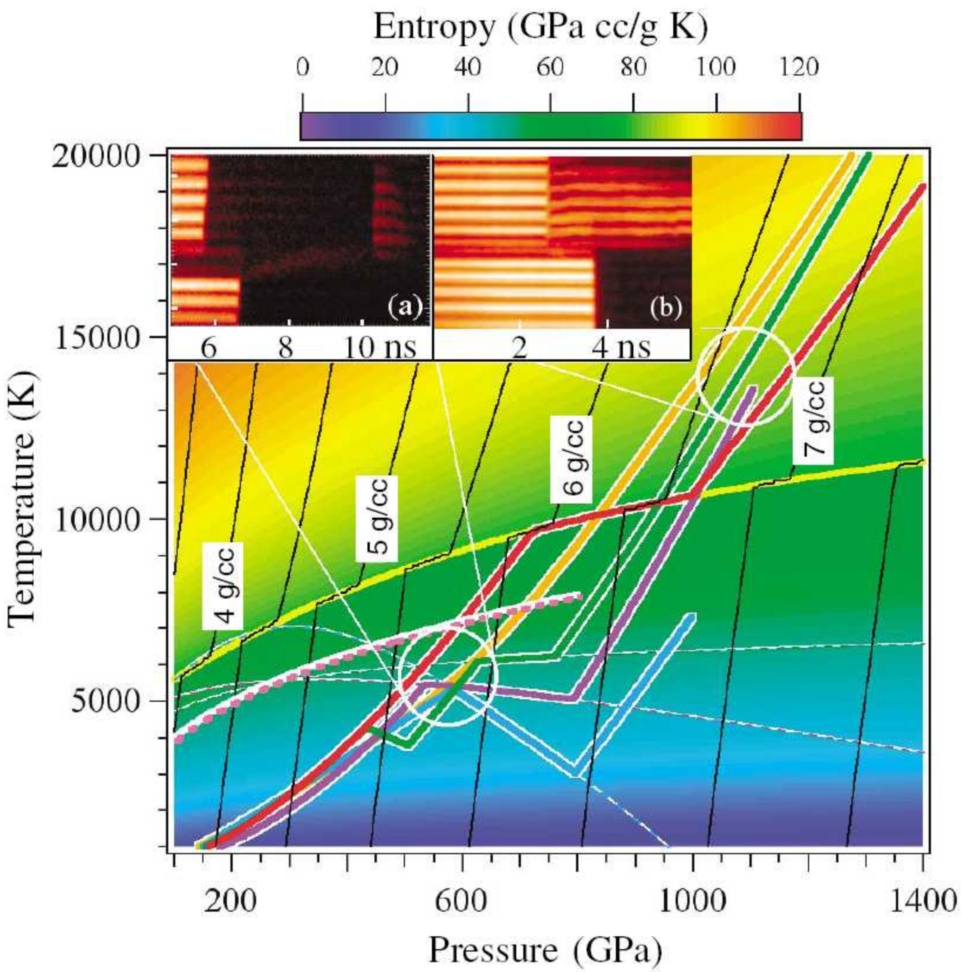
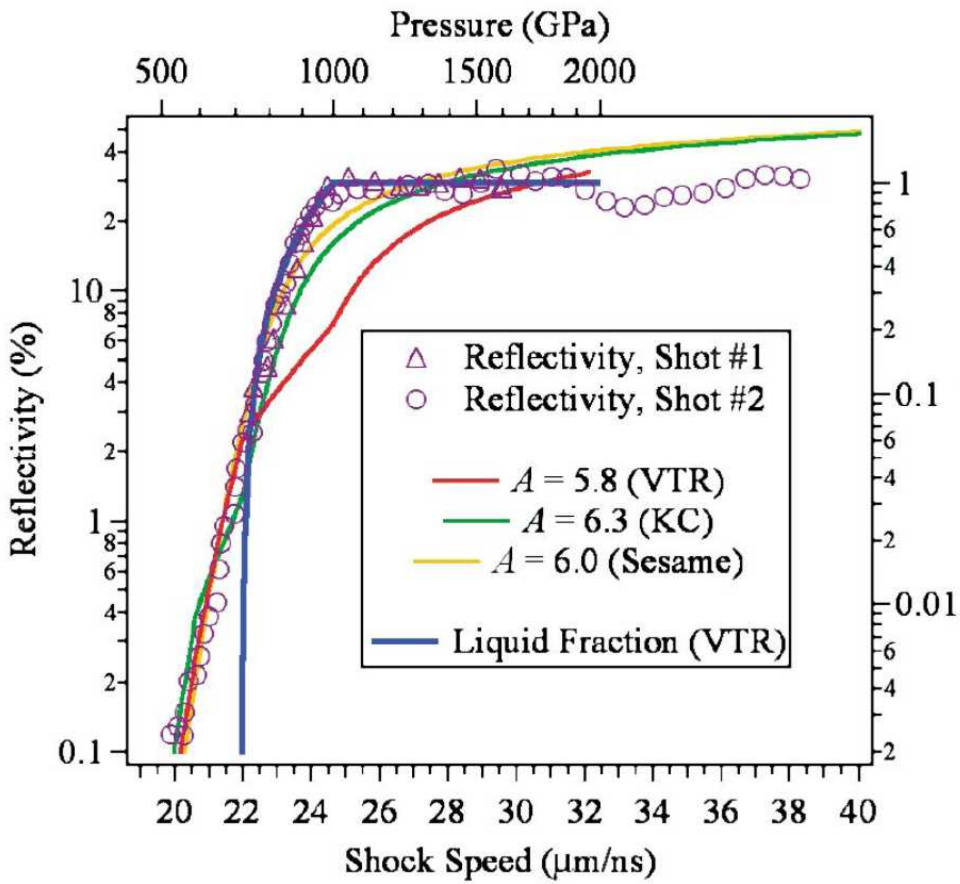
Existing models for diamond exhibit a broad range of predicted melt behavior – melt poorly understood

Several chemical picture models for diamond



Reflectivity study on Omega suggests complete melt near 1100 GPa



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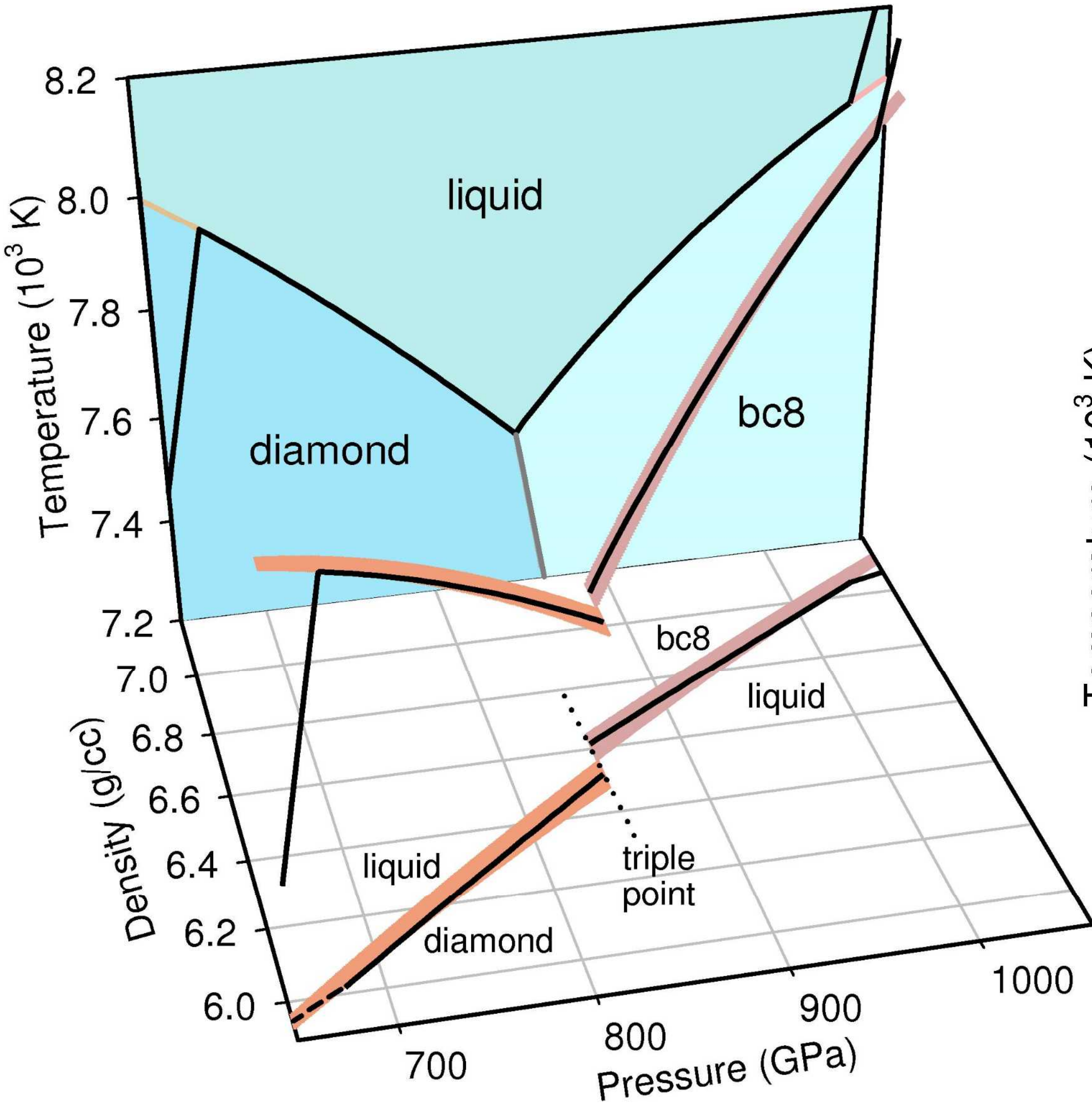
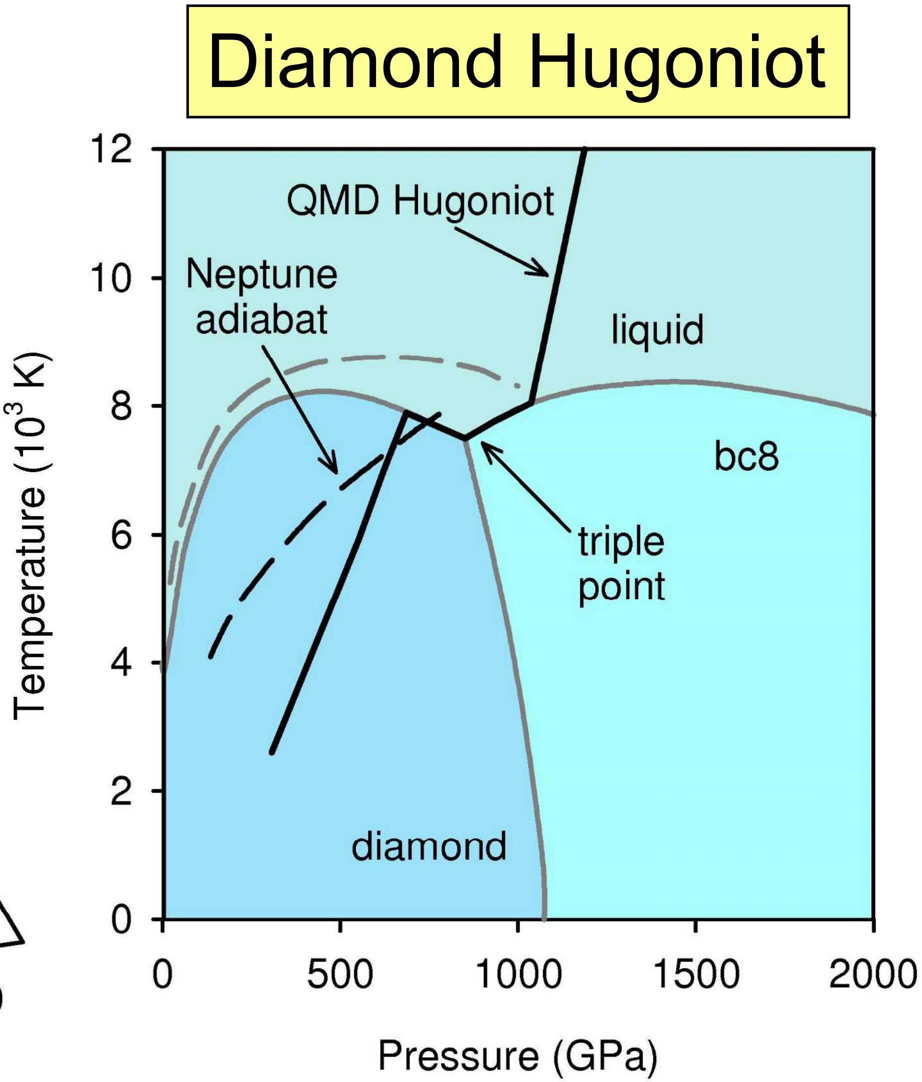
QMD calculations provided estimates for melt and predicted a triple point along the Hugoniot





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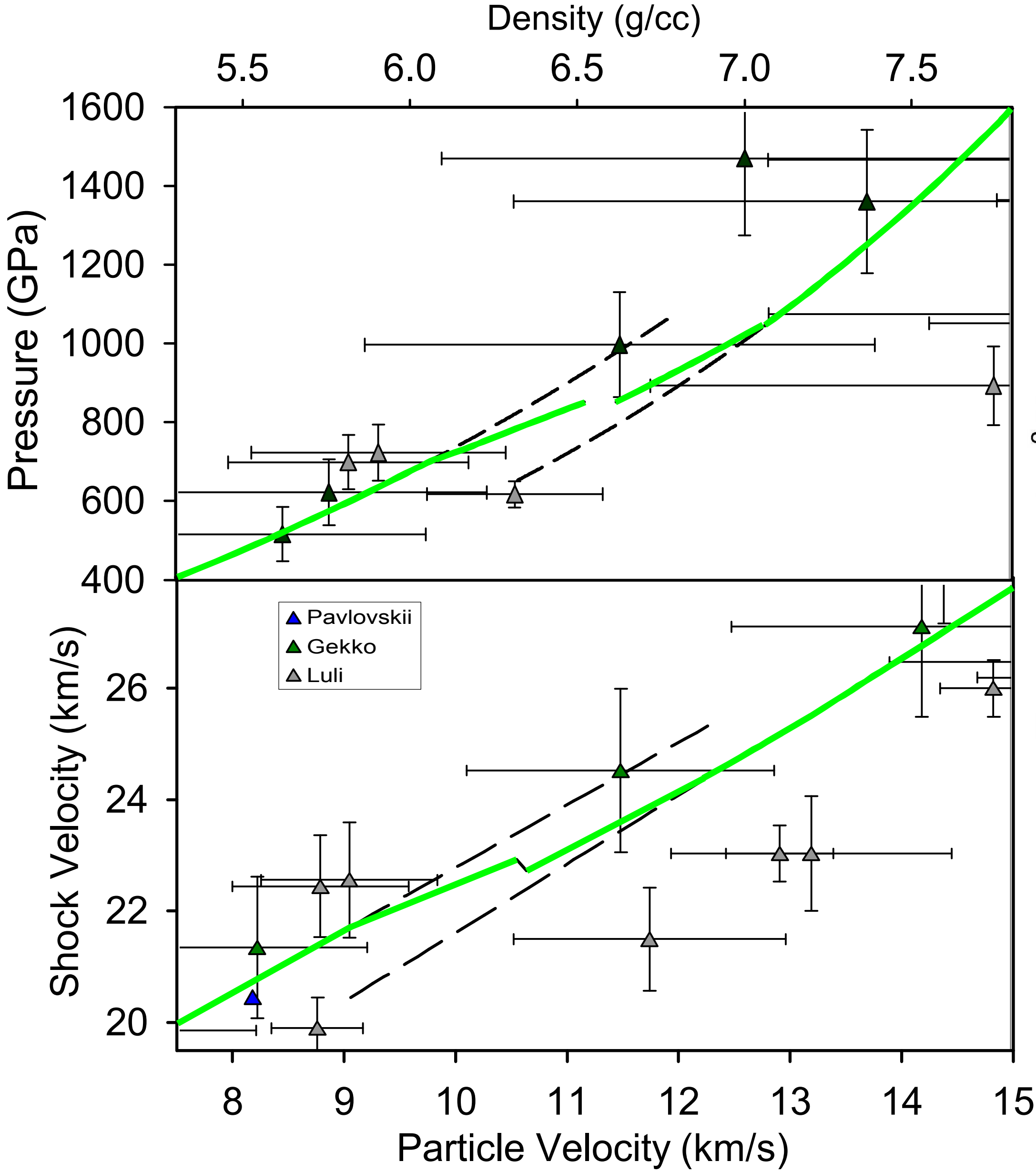
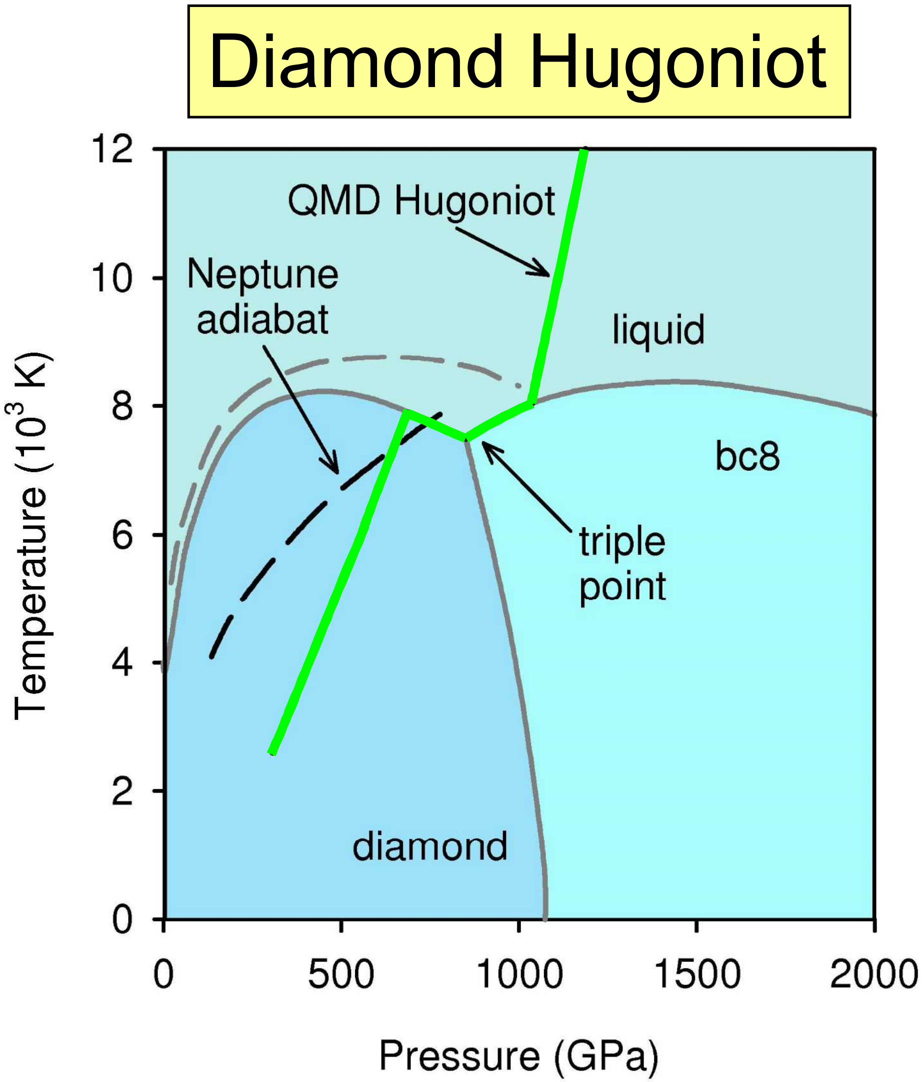
The proposed TP is manifest on the Hugoniot by significant changes in compressibility





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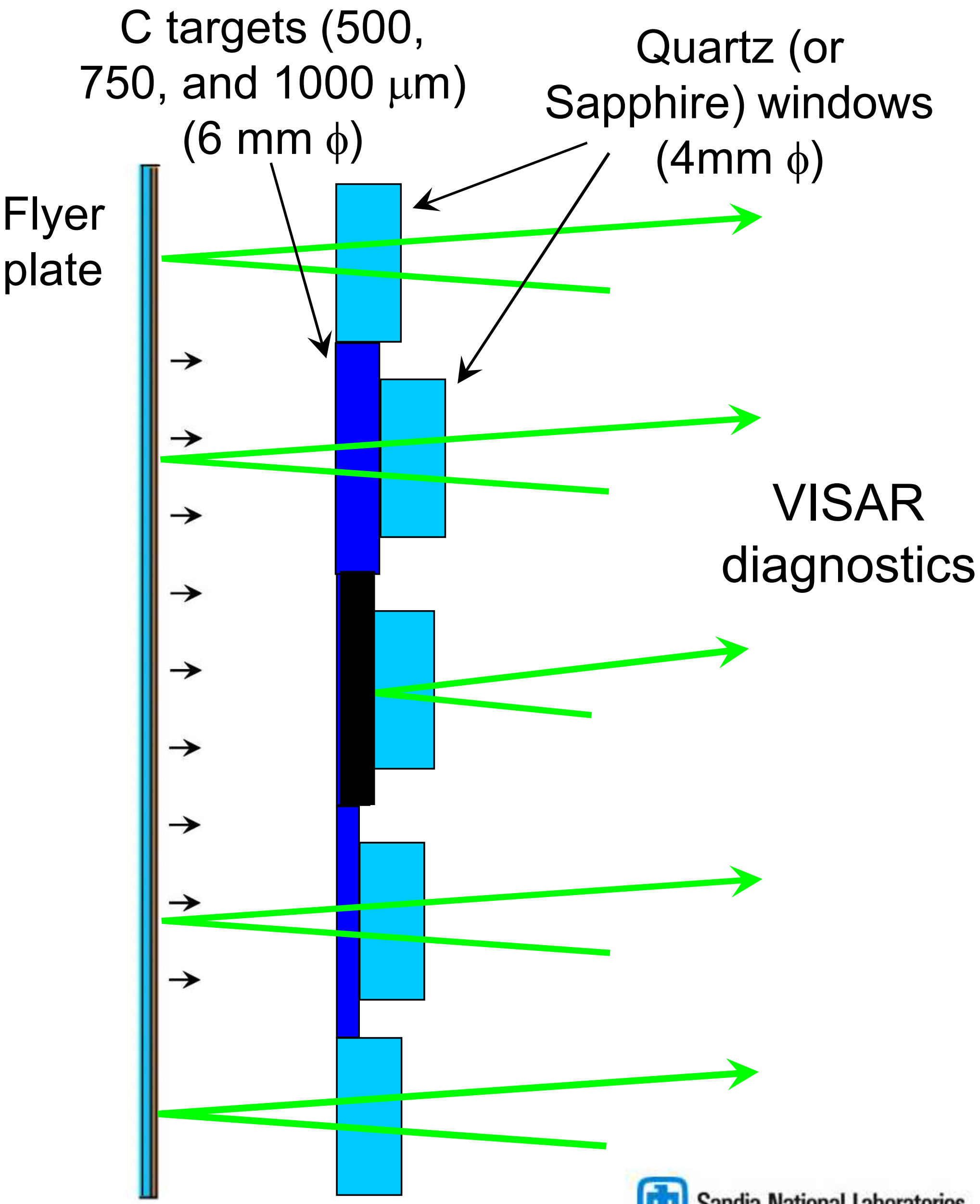
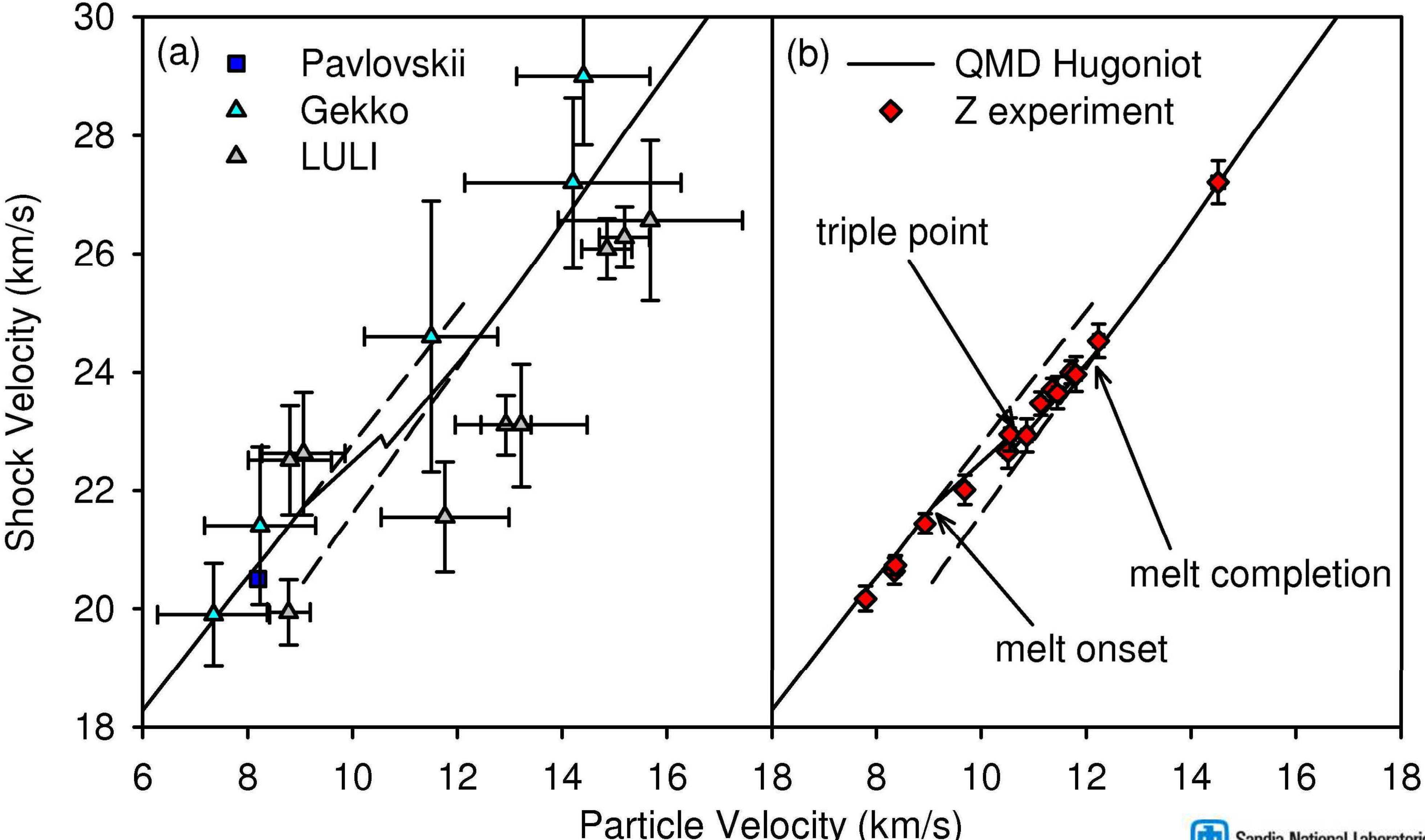
Relatively large flyer plates enabled multiple, redundant measurements increasing accuracy

Diamond experimental configuration



Knudson, Desjarlais and Dolan, Science **322**, 1822 (2008)

This accuracy allowed for quantitative comparison with QMD predictions and evidence of the TP



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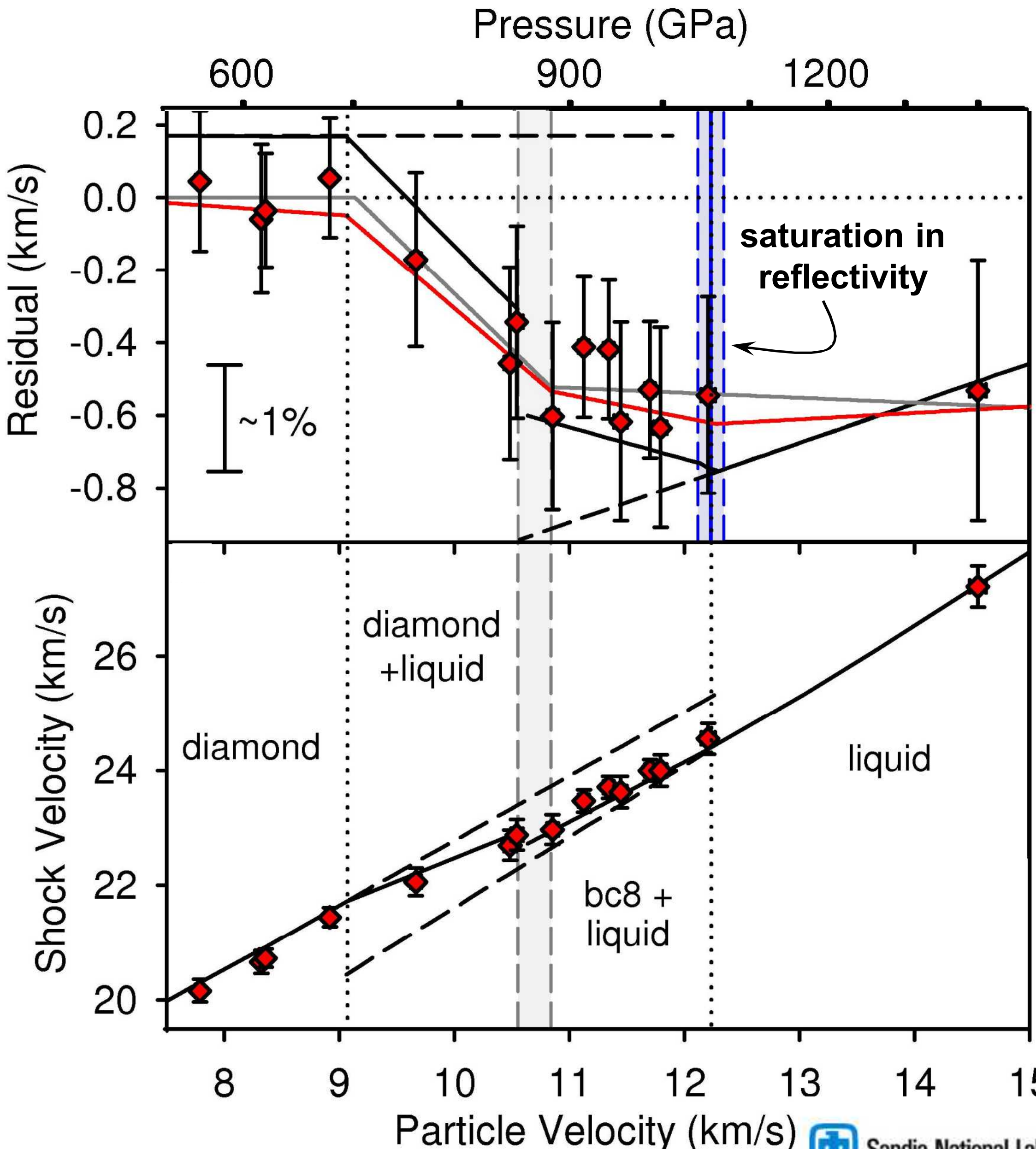
Four piece linear fit leads to consistency with the reflectivity measurements of Bradley, et al.

- Both the three and four piece fits indicate significant changes in slope at ~9.1 and ~10.85 km/s
- Both suggest the onset of melt just below ~700 GPa
- The three piece linear fit would suggest completion of melt below 900 GPa
  - ~200 GPa below the saturation in reflectivity
- The four piece fit is consistent with Bradley, et al. and suggest a TP at ~860 GPa



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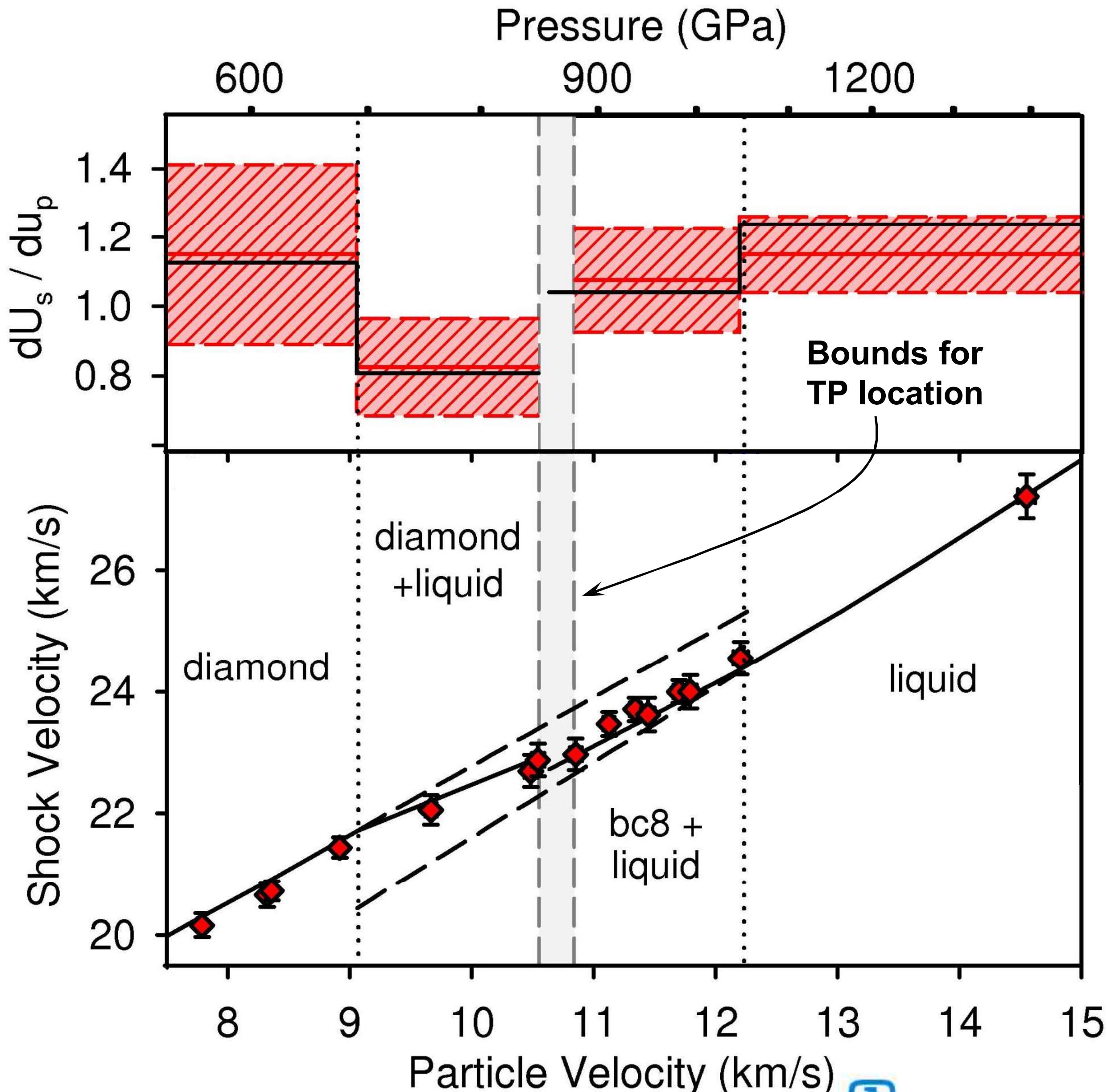
Location of breakpoints and slopes are in excellent agreement with the QMD predictions

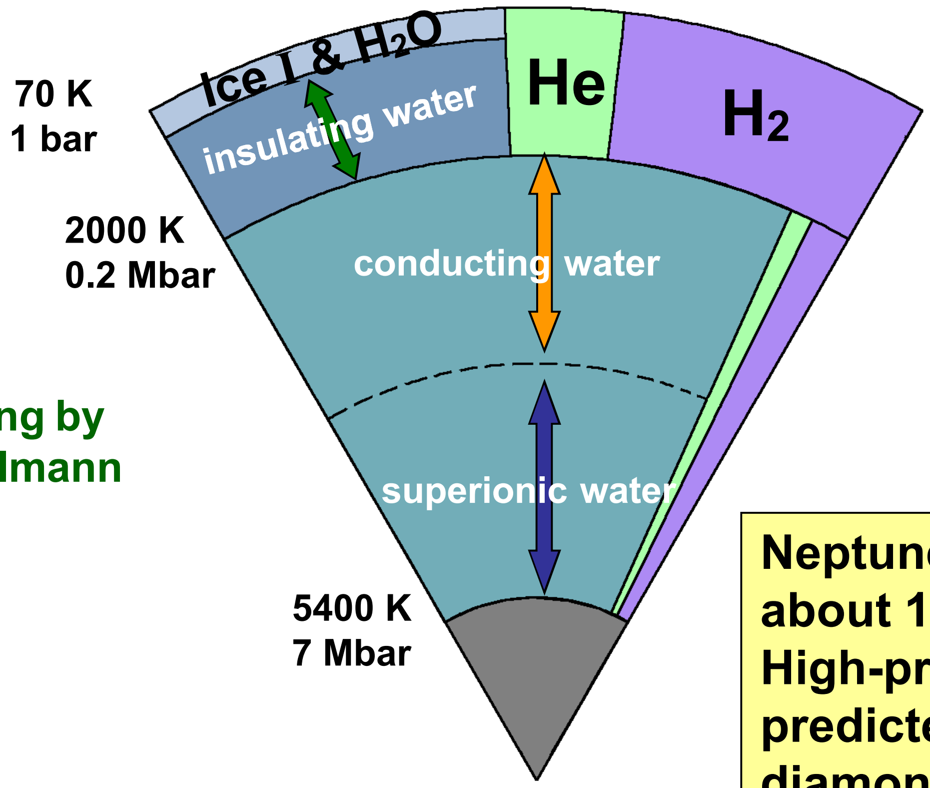
- The breakpoints of the four segment fit are in excellent agreement with those predicted by QMD
- The slope of each segment is also in excellent agreement with the slopes predicted by QMD
- This level of agreement strongly suggests the presence of a higher pressure solid phase of carbon above ~860 GPa



Knudson, Desjarlais and Dolan, Science **322**, 1822 (2008)

Data has been obtained on Z for materials of interest to planetary physics in relevant regimes

Interior of Neptune using the LM-REOS model for water



Modeling by
N. Nettelmann

From R. Redmer
Univ. of Rostock

Neptune and Uranus contain about 10-15% C (in CH_4): High-pressure triple point predicted in carbon between diamond-bc8-liquid phases at 850 GPa and 7500 K

A.A. Correa et al., PNAS 103, 1204 (2006)
M.D. Knudson et al., Science 322, 1822 (2008)

Previous models predicted for the core
T_{core} = 8000 K: Zharkov & Trubitsyn (1978)
T_{core} = 7000 K: Stevenson (1982)

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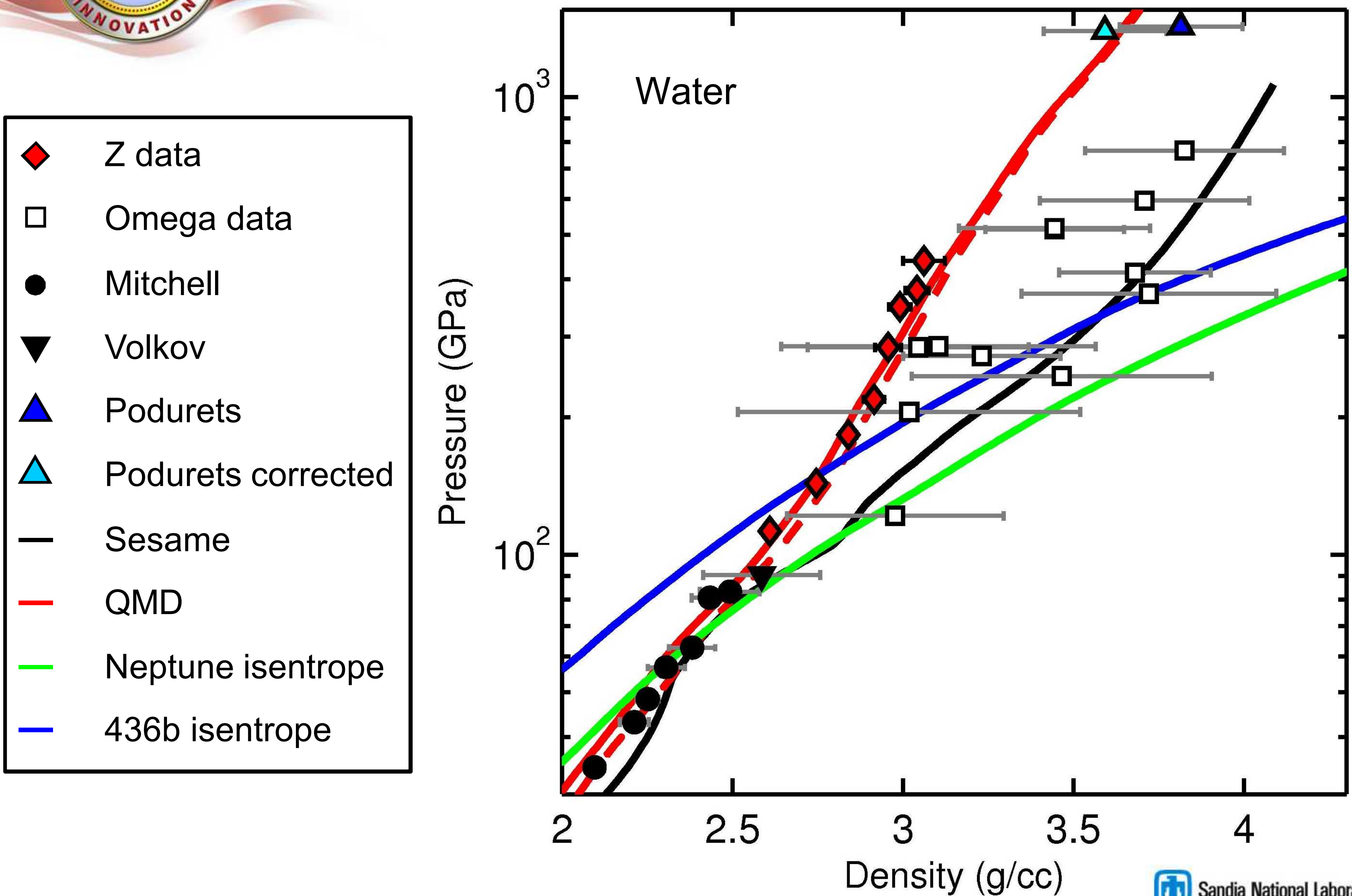
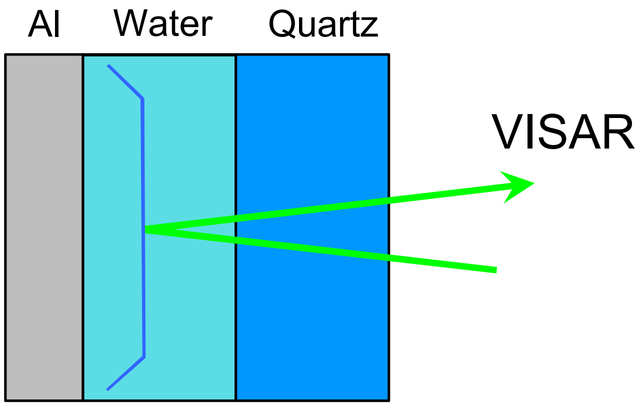
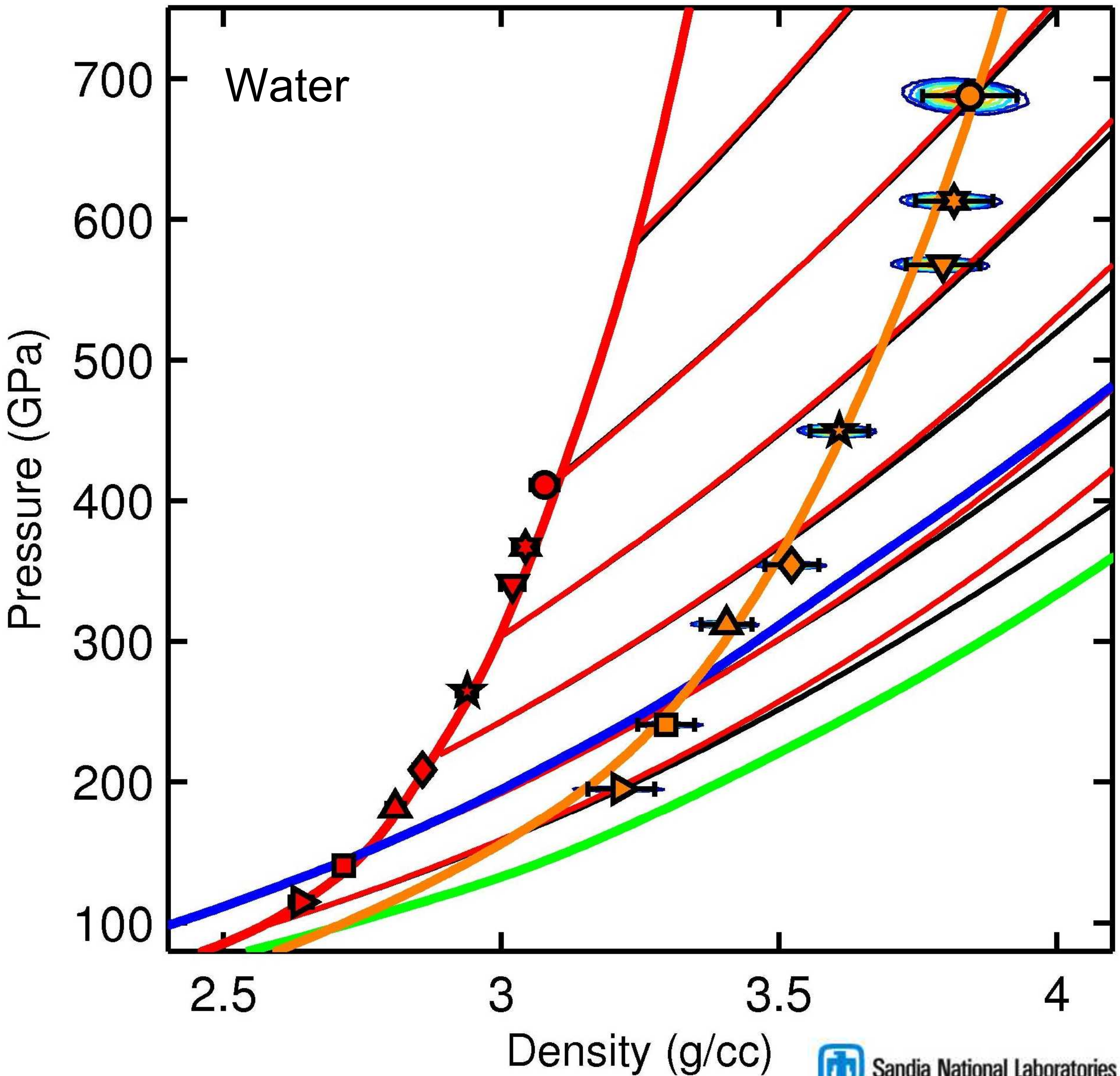
Recent water Hugoniot data on Z consistent with QMD calculations – supports new Neptune model



Reshock measurements using quartz provide a good test of QMD isentropes in planetary regimes





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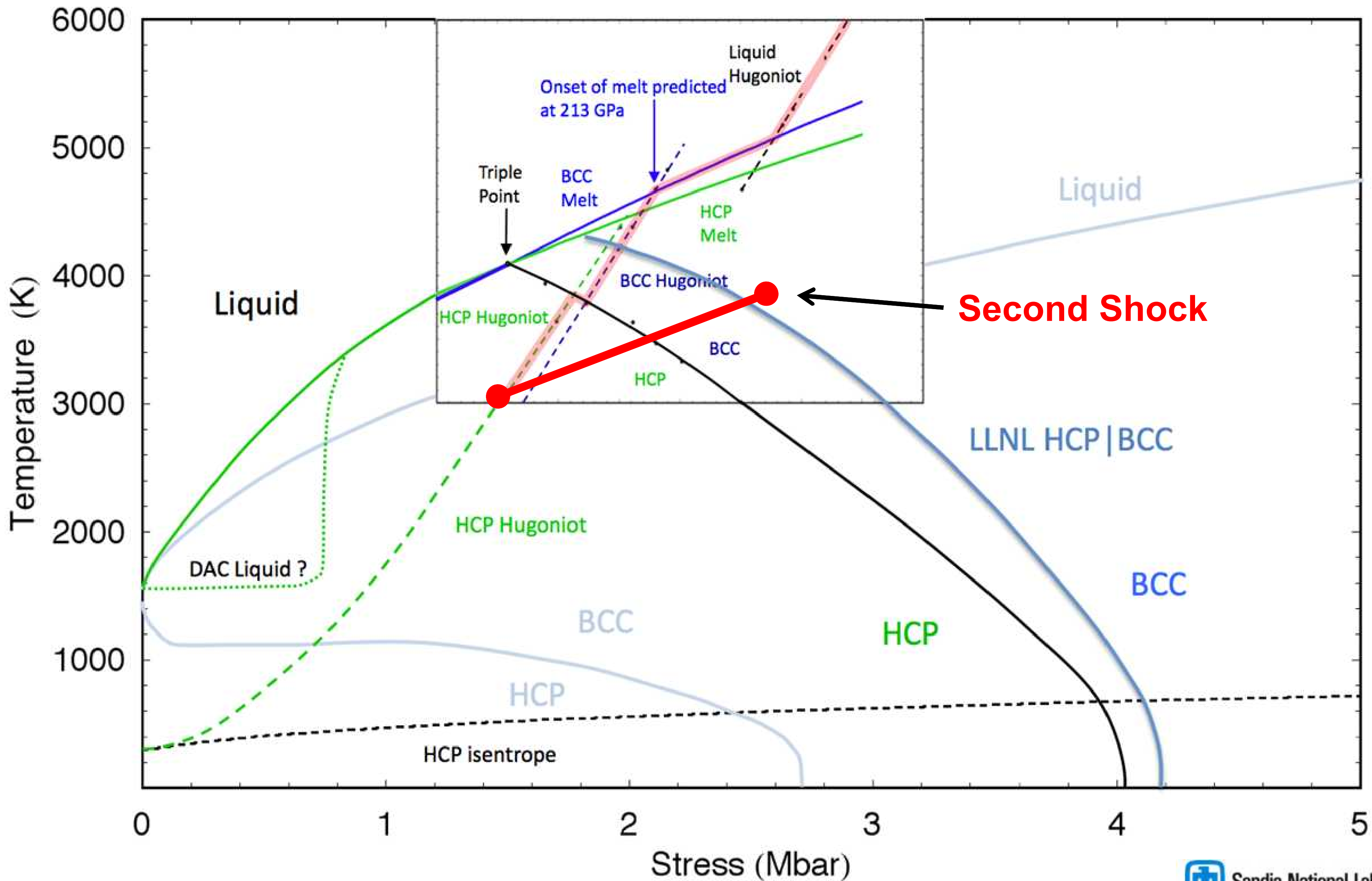
Al/Cu composite technique is being extended to multi-layer flyer plates for double shock experiments



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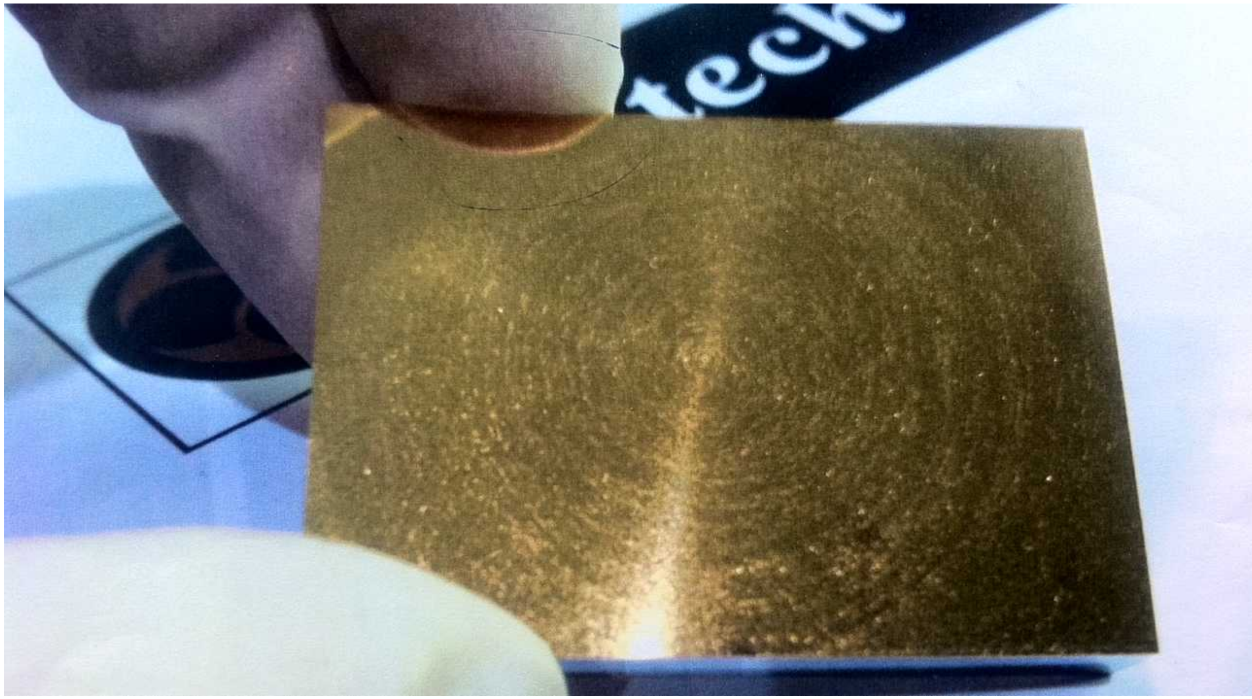
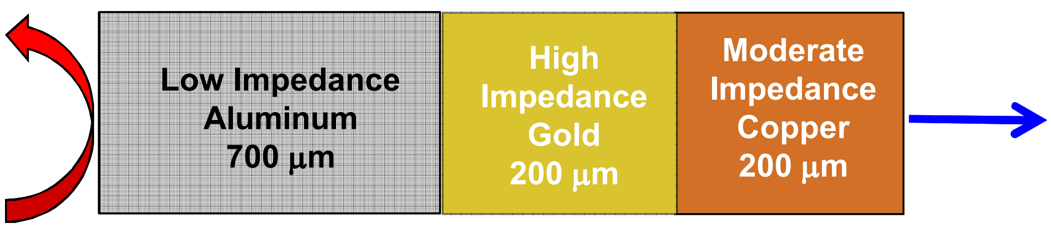
Fabrication of the plates is a complex process to ensure quality interfaces and uniform thicknesses

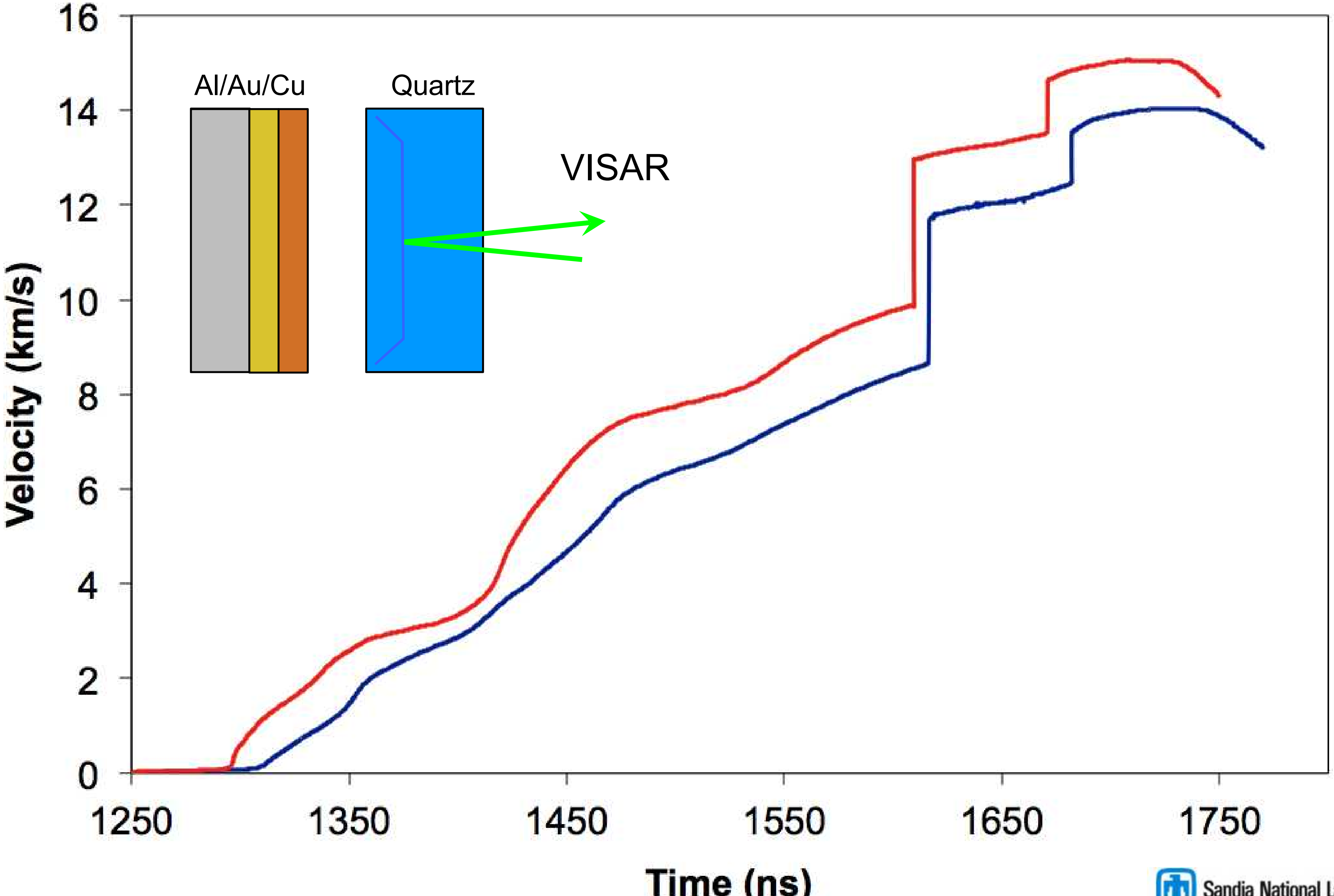


Al / Au / Cu



Solid Density Electroplated and Diamond Turned Layers

Recent data demonstrates shockless acceleration and sharp interfaces due to solid state bonding



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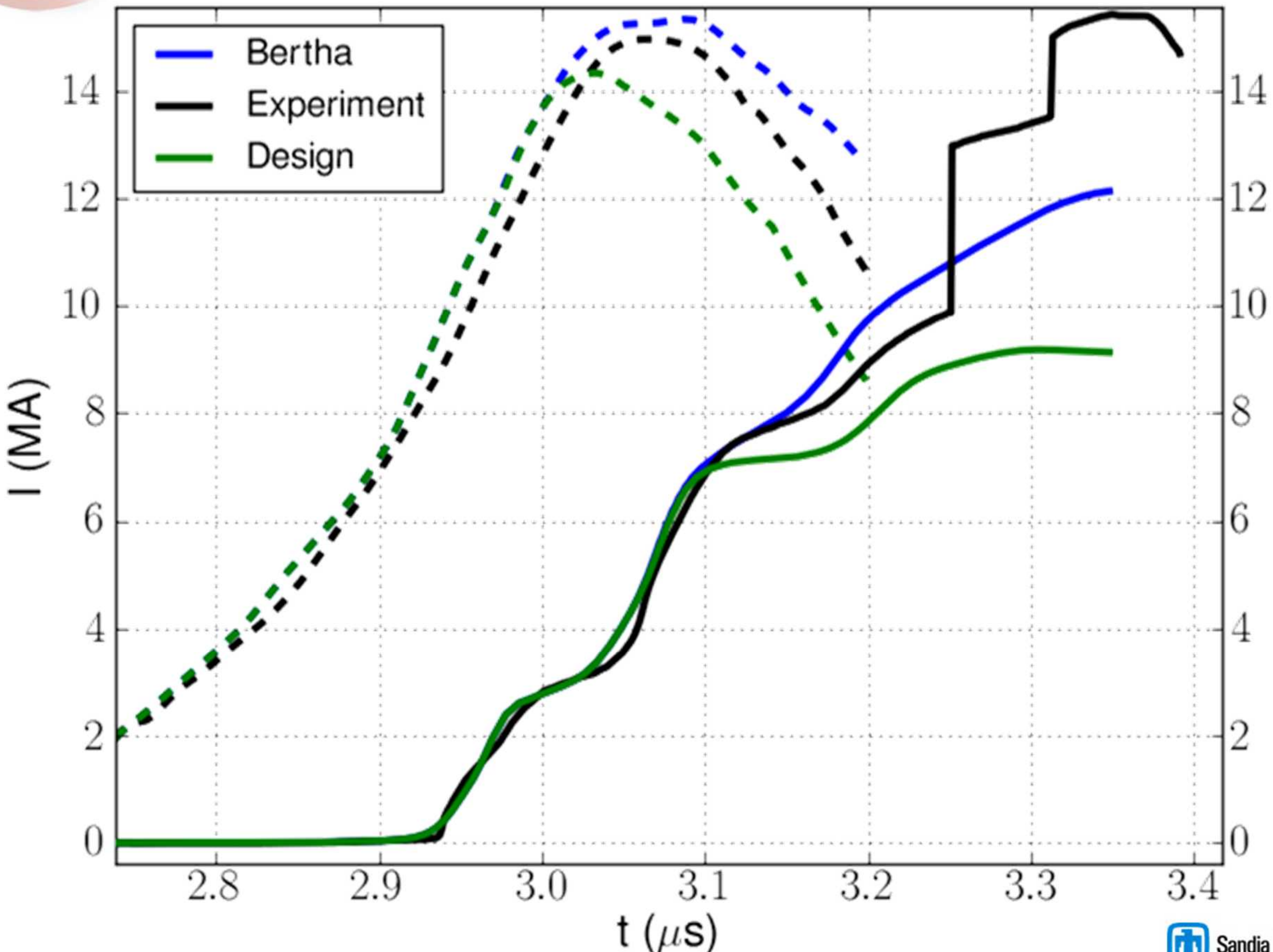
These data will also help constrain the fall-off of the current pulse for future experiment design



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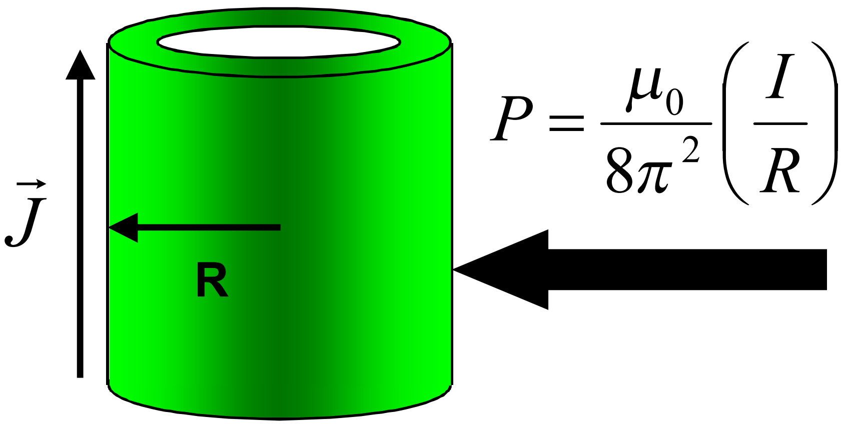
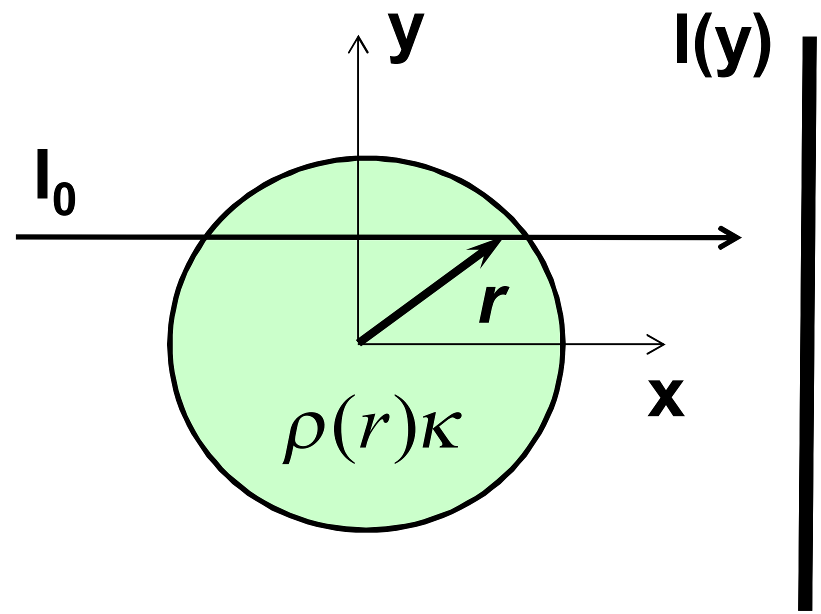
Cylindrical implosion technique has been developed to take advantage of convergent geometry

Be Liner Z-Pinch Implosion



$$P = \frac{\mu_0}{8\pi^2}\left(\frac{I}{R}\right)^2$$

Two-frame 6151 eV x-ray radiography



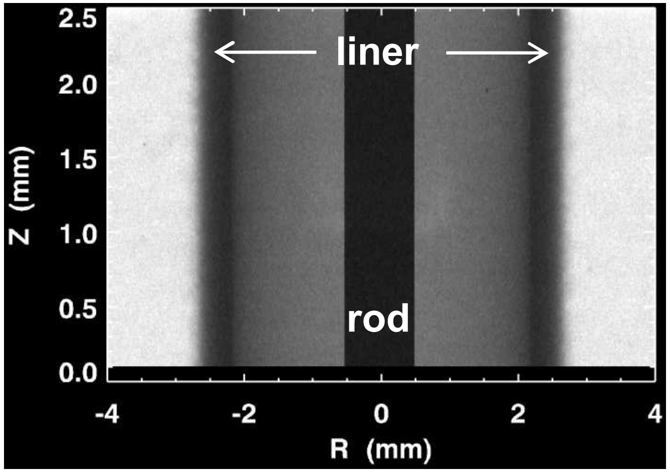
Abel inversion yields liner density vs. r

$$\rho(r) = -\frac{1}{\kappa\pi}\int_r^1 \frac{d\ln[I(y)/I_0]}{dy}\frac{dy}{\sqrt{y^2 - r^2}}$$

$$\kappa = opacity$$

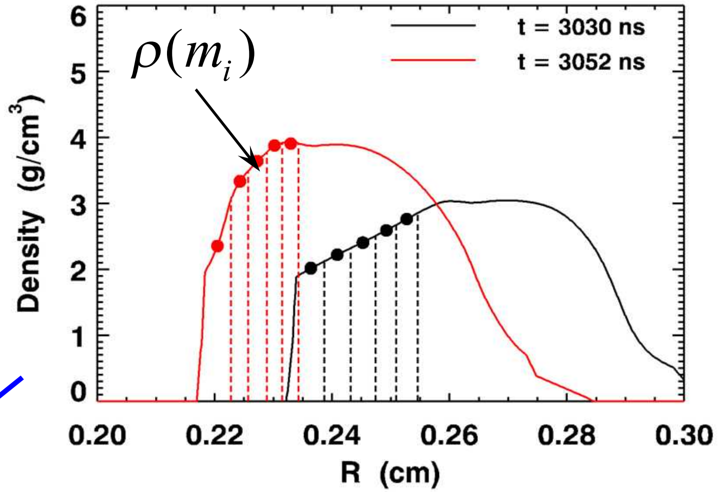
Ensemble of radiographs and Lagrangian hydro equations used to calculate total pressure in liner

6151 eV Backlight Images



Abel inversion

Liner Density vs. R (m_i = 10 mg)



Velocity / Position

$$\frac{\partial (rv)}{\partial m} = \frac{1}{2\pi} \frac{D}{Dt} \left(\frac{1}{\rho} \right)$$

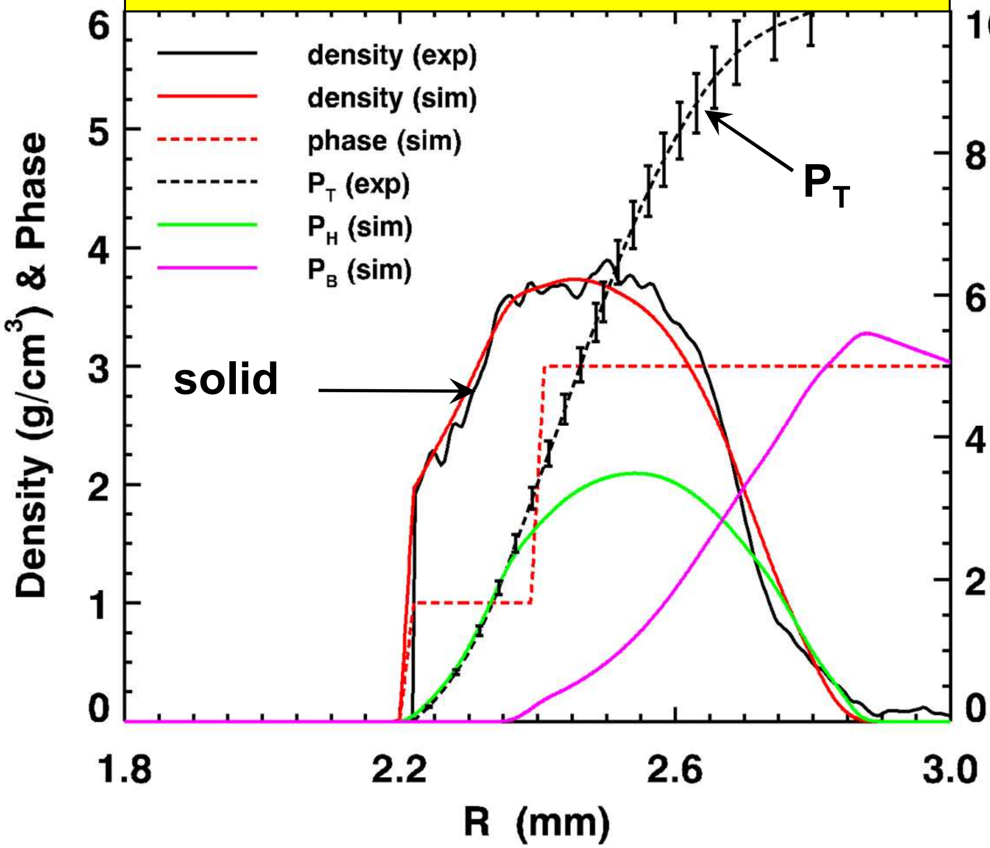
Total Pressure

$$\frac{\partial P_T}{\partial m} = -\frac{1}{2\pi r} \frac{Dv}{Dt}$$

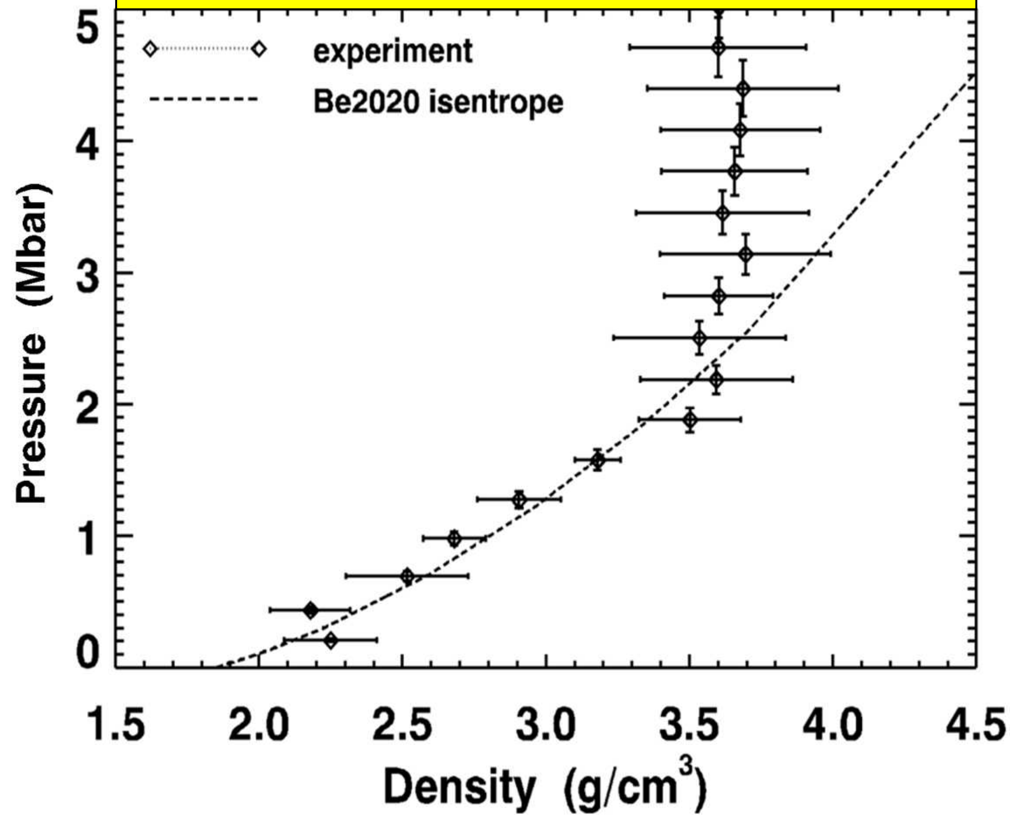
Sandia National Laboratories

Technique has been successfully demonstrated on Be to ~2.5 Mbar, with promise of higher stress

Measured / Simulated Density and Pressure vs. R

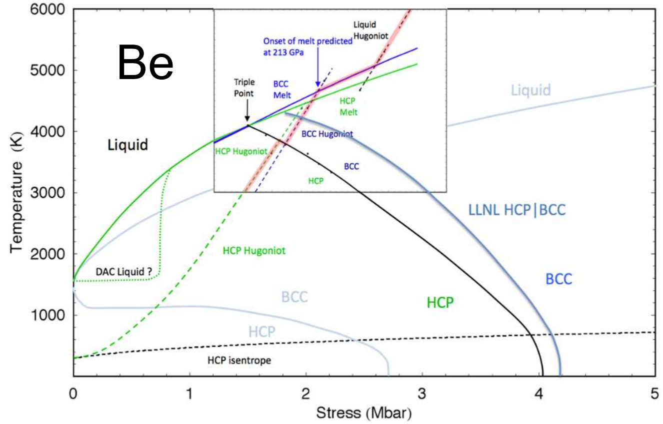


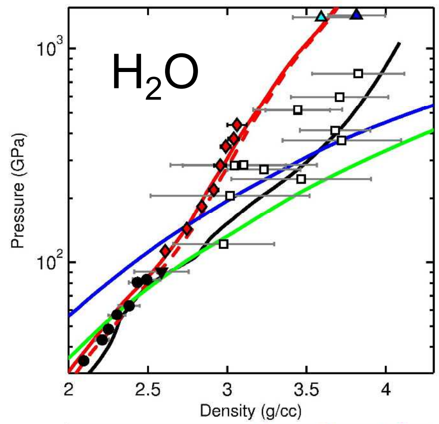
Pressure vs. Density (Be Liner ICE)

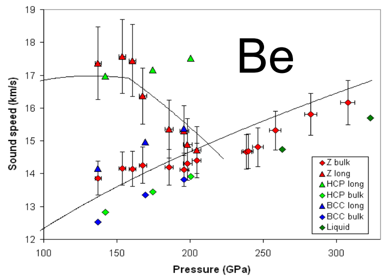


Z has been used to address several interesting problems in the multi-Mbar regime

Quartz

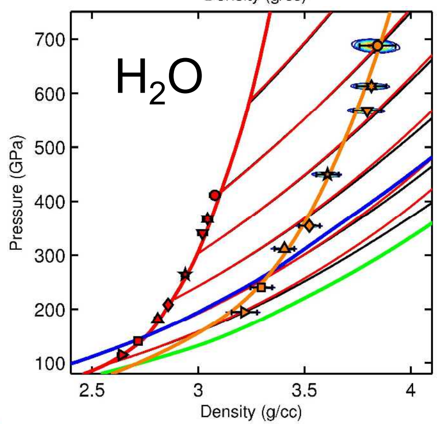


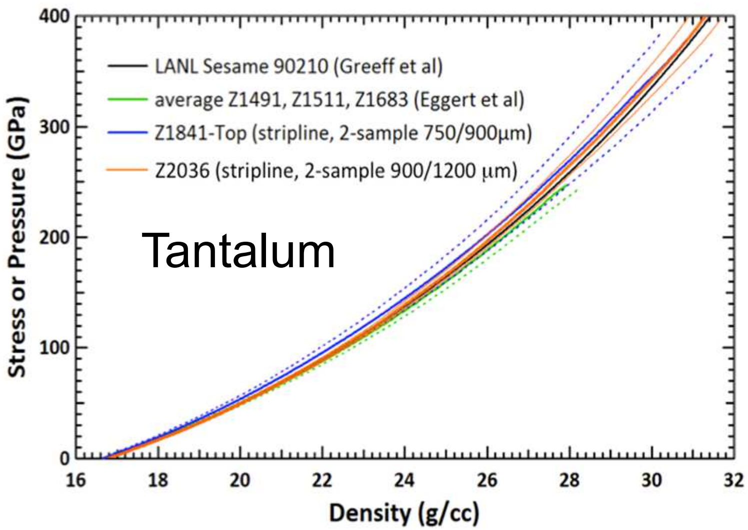




C

D_2





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