SAND2010-1614C

Dynamic Material Properties Experiments Using Pulsed Magnetic Compression

"From Static to Dynamic" -1st Annual Meeting of the Institute for Shock Physics
The Royal Society of London   February 22-23, 2010

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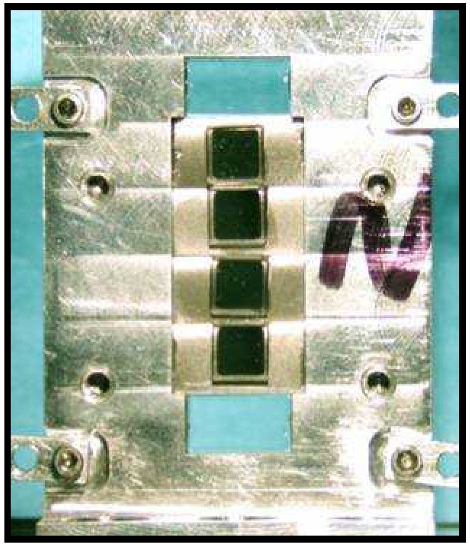
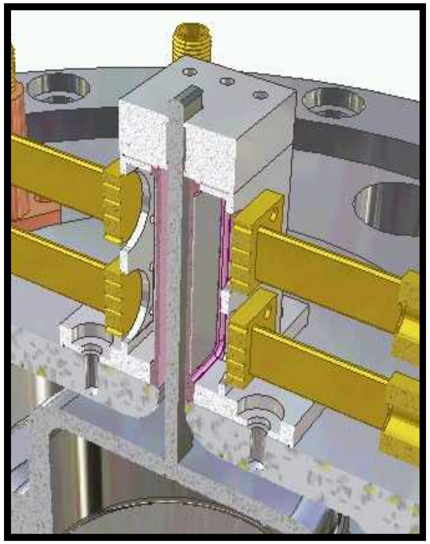
Sandia National Laboratories, Albuquerque, NM





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National Nuclear Security Administration

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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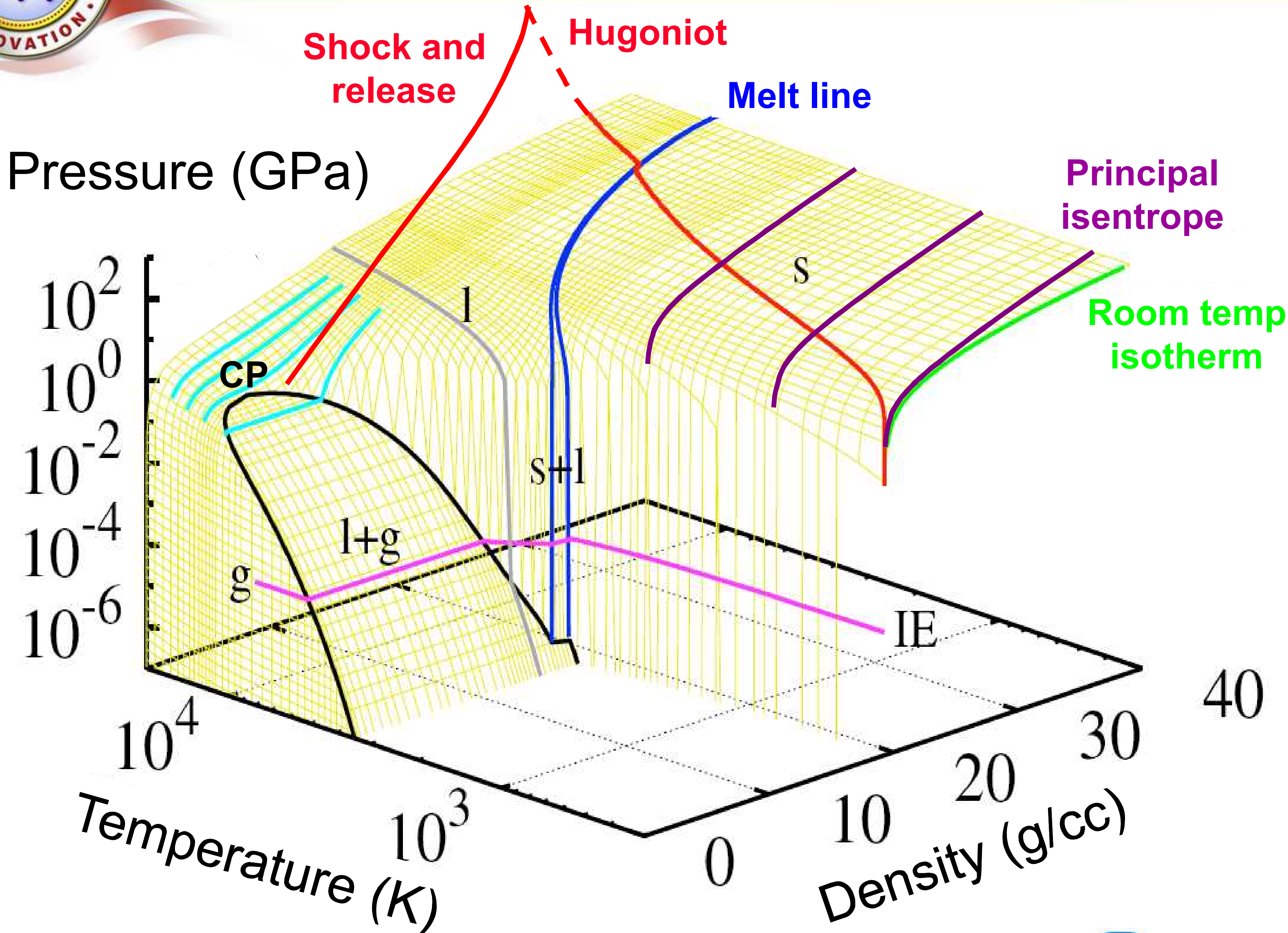
Acknowledgements

- **Mike Desjarlais**
  - Quantum Molecular Dynamics (QMD) calculations
- **Jean-Paul Davis, Dan Dolan, Seth Root**
  - Experimental design, data analysis
- **Jean-Paul Davis, Ray Lemke, Tom Haill, Dave Seidel, William Langston, Rebecca Coats**
  - MHD unfolds, Quicksilver simulations, current analysis
- **Jean-Paul Davis, Devon Dalton, Ken Struve, Mark Savage, Keith LeChien, Brian Stoltzfus, Dave Hinshelwood**
  - Bertha model, pulse shaping
- **Jason Podsednik, Charlie Meyer, Devon Dalton, Dustin Romero, Anthony Romero, entire Z crew…**
  - Experiment support
- **LANL: Rusty Gray, Dave Funk, Paulo Rigg, Carl Greeff**
  - Ta samples and equation of state

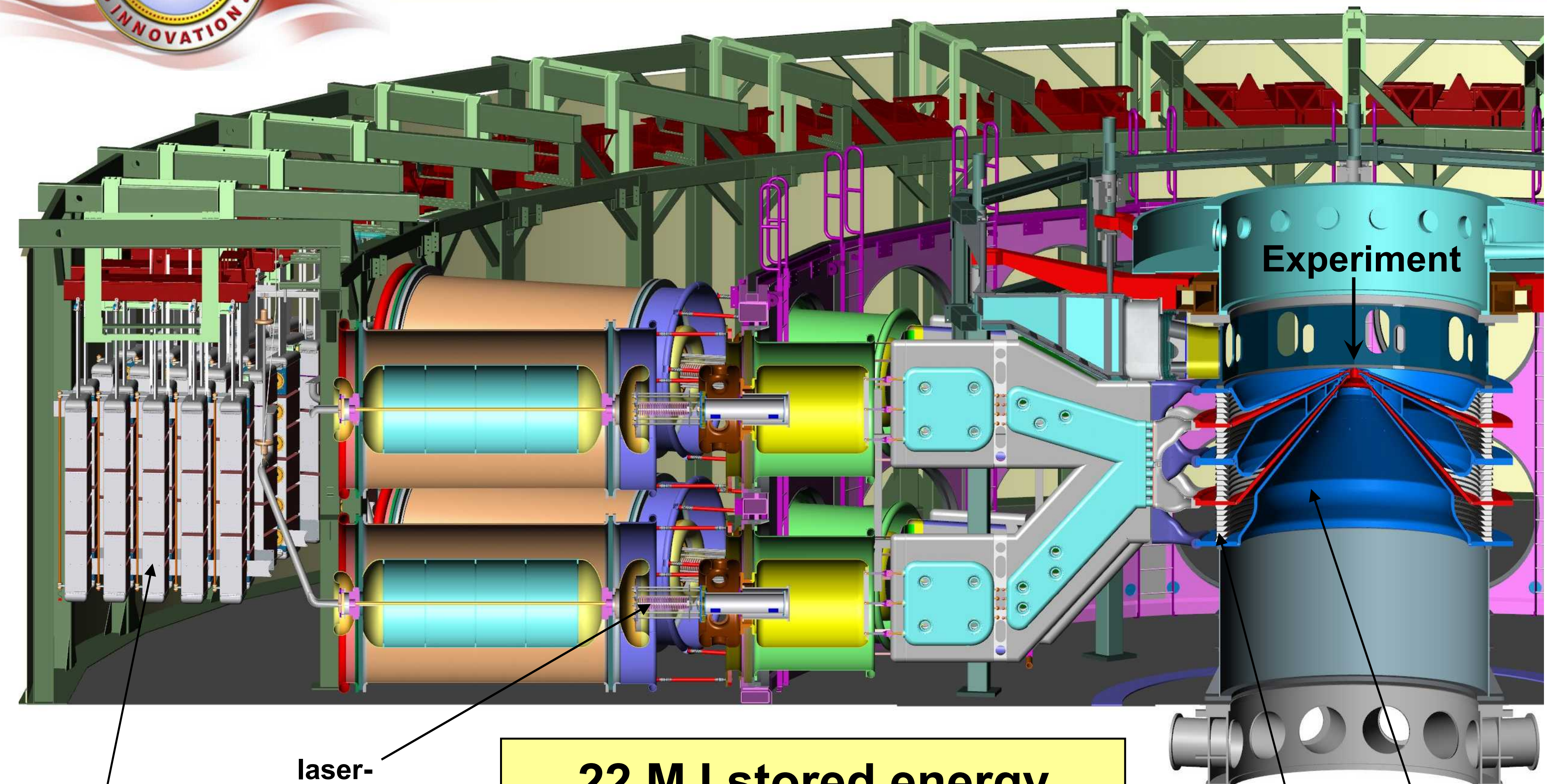
Outline

- Pulsed Compression on the Z Accelerator
- High-Stress Isentropic compression measurements
  - Tantalum
- High-Pressure Hugoniot measurements
  - Quartz
- Melting of Diamond in the Multi-Mbar Regime

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

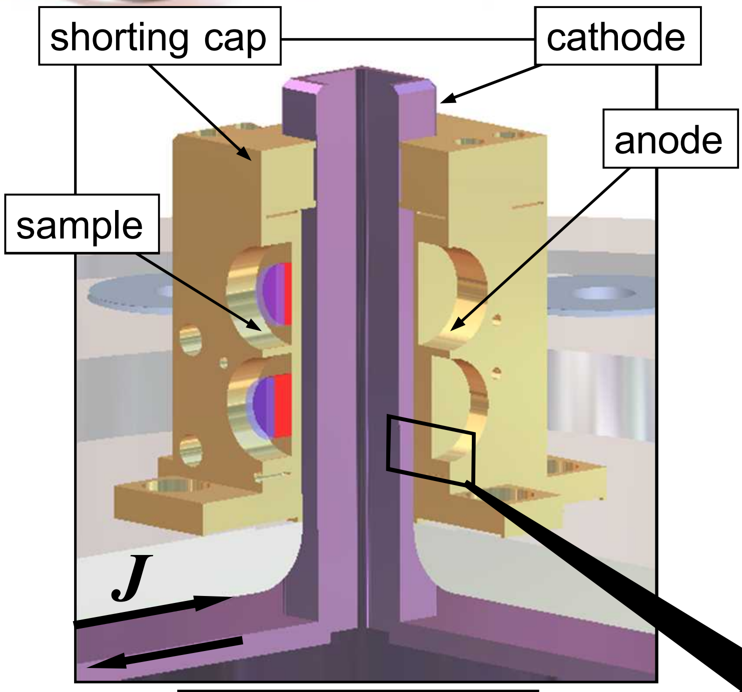


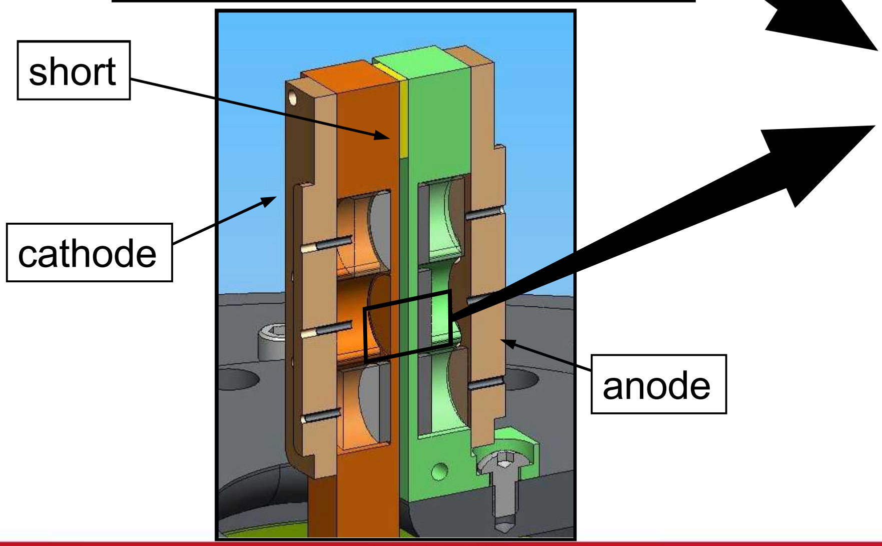
The Sandia Z Machine



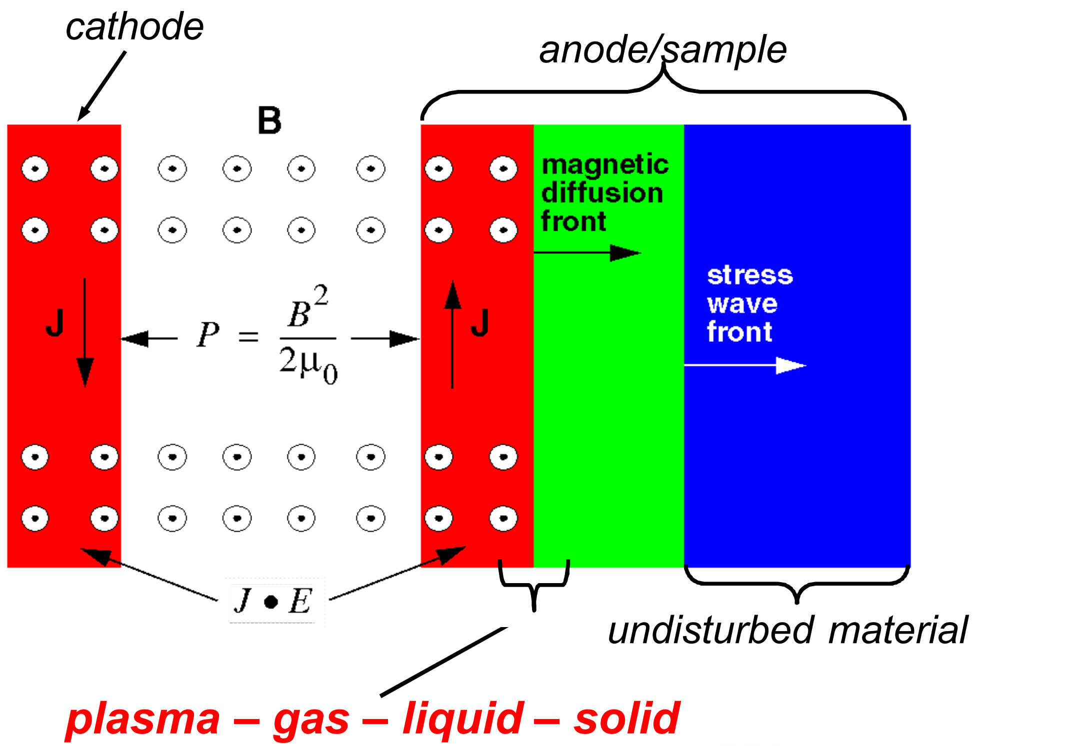
22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

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





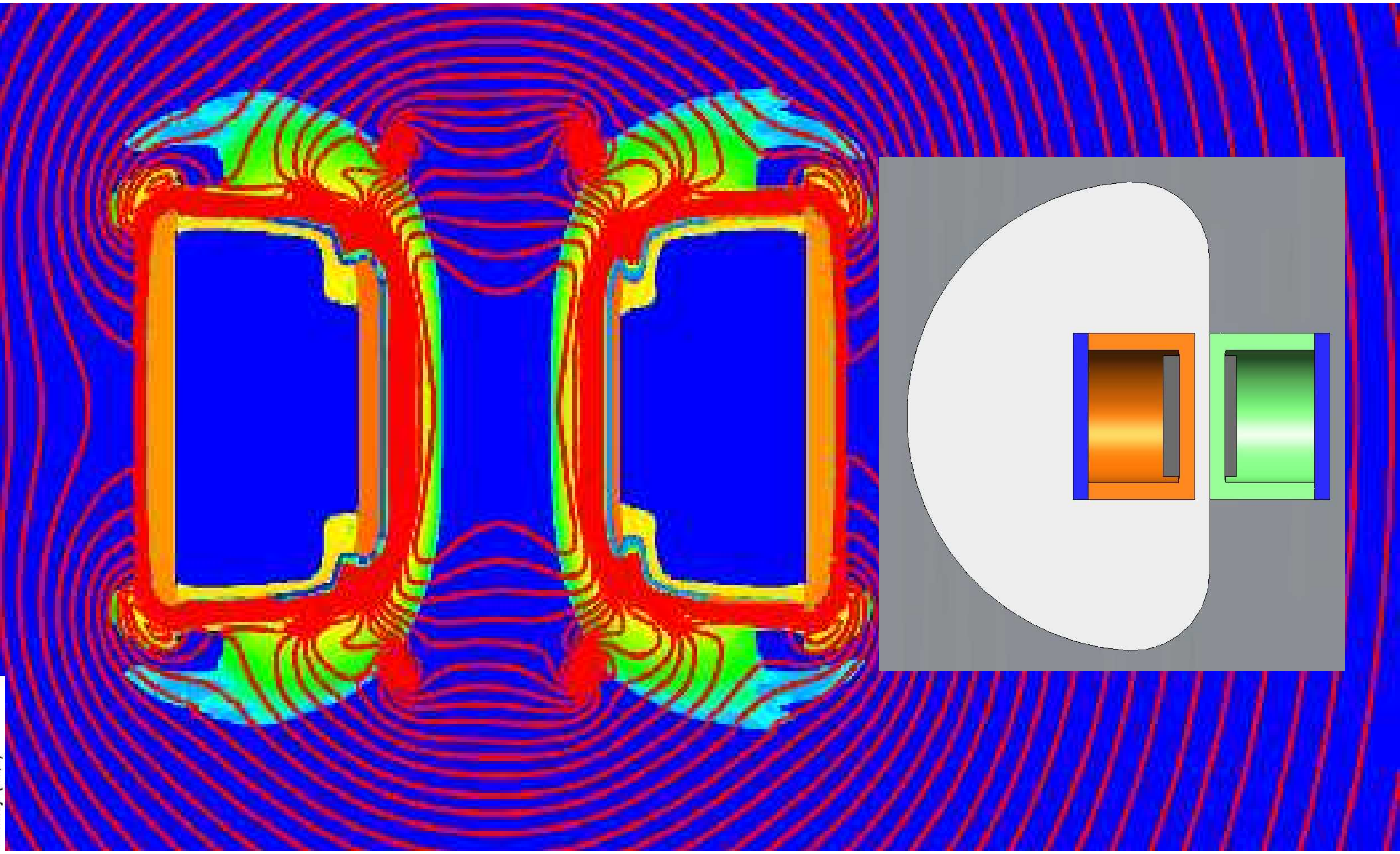
- pulse of electric current through rectangular coaxial electrodes (shorted at one end) induces magnetic field
- $J \times B$ magnetic force transferred to electrode material

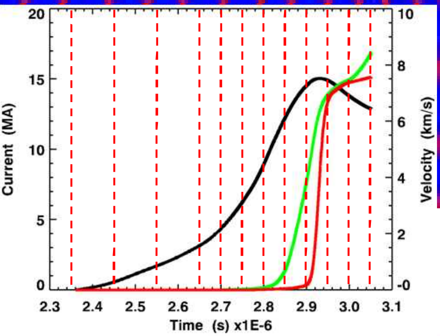


Fully self-consistent, 2-D MHD simulations required to accurately predict experimental load performance

10 mm wide stripline

t = 3050 ns





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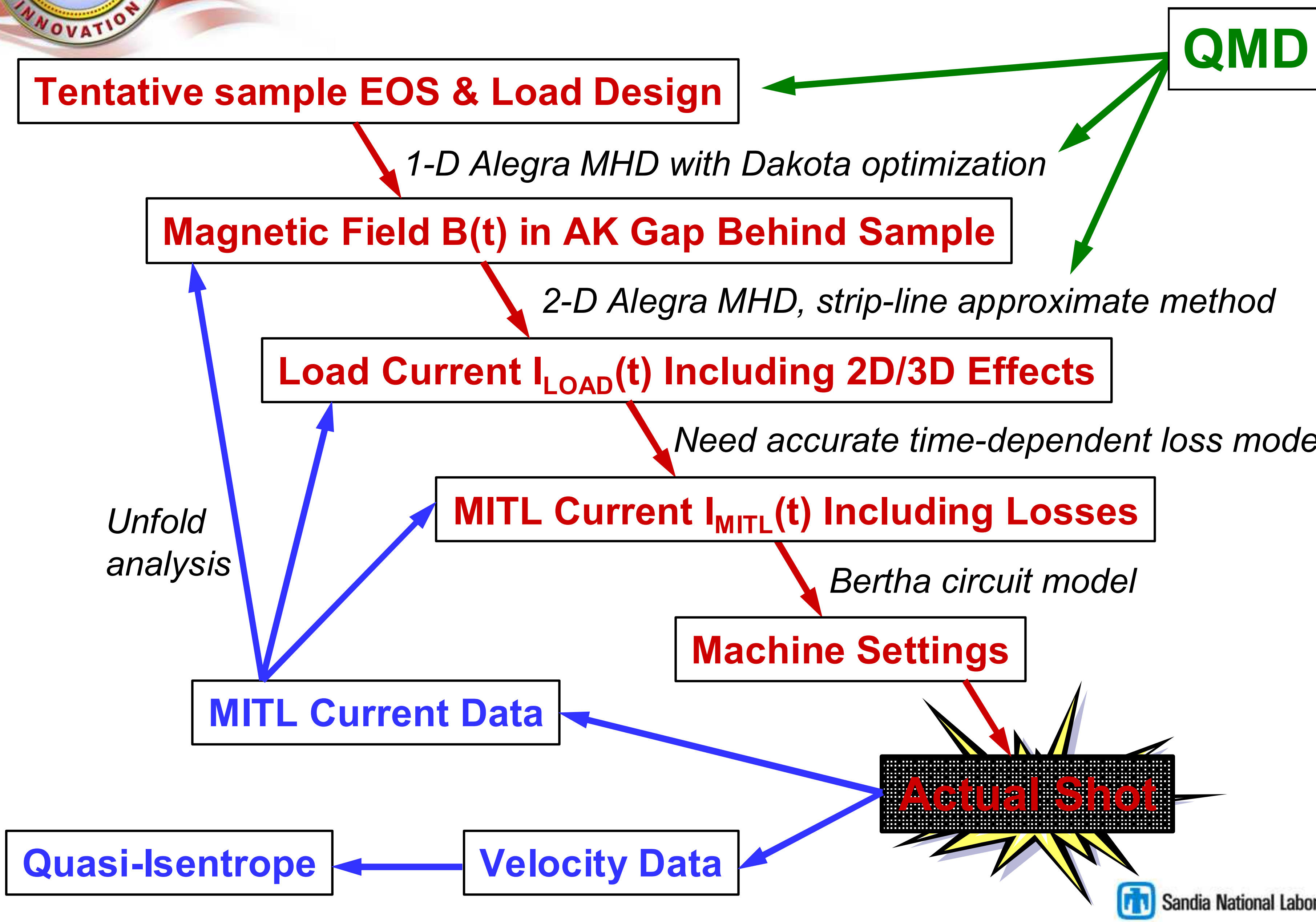
Success requires integration of theoretical, computational, and experimental capabilities



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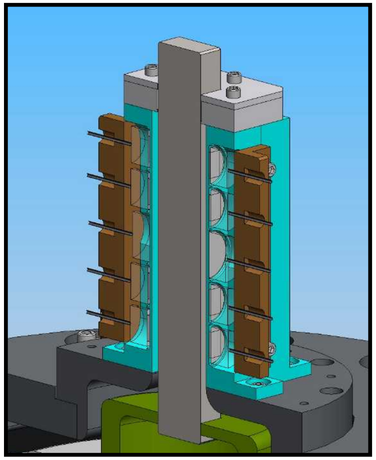
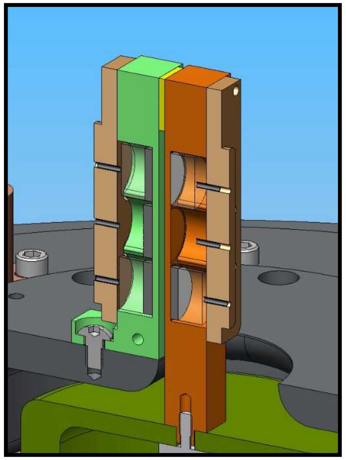
Two platforms have been developed for accurate equation of state studies – both major advances

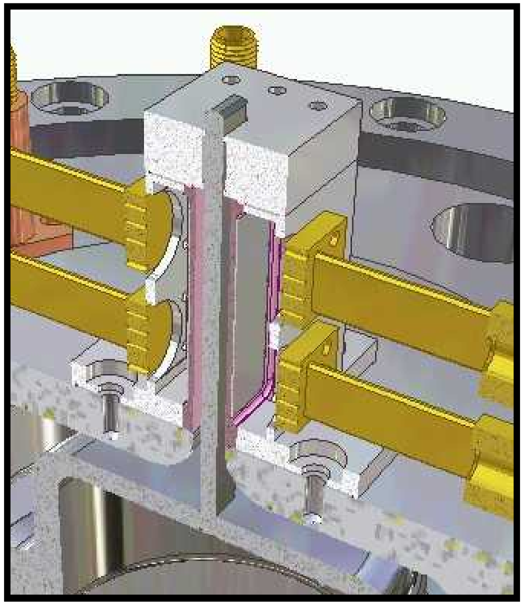




Isentropic Compression Experiments (ICE)*

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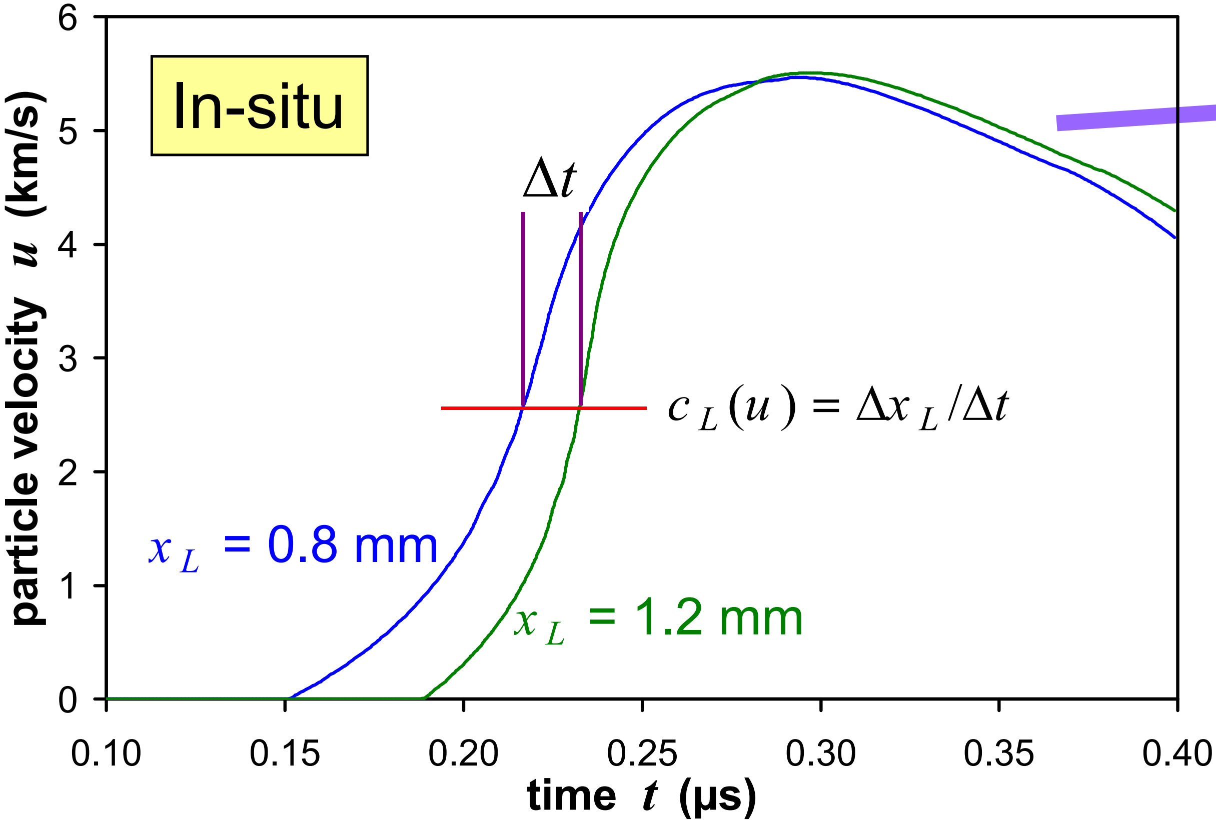
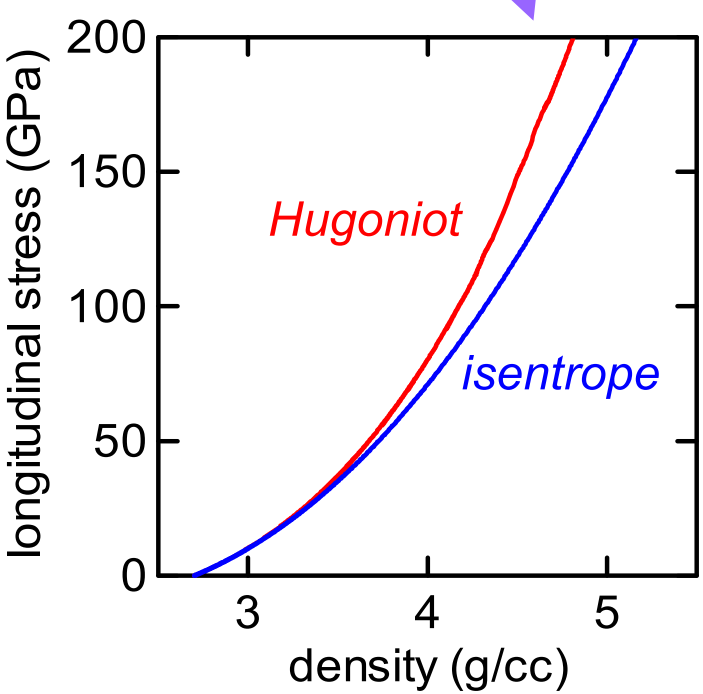
Ramp compression provides a measure of the stress-density response of a material to peak stress



conservation equations

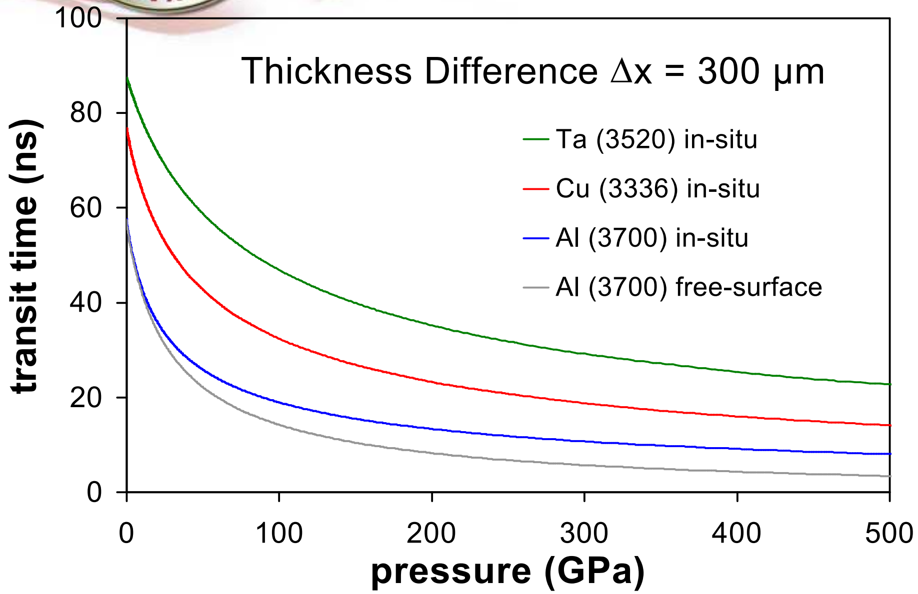
$$d\sigma_x = \rho_0 c_L du$$

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



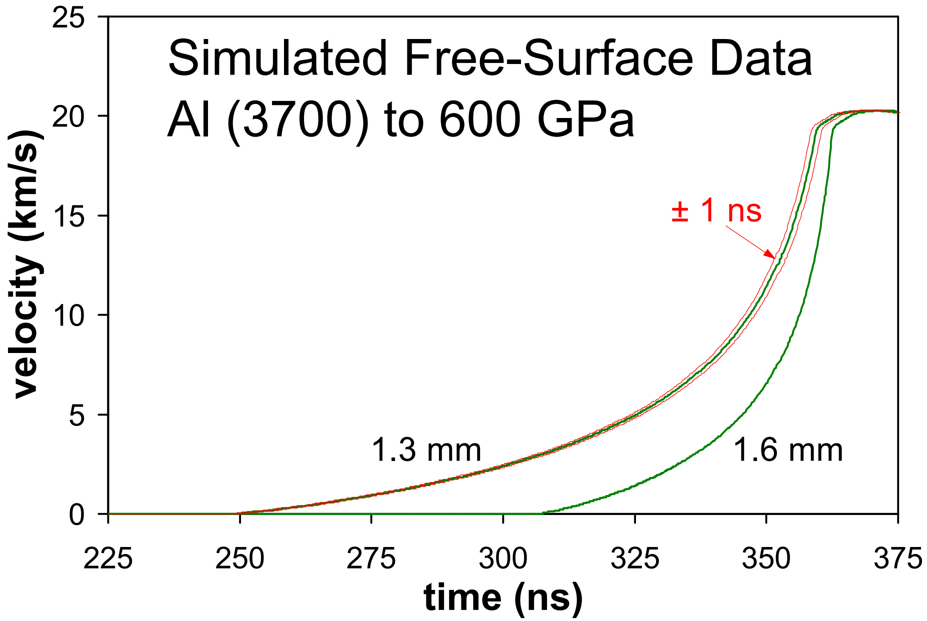
- requires simple right-going waves
- compression is usually quasi-isentropic due to dissipative phenomena (plastic work, viscosity, thermal conduction, *etc*.)

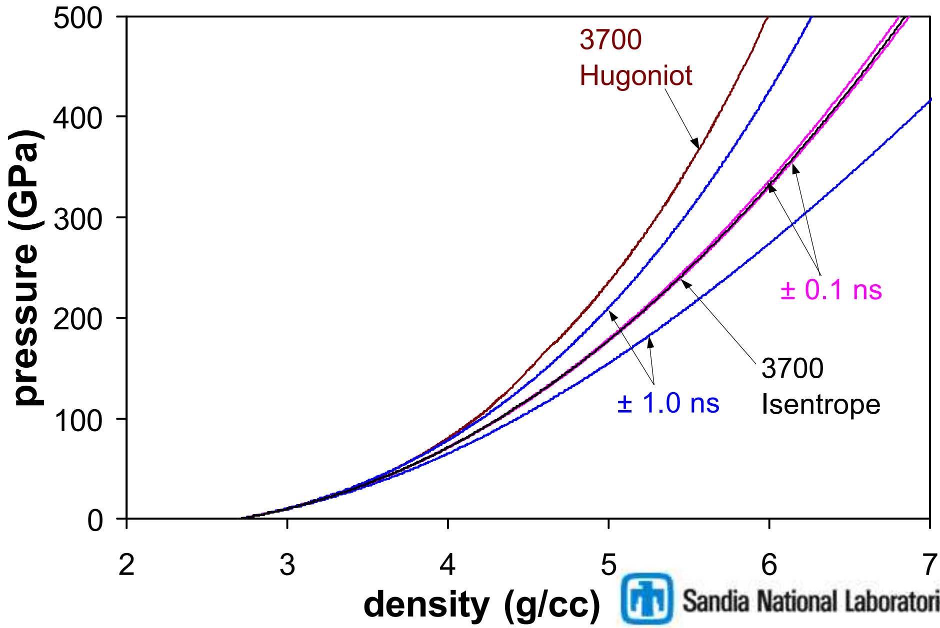
High-stress ICE experiments place stringent demands on wave profile measurements



Very high Lagrangian sound speeds at high stress result in small transit times – this places stringent demands on timing accuracy.

~100 ps timing accuracy required to obtain ~1% accuracy in density





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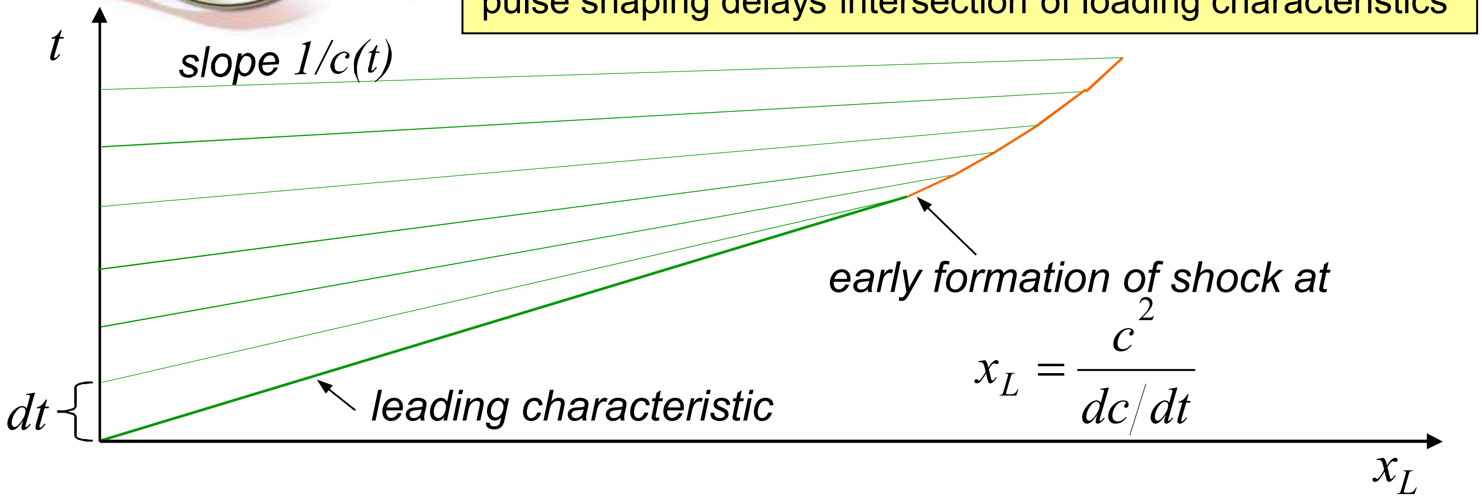
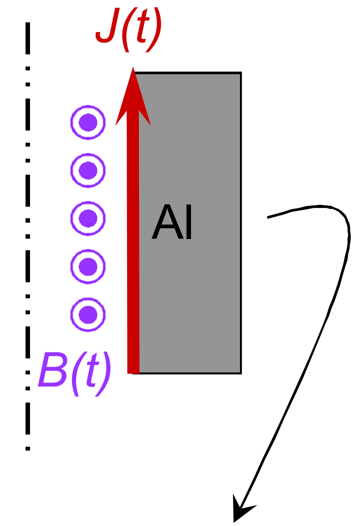
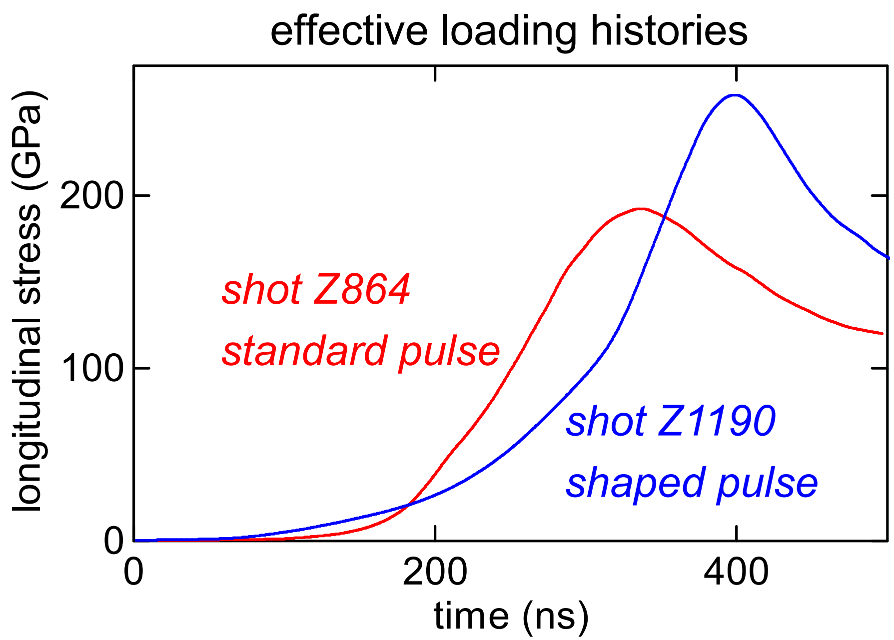
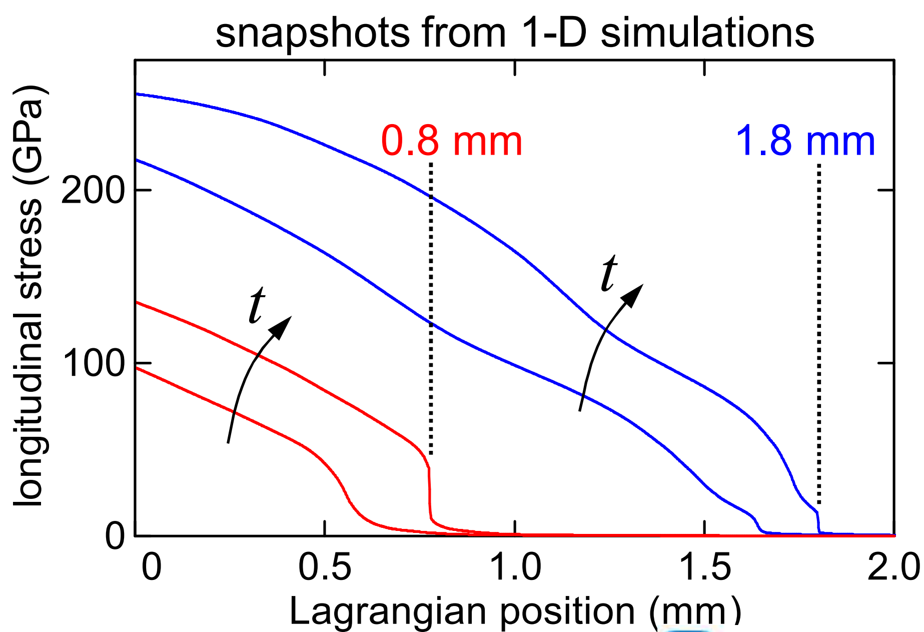
The rapid increase in sound speed requires pulse shaping to delay shock formation

pulse shaping delays intersection of loading characteristics









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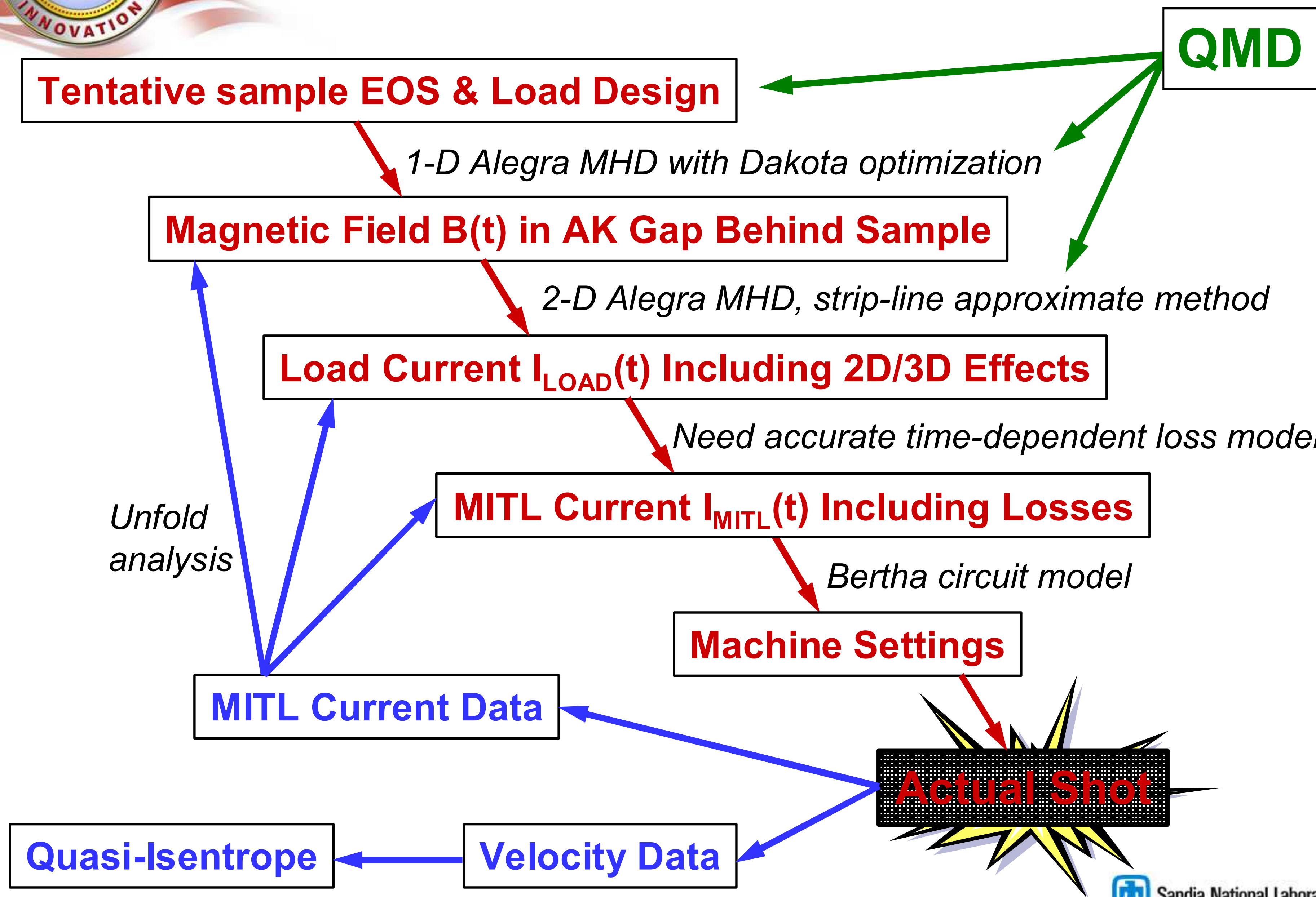
This process was followed to design an ICE experiment on Ta to 400 GPa



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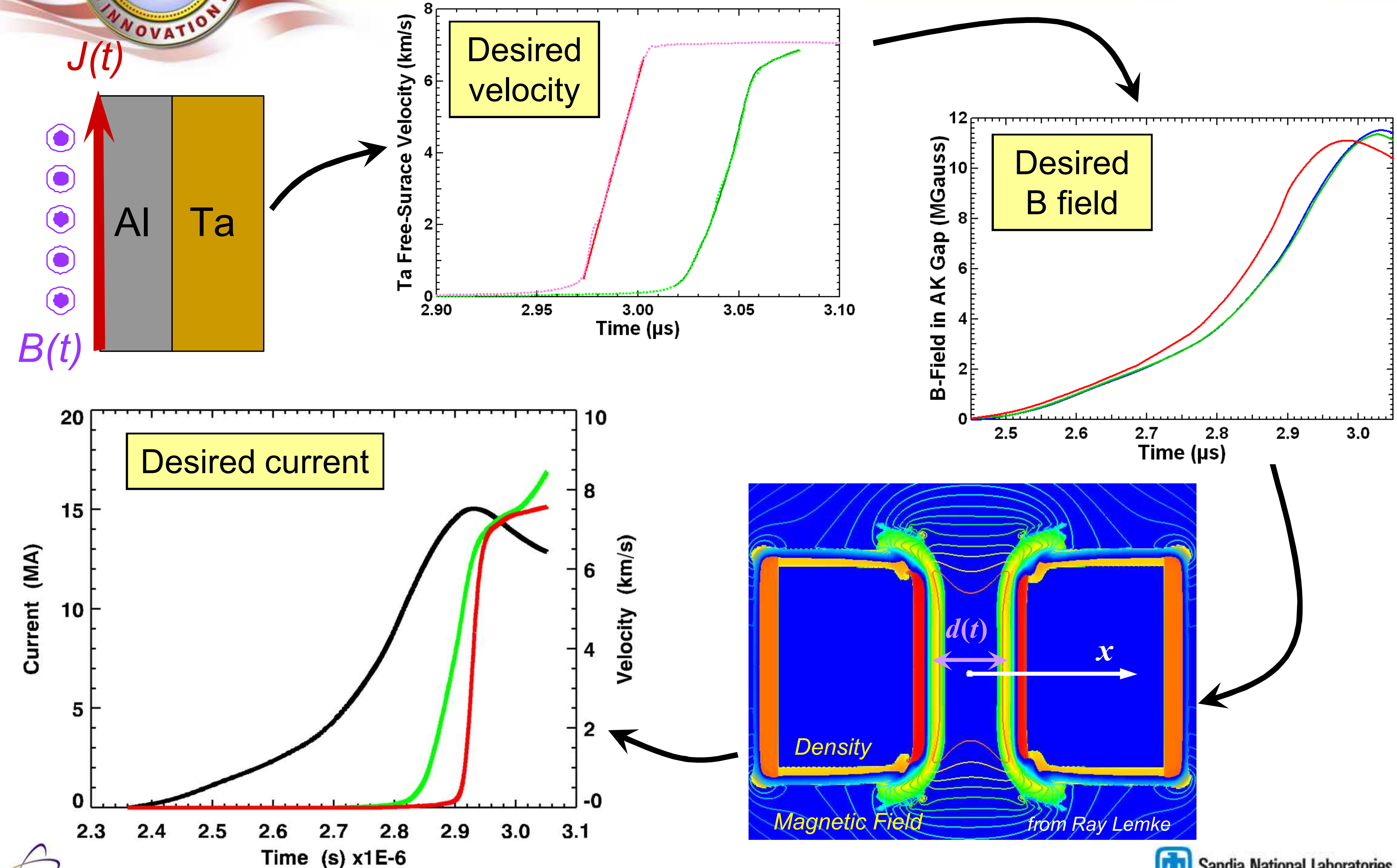
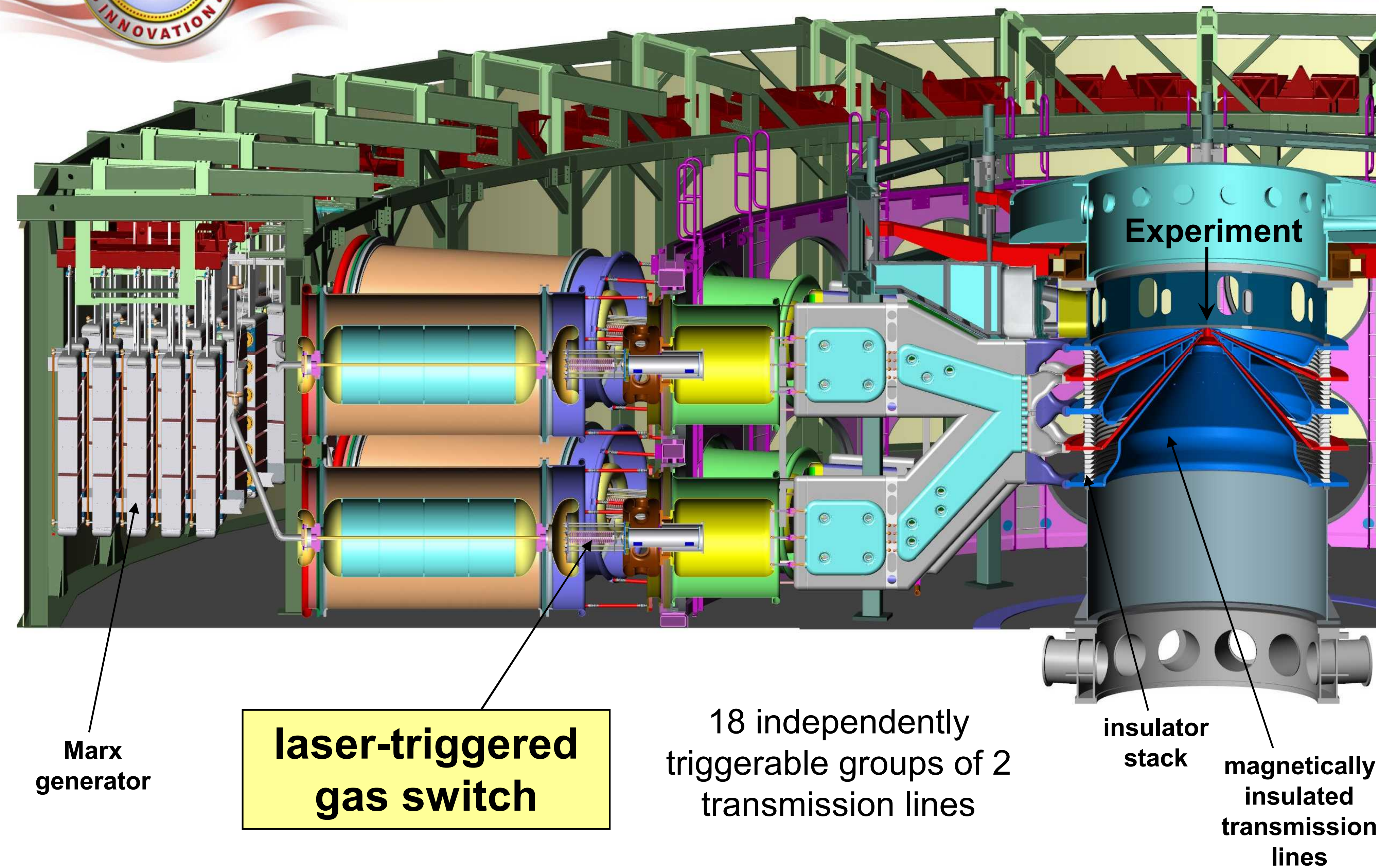
Desired current is determined through several iterative 1-D and 2-D MHD simulations



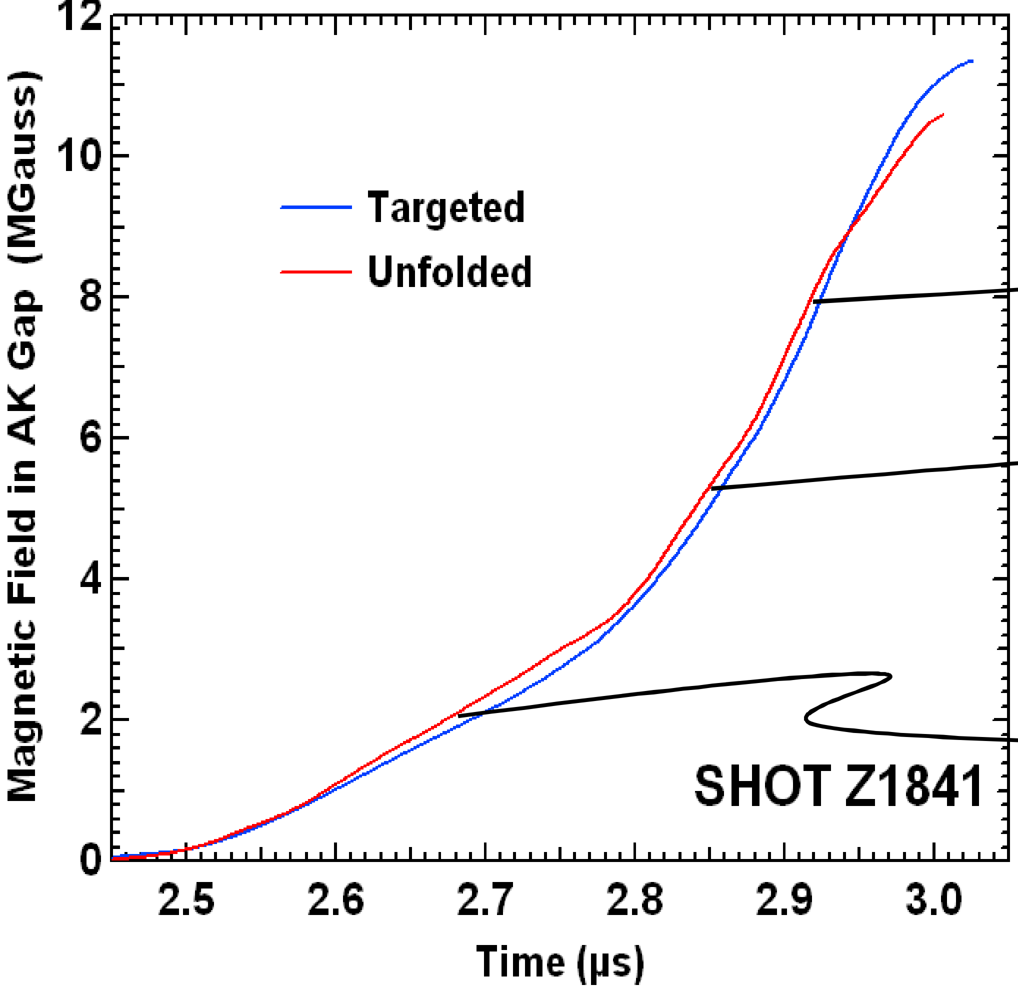
Independently triggerable gas switches provide the variability necessary for pulse shaping



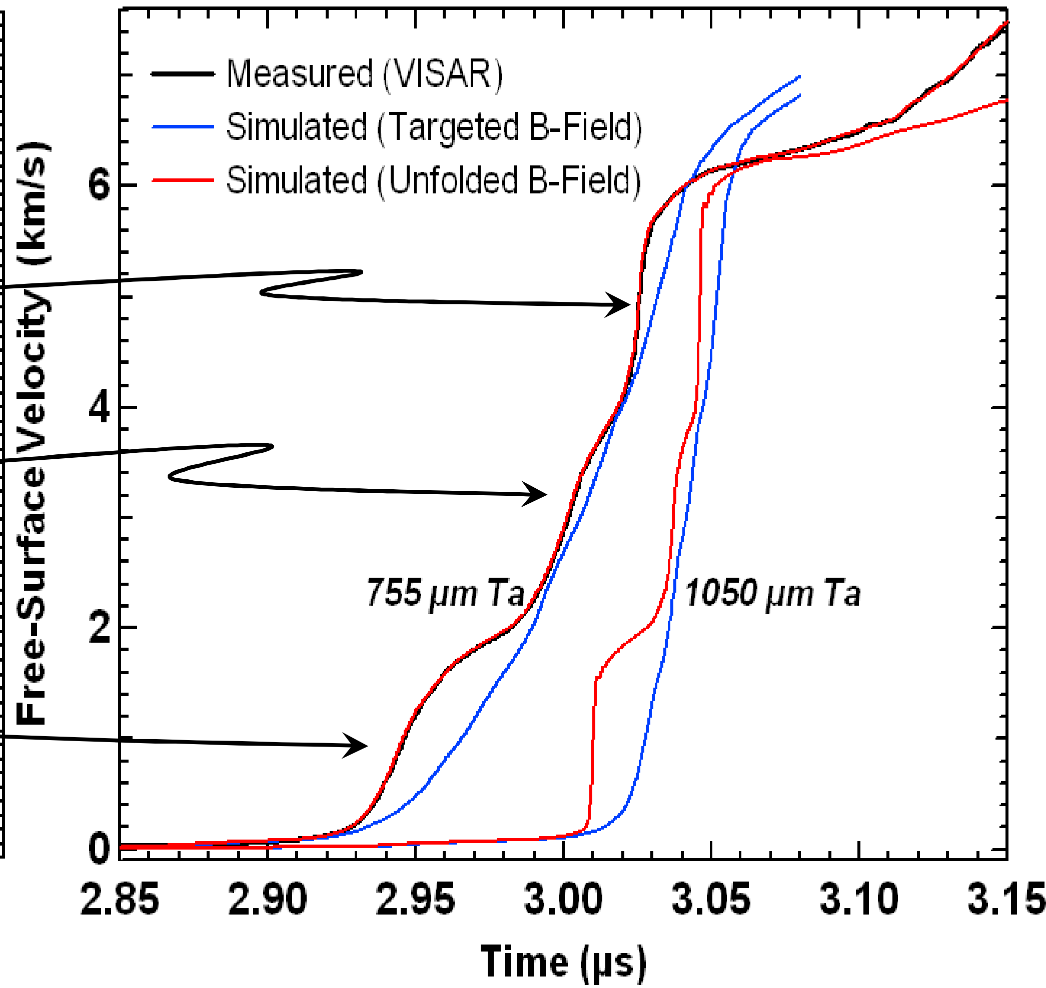
18 independently triggerable groups of 2 transmission lines

The Bertha circuit model enables fairly accurate prediction of machine performance

Current comparison



Wave profile comparison



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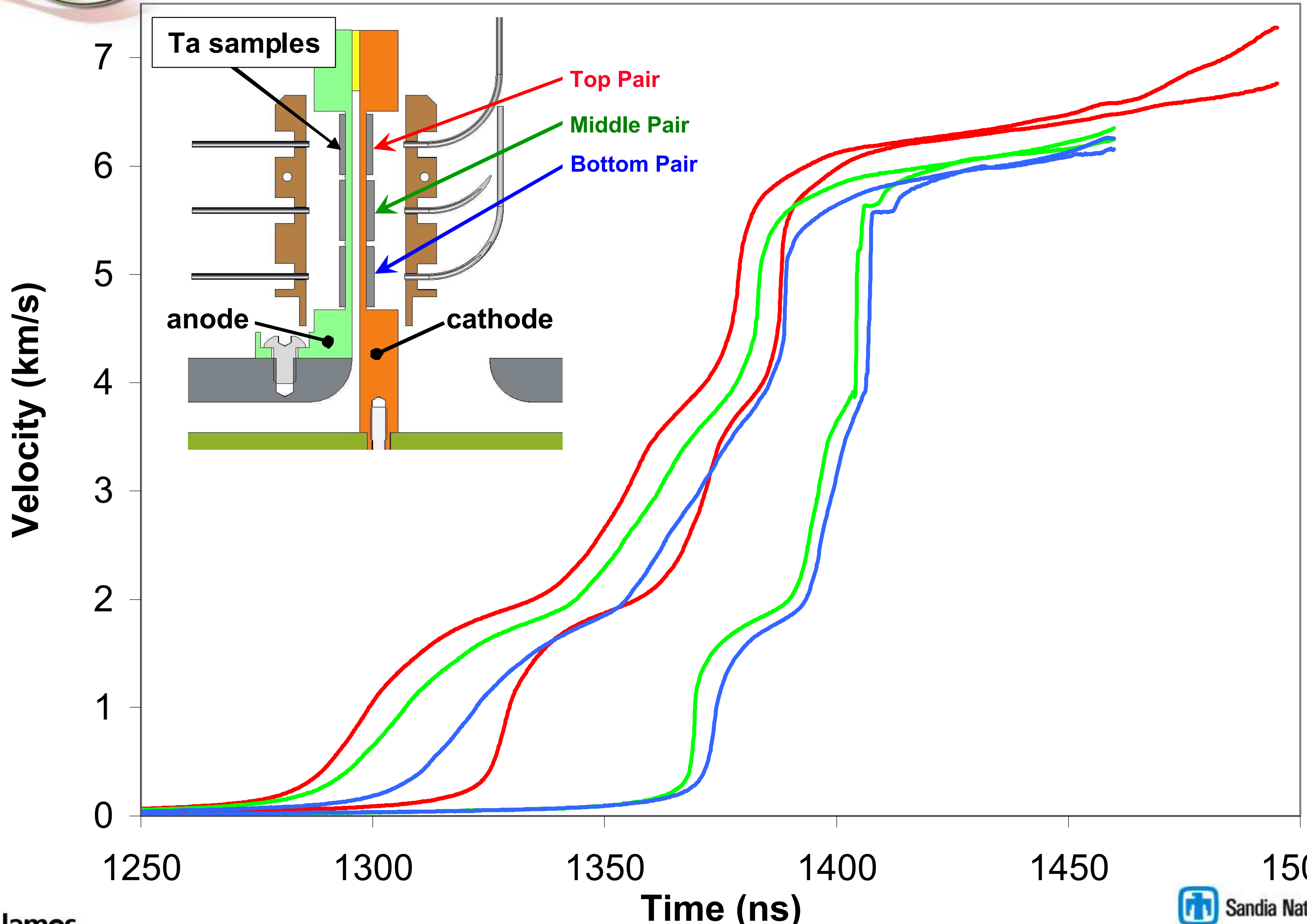
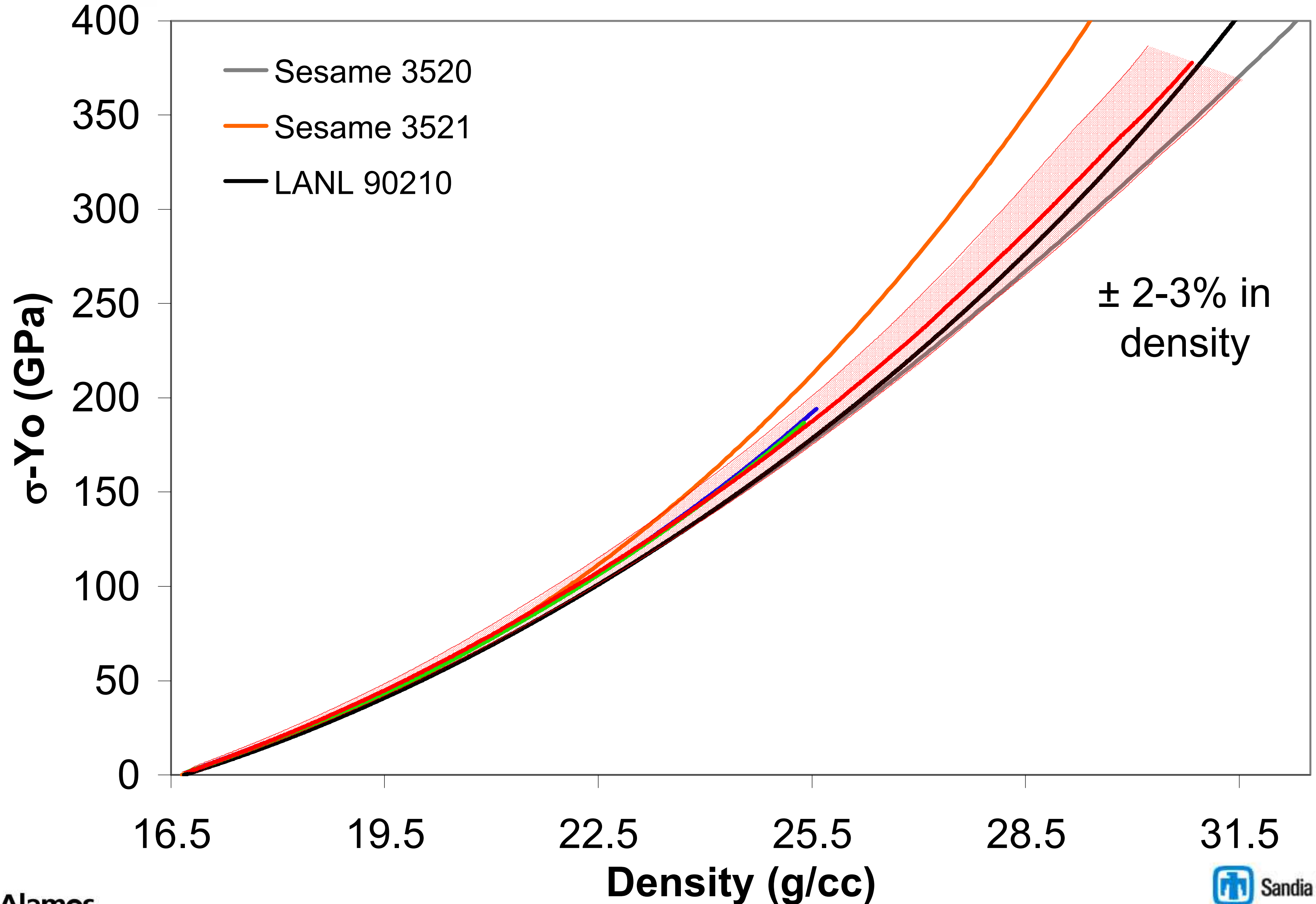
Data have been obtained which enable extraction of the Ta isentrope to nearly 400 GPa



The extracted isentrope discriminates between various tabular equations of state for Ta



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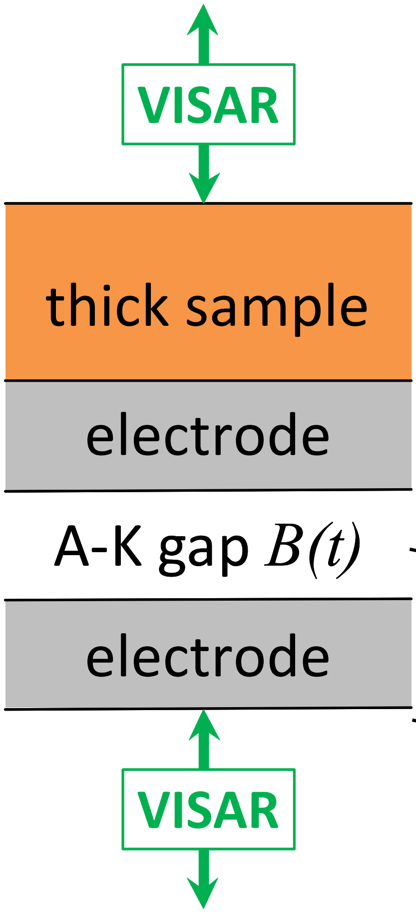
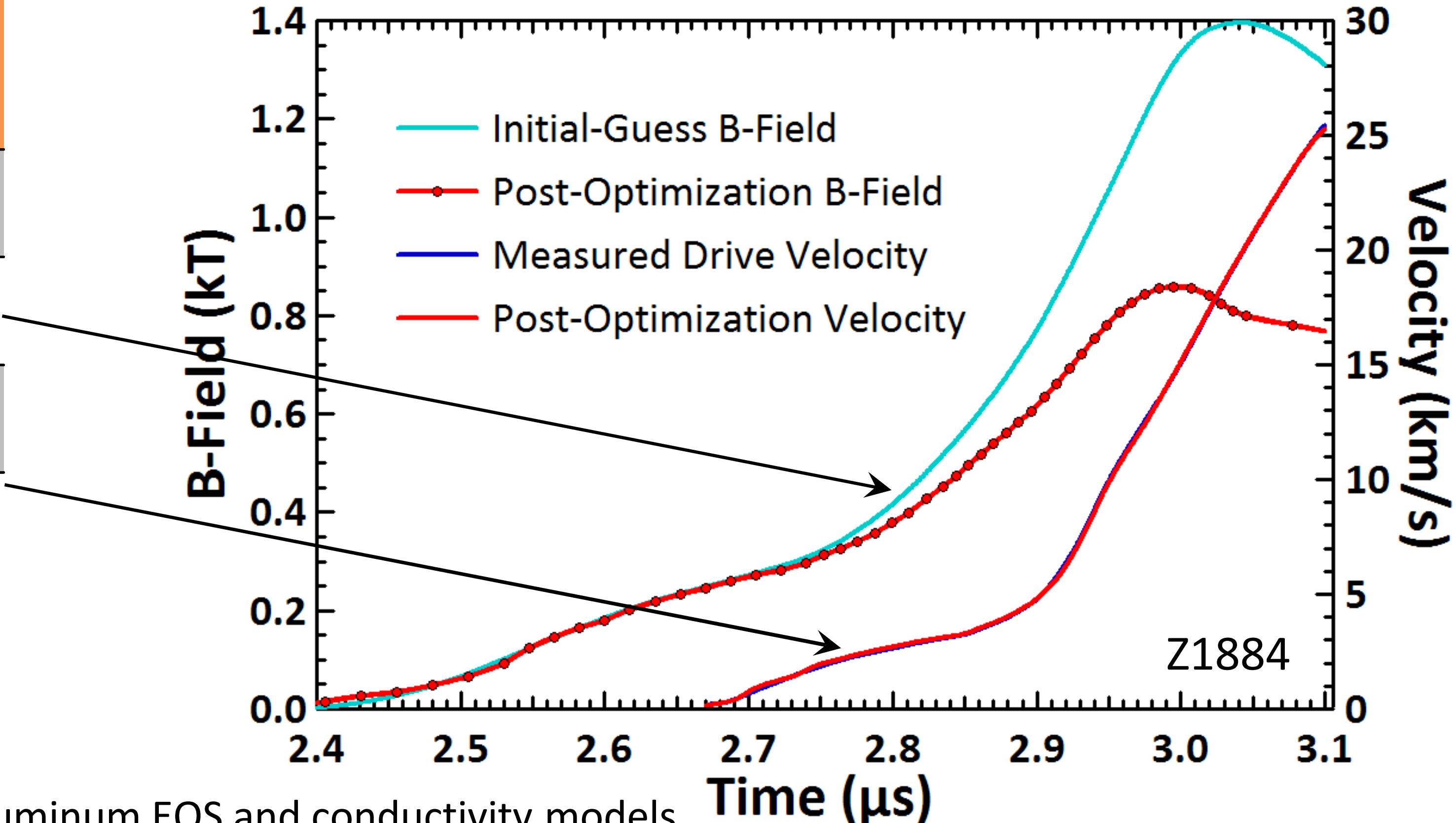
We are pursuing a single sample technique to take advantage of the relative large sample thickness

- Dakota optimization framework drives Alegra 1-D MHD simulations
- *B(t)* represented by constrained cubic spline (25-50 points) with time shift and stretch factors
- objective function is metric of isometry between simulated and experimental velocity history at electrode back surface





MHD simulations:

- high confidence in aluminum EOS and conductivity models
- high spatial resolution (2.5-µm cells)

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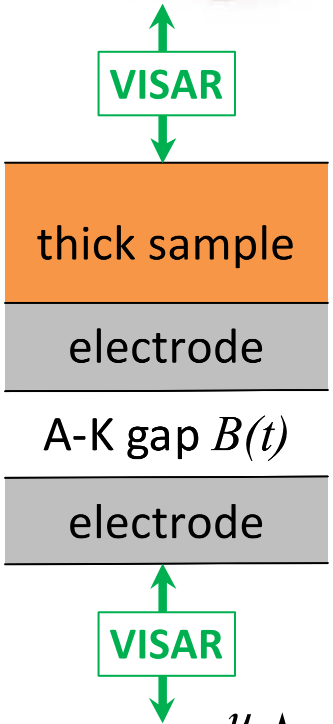
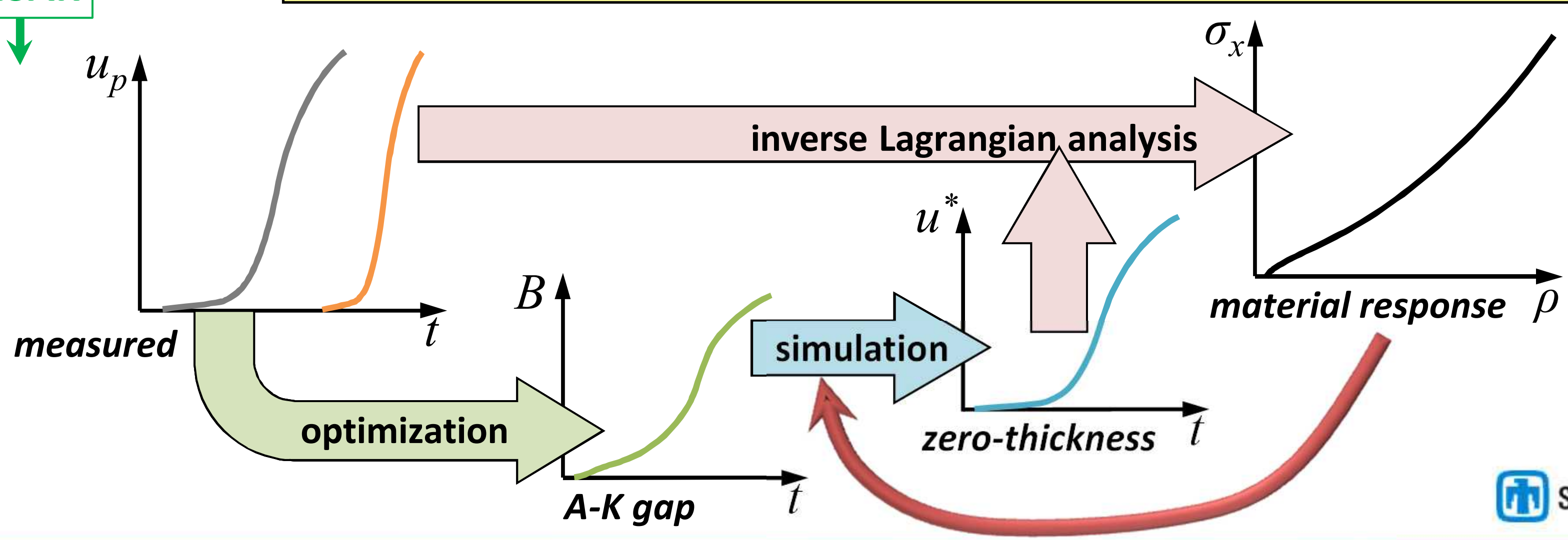
Single sample yields isentrope by iterating inverse analysis with simulated "zero-thickness" velocity

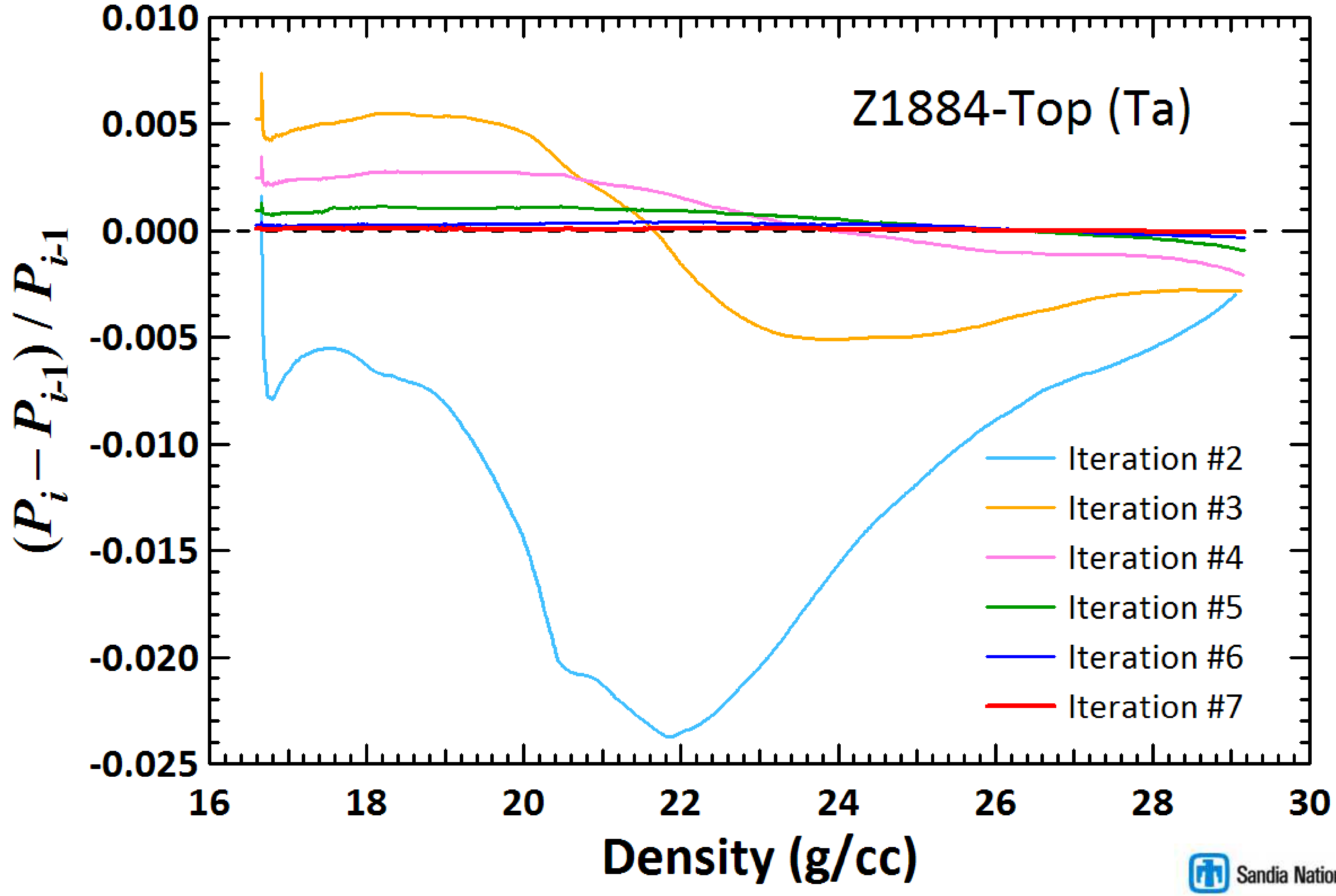
1. measure velocity at back faces of sample and opposite electrode
2. use optimization to determine $B(t)$ from electrode measurement
3. use $B(t)$ and first-guess sample EOS (Sesame table + strength) to simulate electrode/sample interface "zero-thickness" velocity
4. perform inverse Lagrangian analysis on simulated "zero-thickness" velocity and measured back-face velocity of sample
5. convert resulting $\sigma_x(\rho)$ curve to full tabular EOS by assuming constant c_V and Γ/V, equating stress to pressure (strength folded into EOS)
6. use $B(t)$ and new tabular EOS to simulate electrode/sample interface
7. repeat steps 4-6 until material response converges



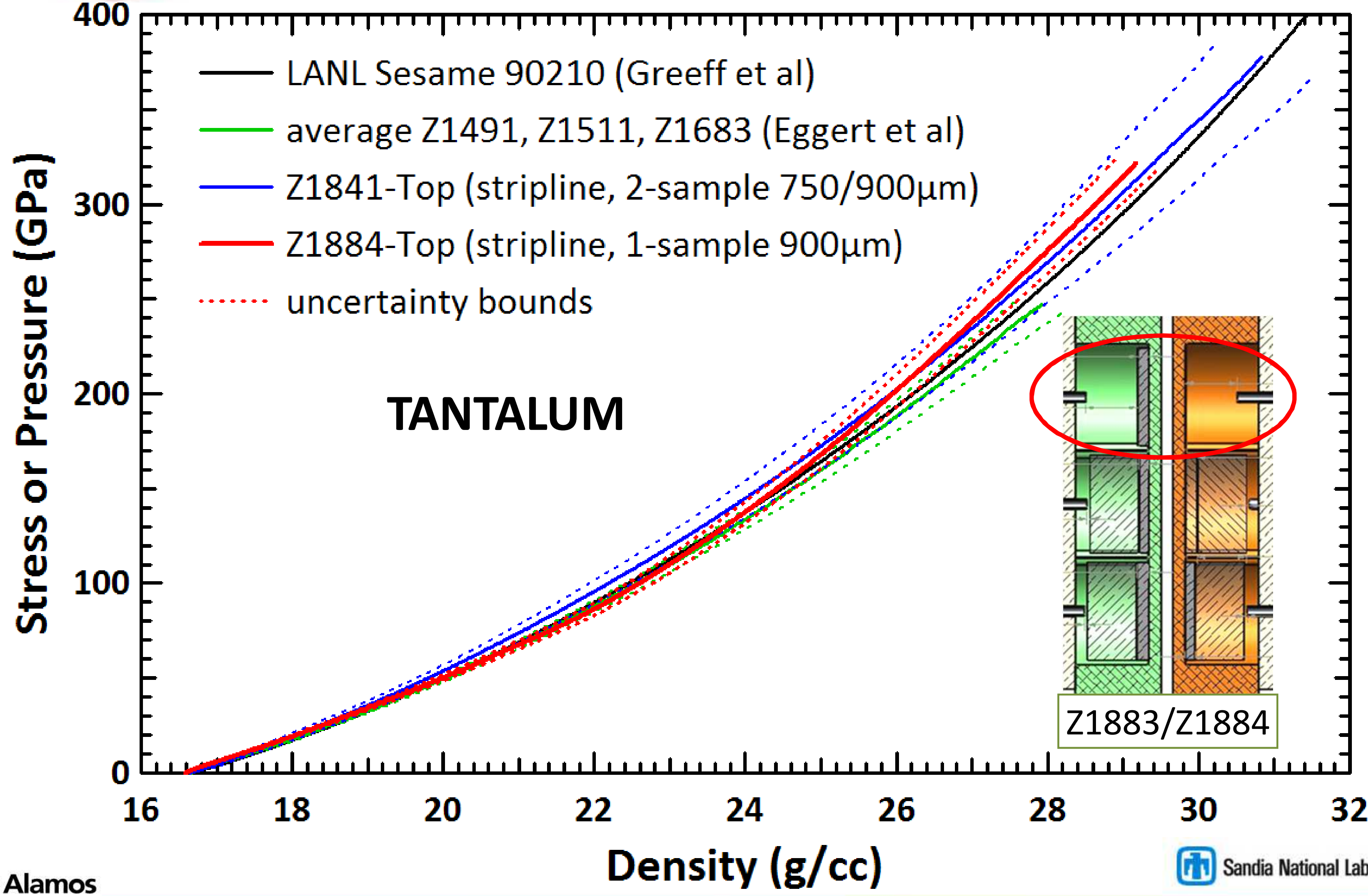


Outer loop of single-sample approach converges

result changes < 0.015% from 6th to 7th iteration



Single-sample measurement of tantalum to 320 GPa decreases uncertainty over two-sample measurement



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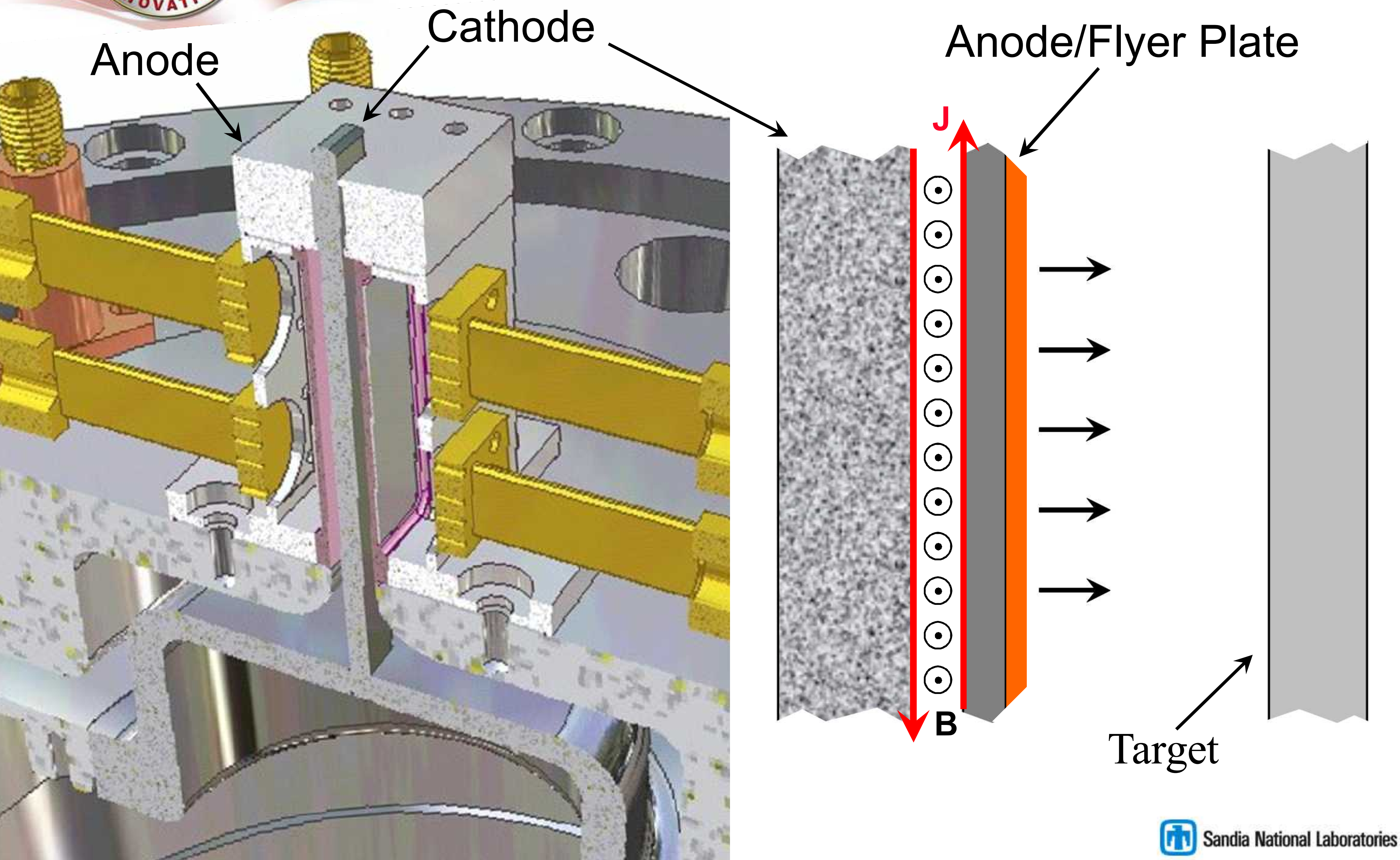
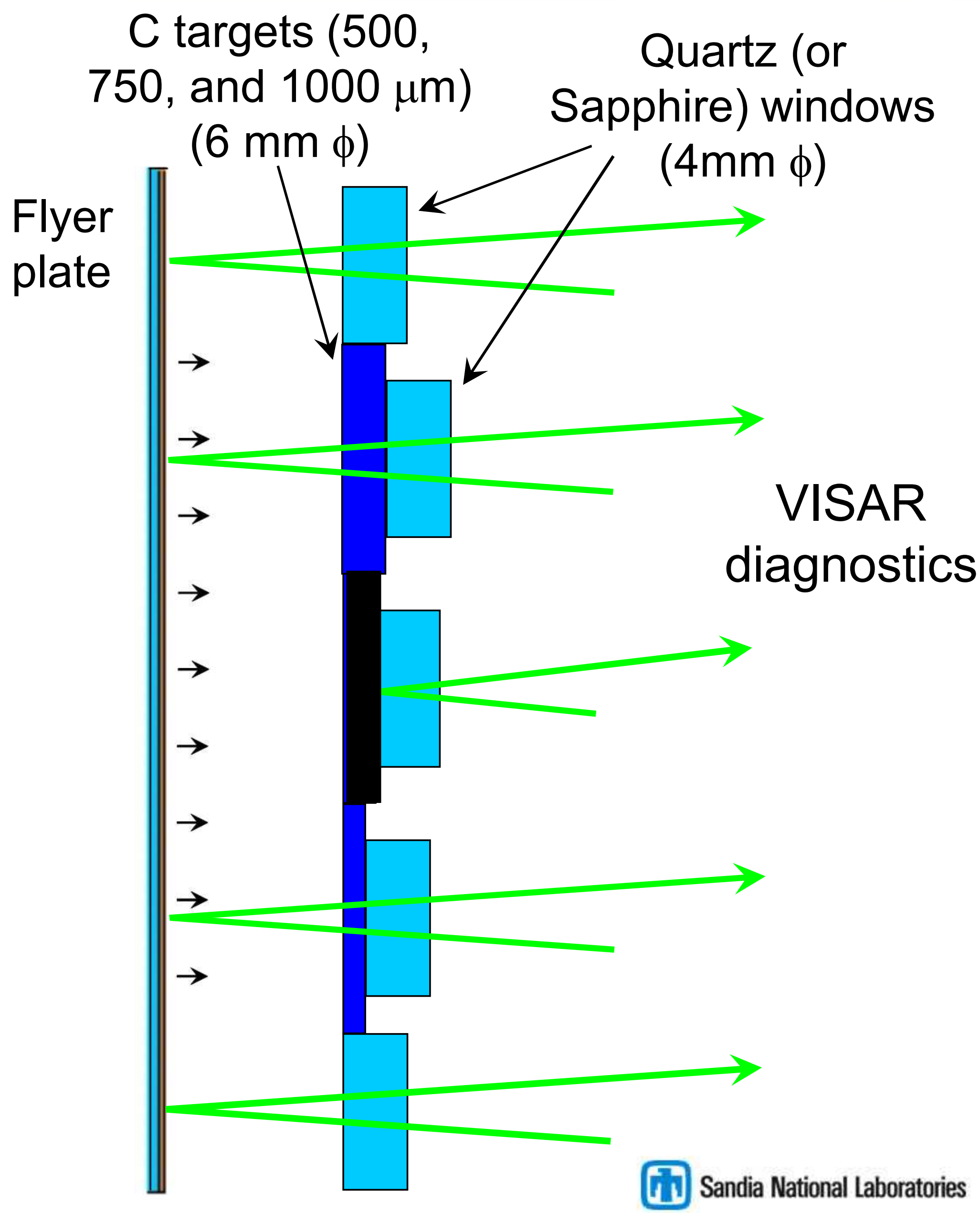
With proper pulse shape and design the anode can be launched as an effective high-velocity flyer plate



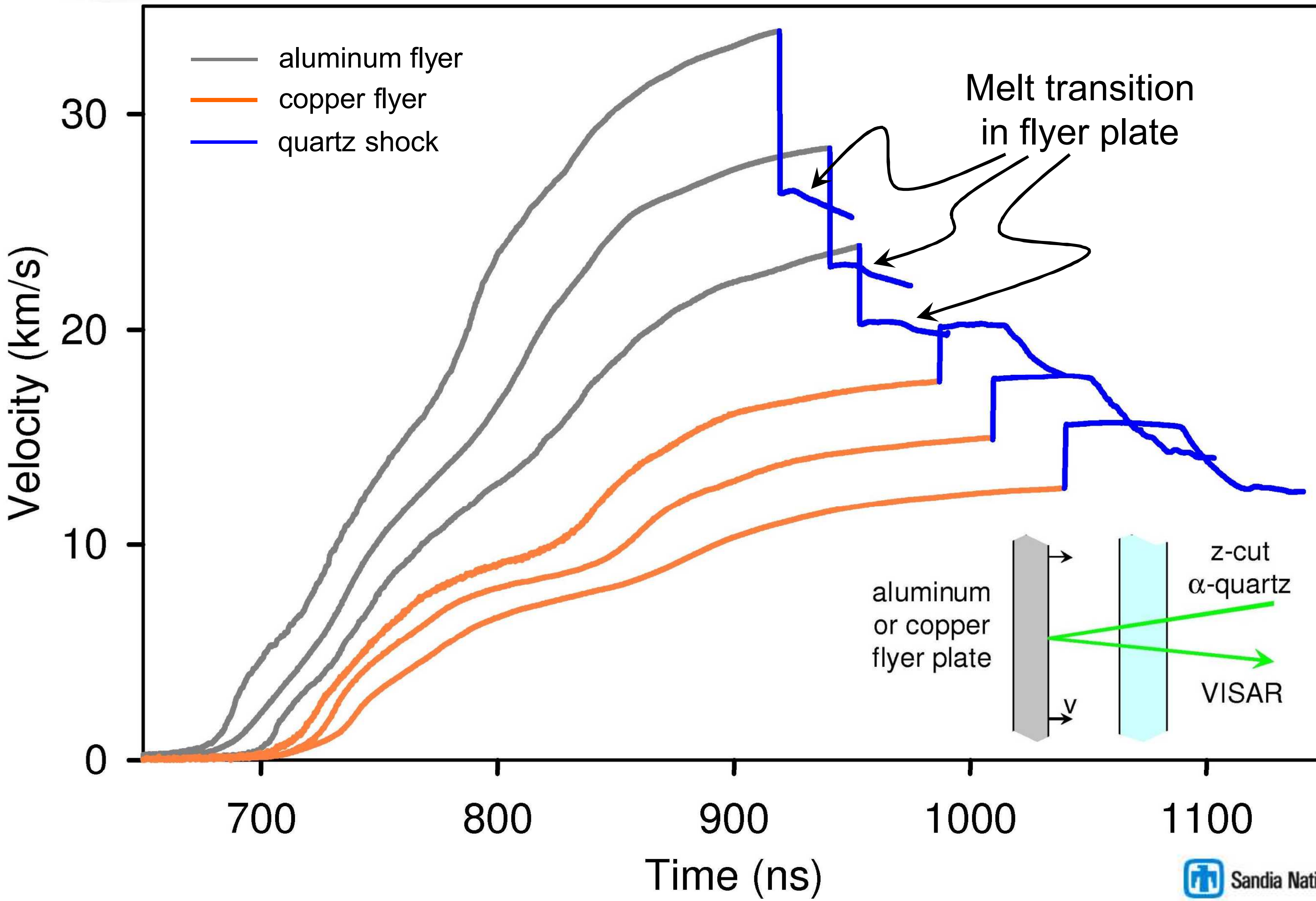
Quartz has been used as a transparent window enabling multiple flyer velocity measurements

Typical configuration



Knudson, et al., Science 322, 1822 (2008)

VISAR provides highly accurate in line flyer plate and quartz shock velocity measurements



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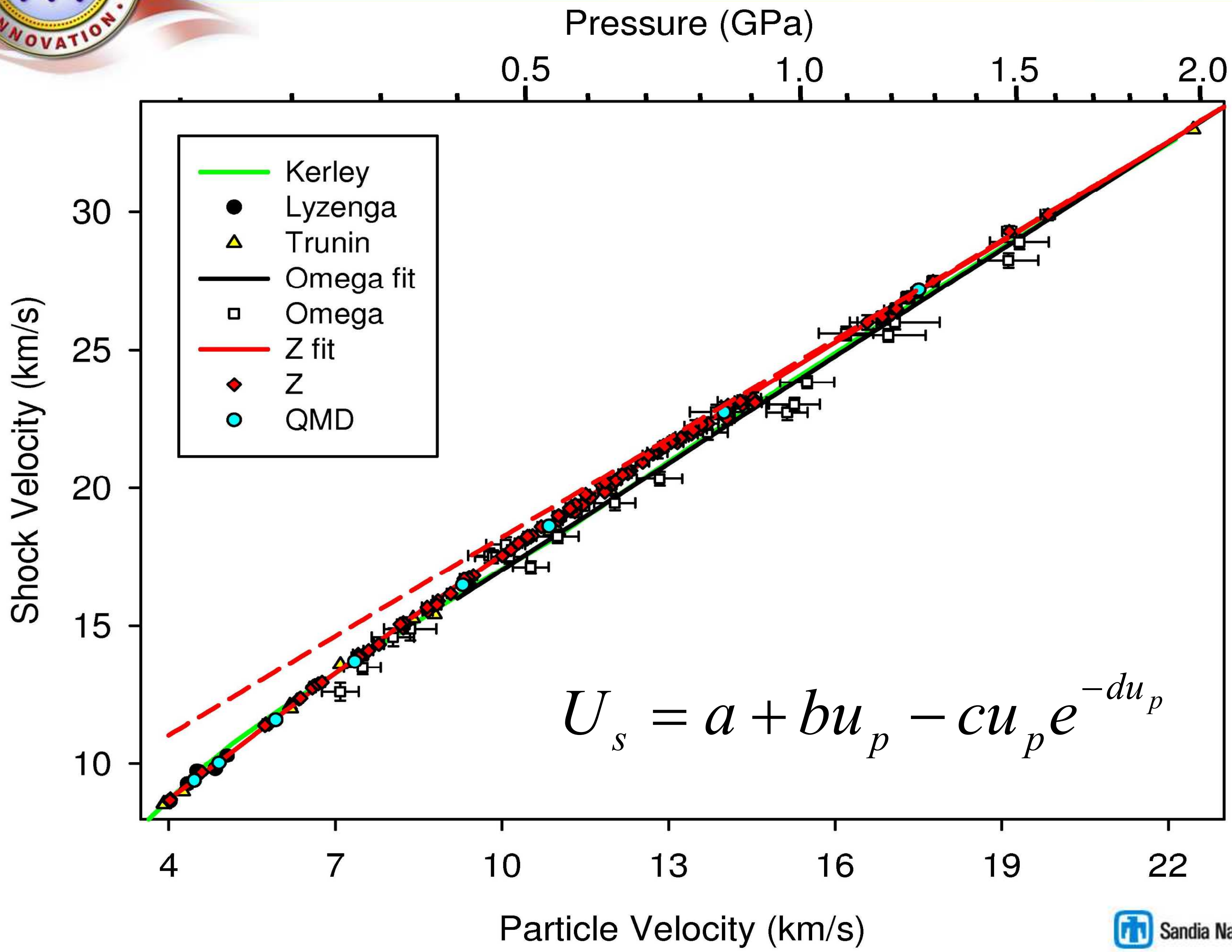
U_s-u_p Hugoniot for α-Quartz



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

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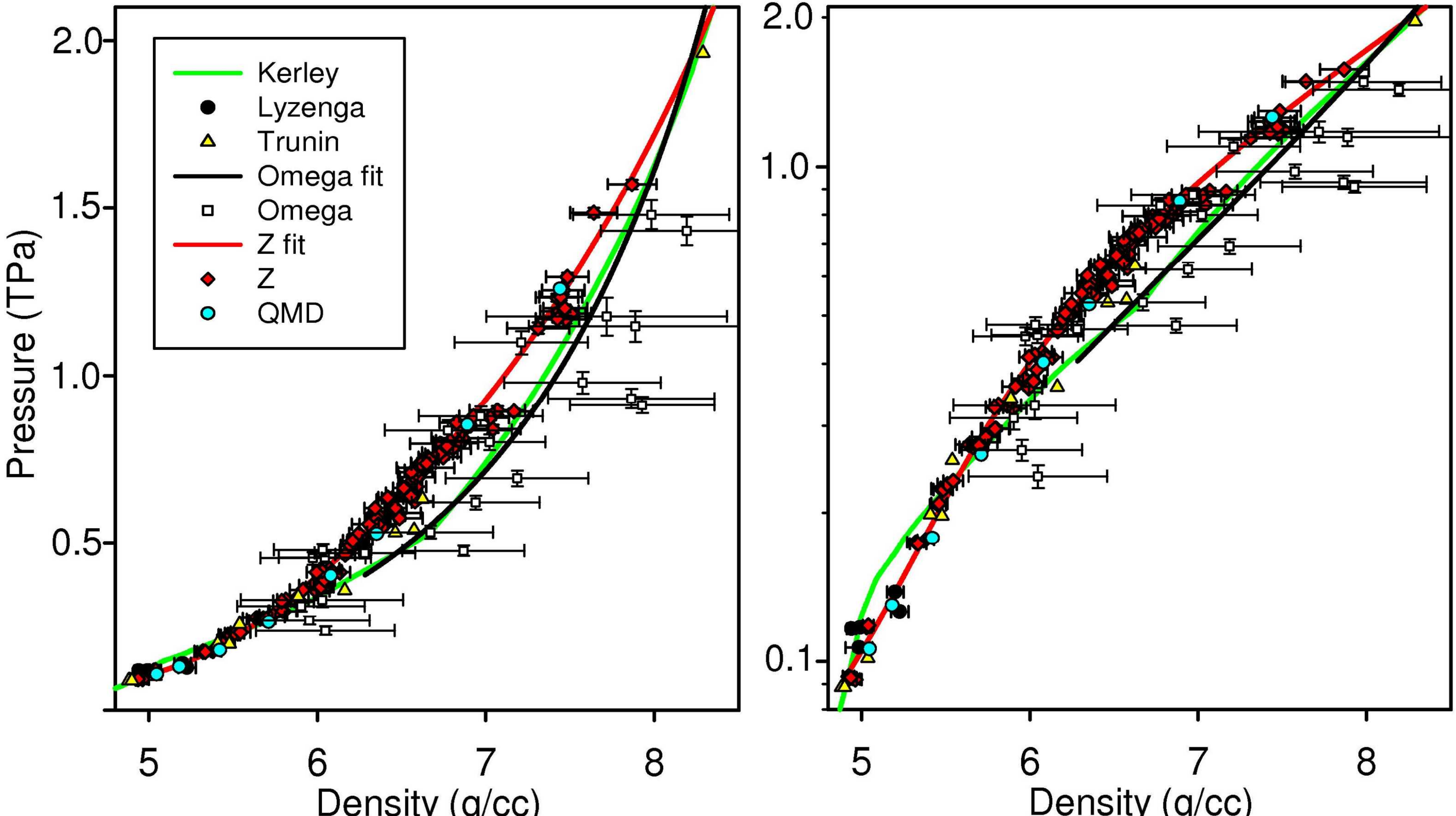
Knudson, et al., PRL 103, 225501 (2009)

Pressure – density Hugoniot for α-Quartz



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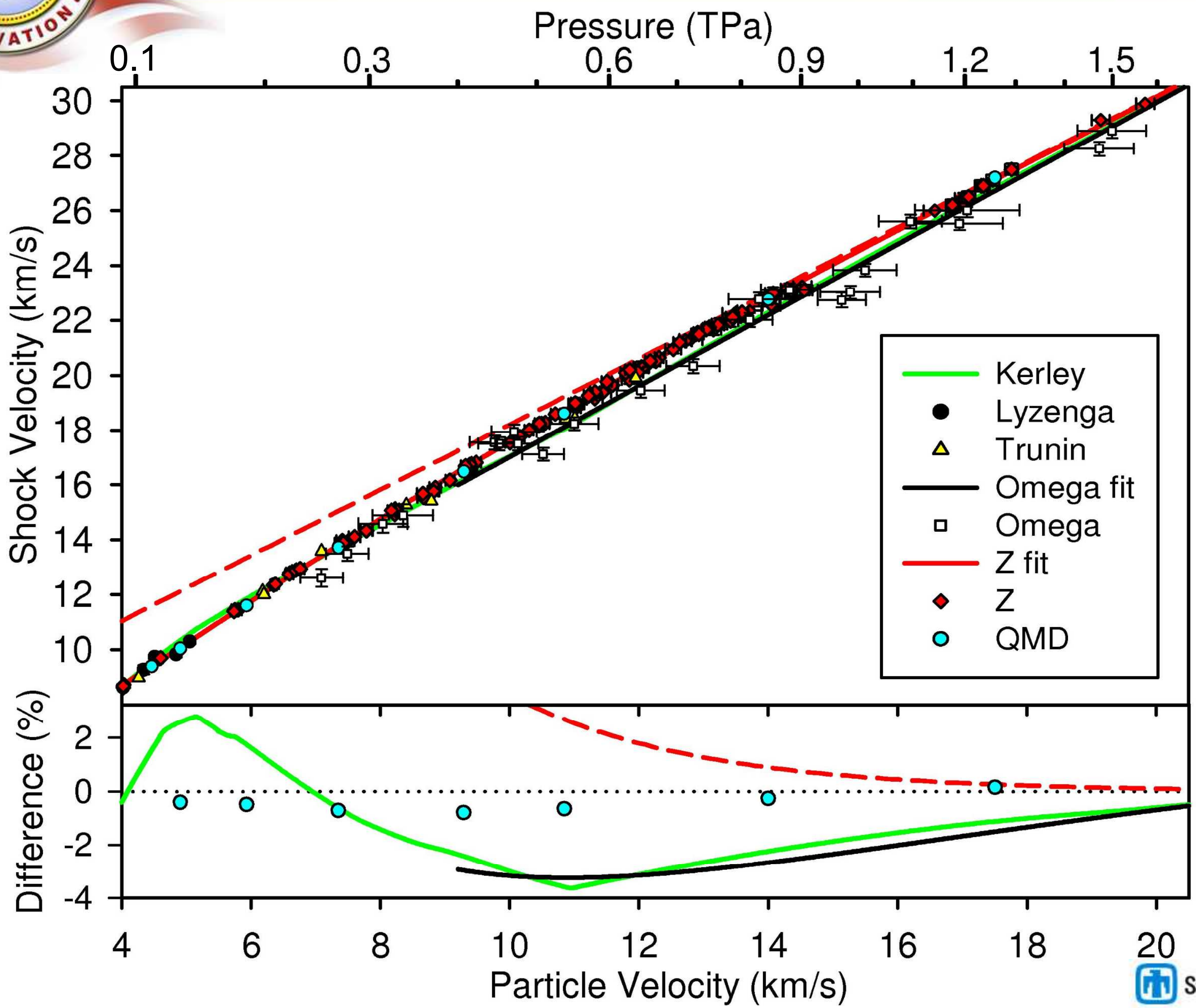
U_s residuals with respect to the Z-fit indicate dissociative effects extend to much higher pressure



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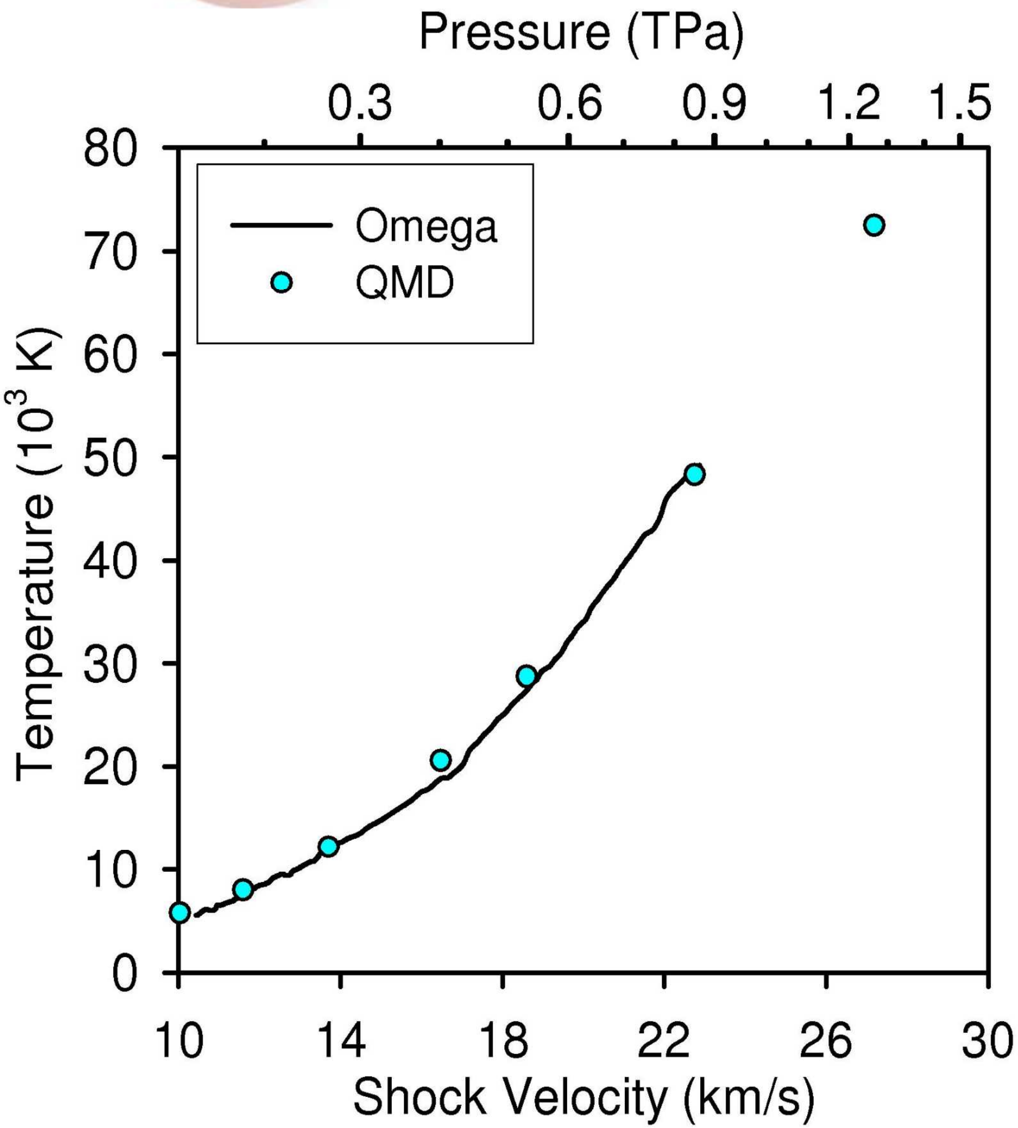
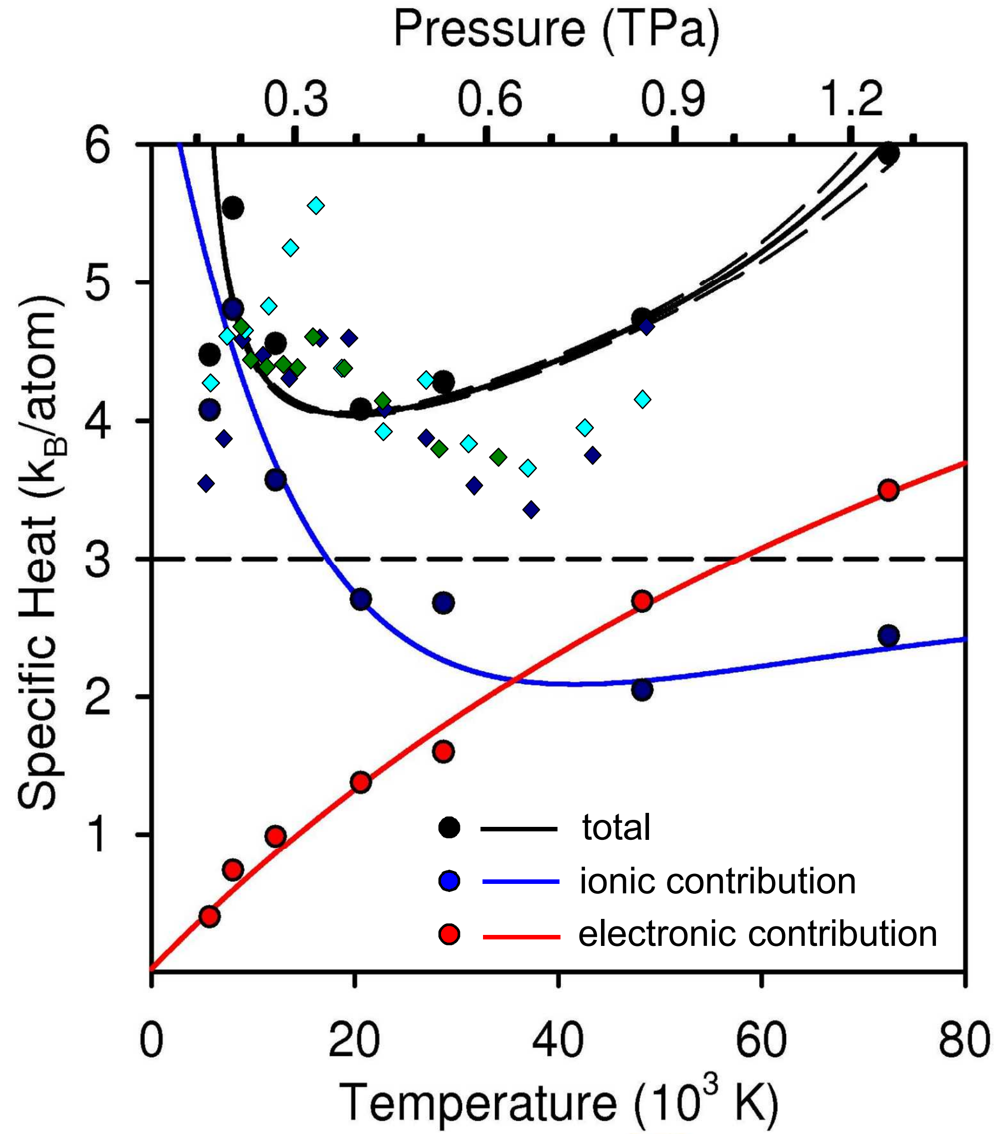
QMD calculations provide unique insight into the dynamics of the fluid at multi-Mbar pressures





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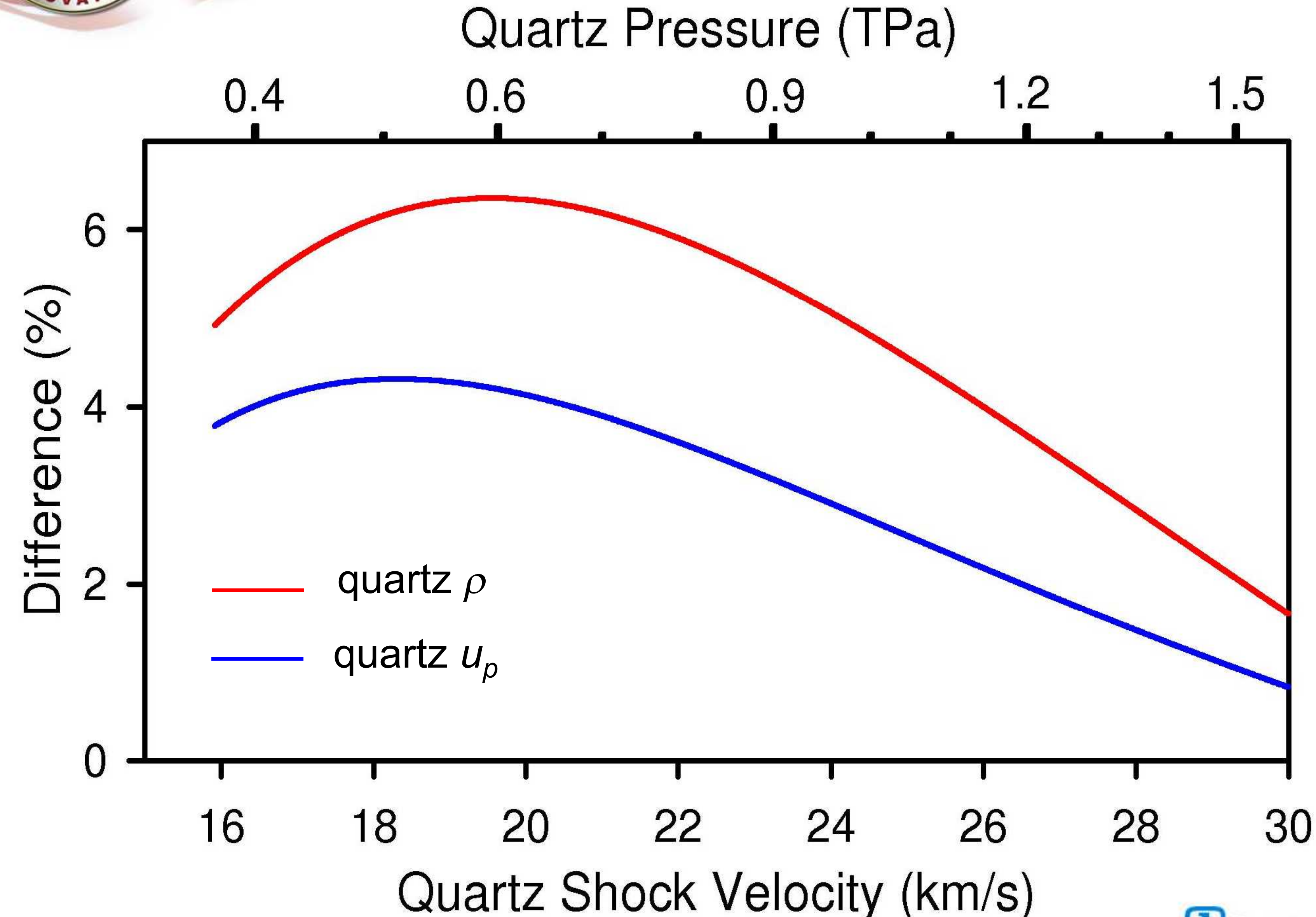
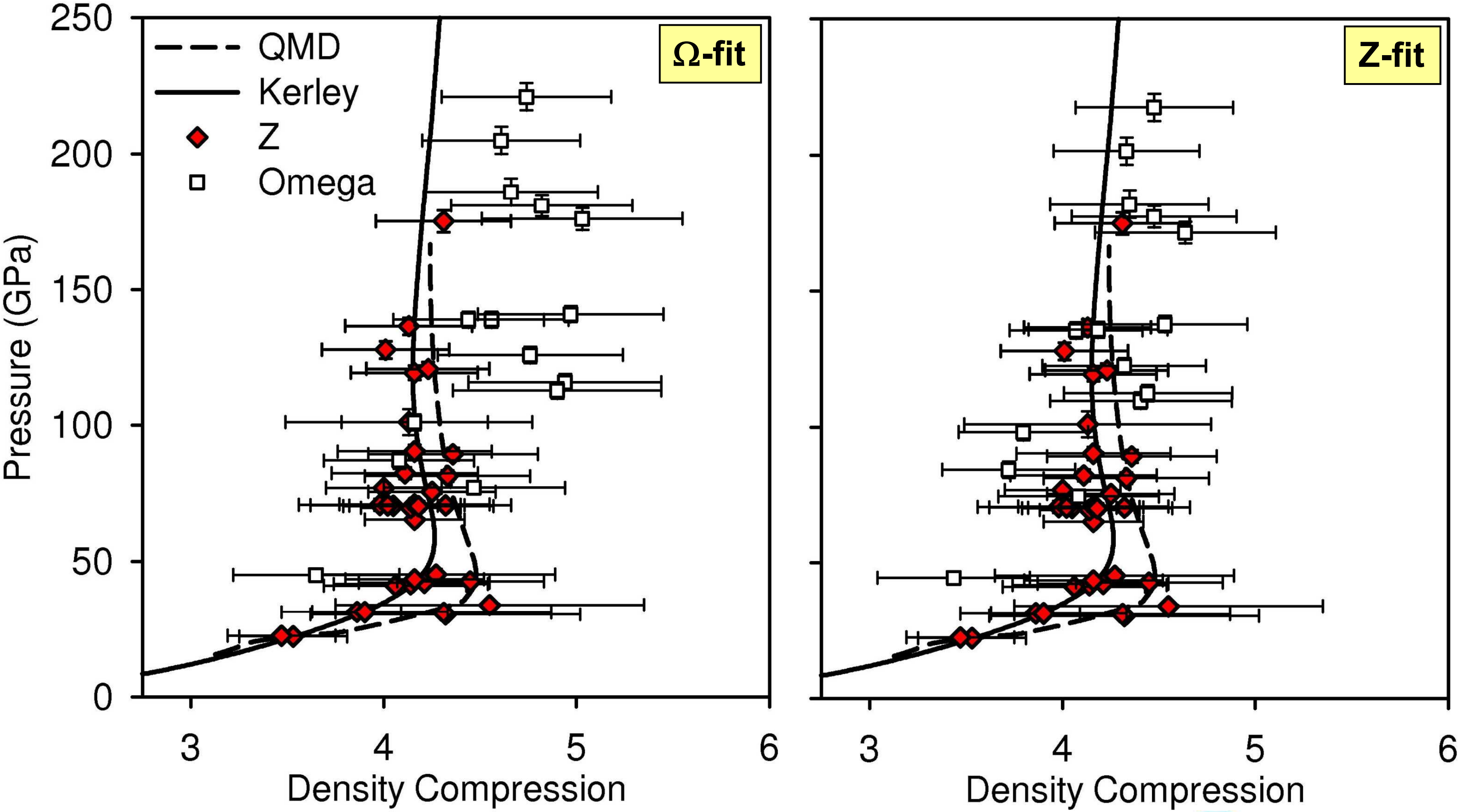
Hicks, et al., Phys. Rev. Lett. 97, 025502 (2006)

Differences in Z- and Ω-fits will have a significant impact on quantities inferred from quartz U_s



Knudson, et al., PRL 103, 225501 (2009)

Recently published deuterium data becomes significantly stiffer upon reanalysis



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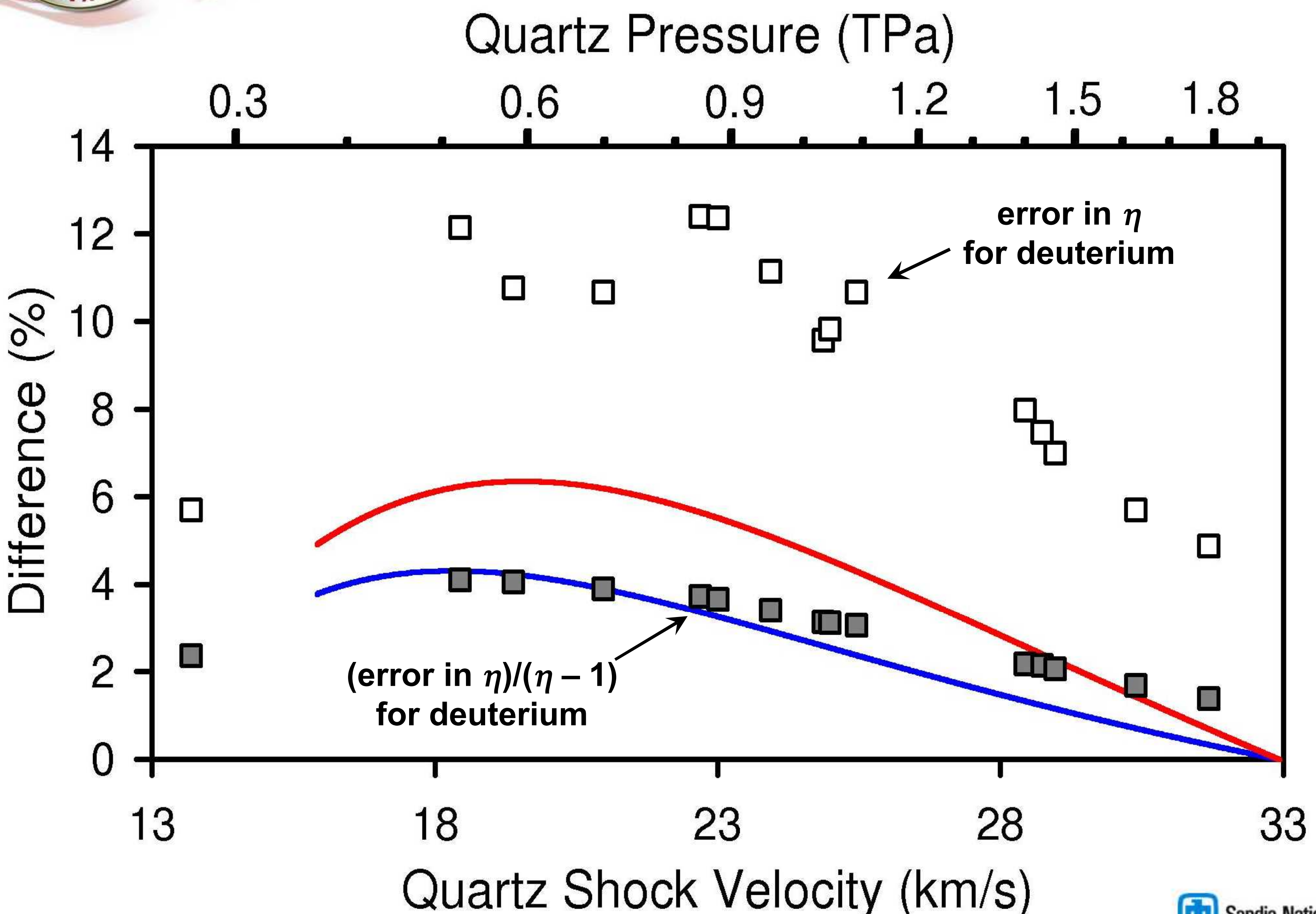
Errors in density compression, η, are given by the error in quartz u_p multiplied by the factor $(\eta - 1)$



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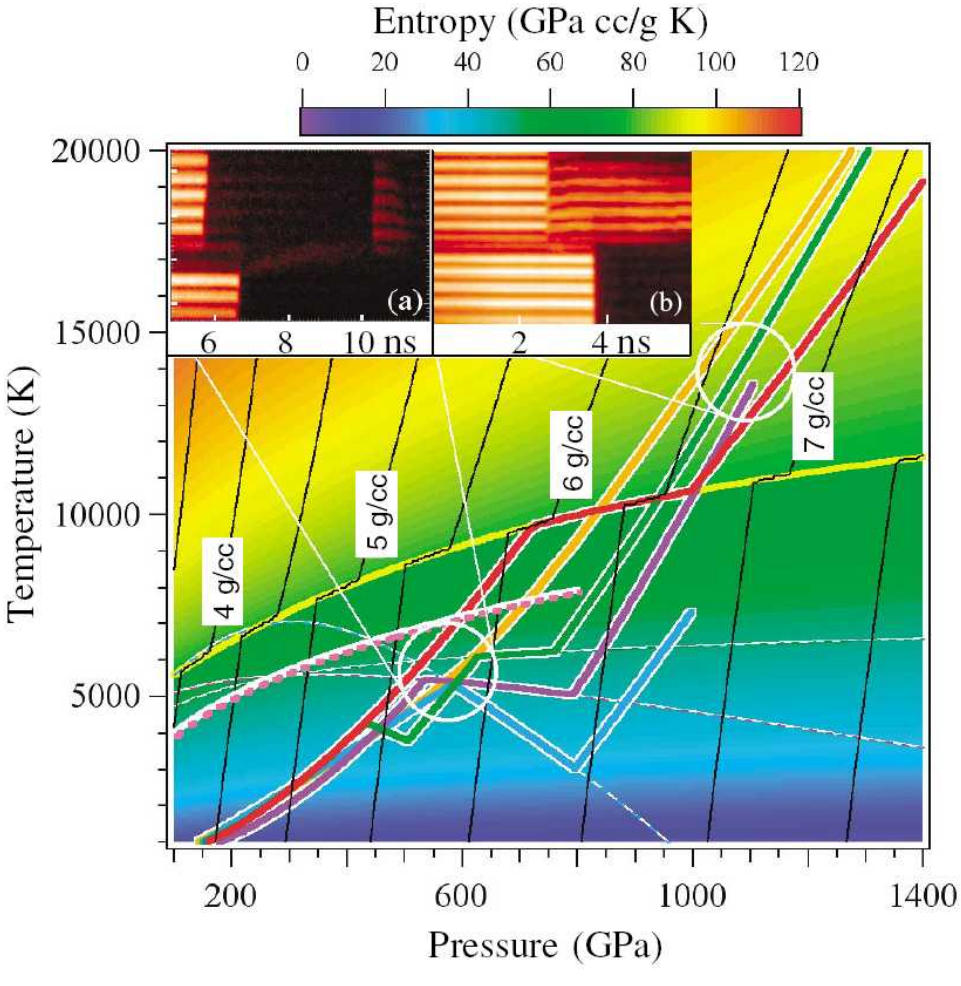
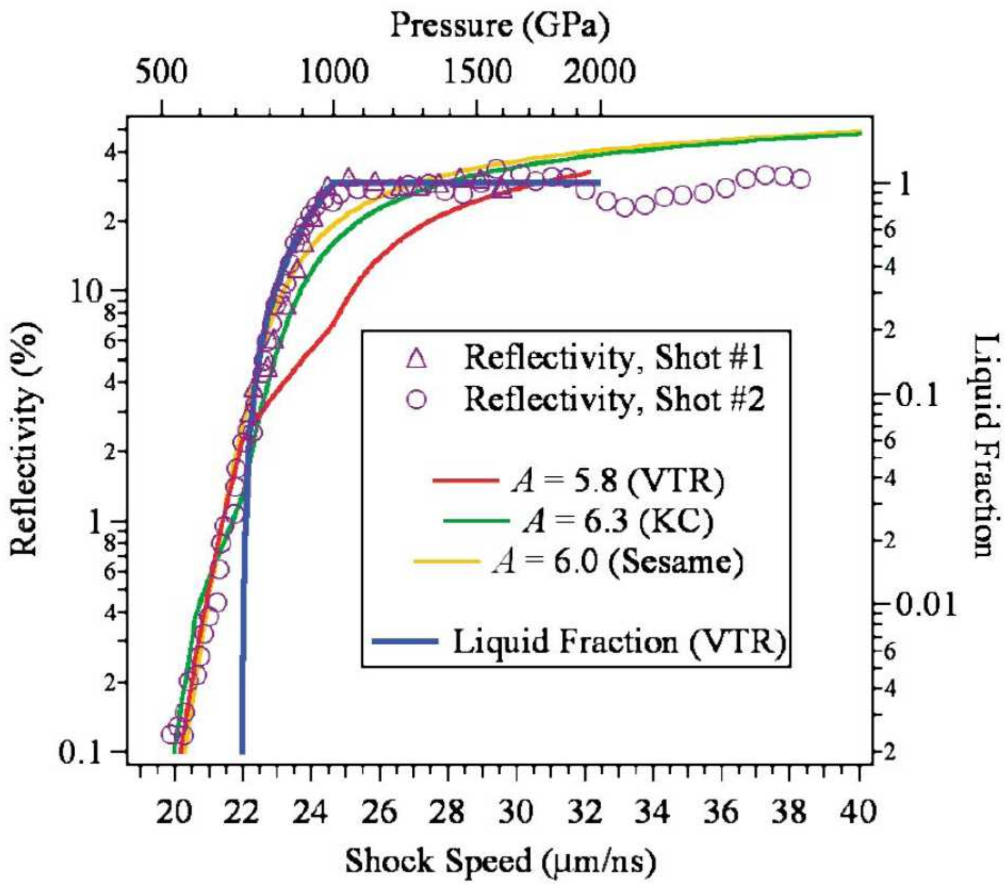
Existing models for diamond exhibit a broad range of predicted melt behavior – melt poorly understood

Several chemical picture models for diamond



Reflectivity study on Omega suggests complete melt near 1100 GPa



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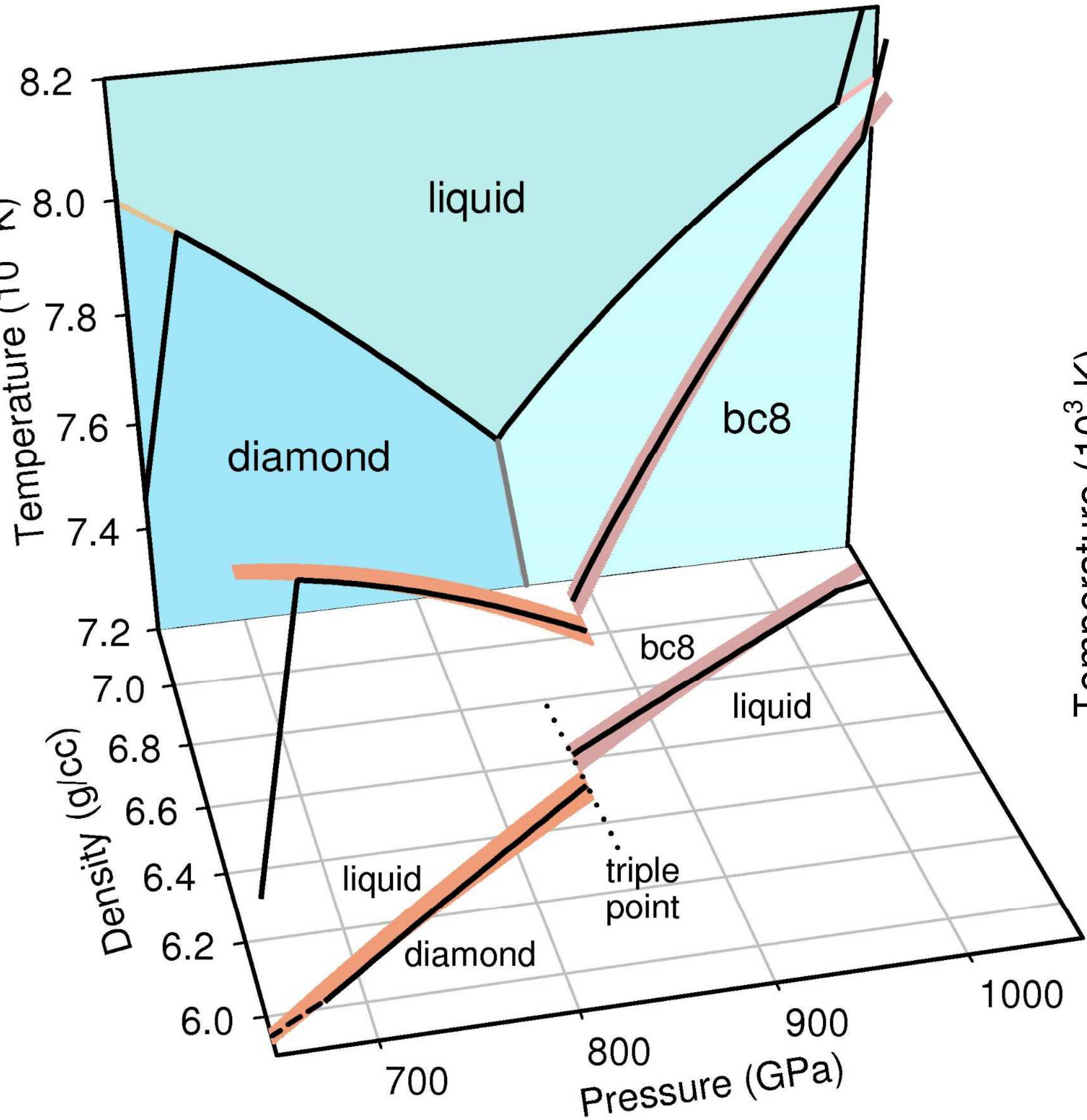
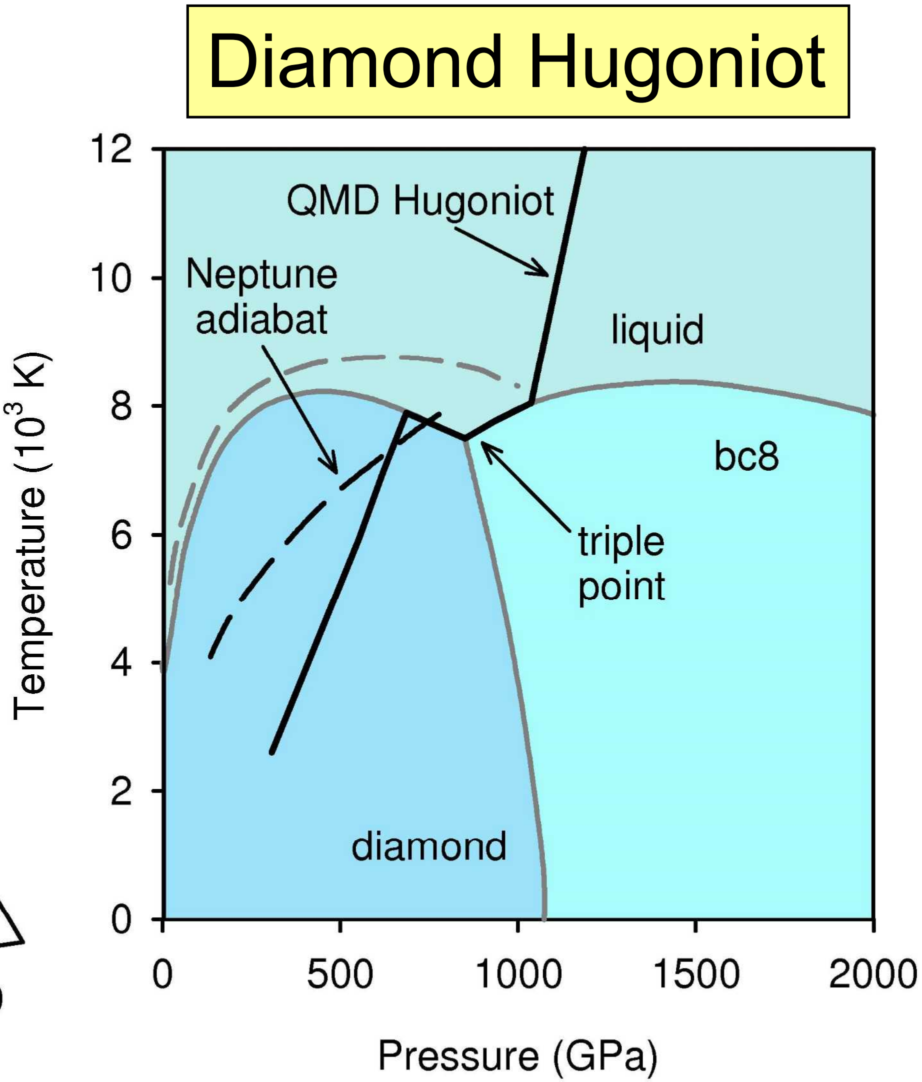
Quantum Molecular Dynamics calculations provided estimates for melt and predicted a triple point (TP)





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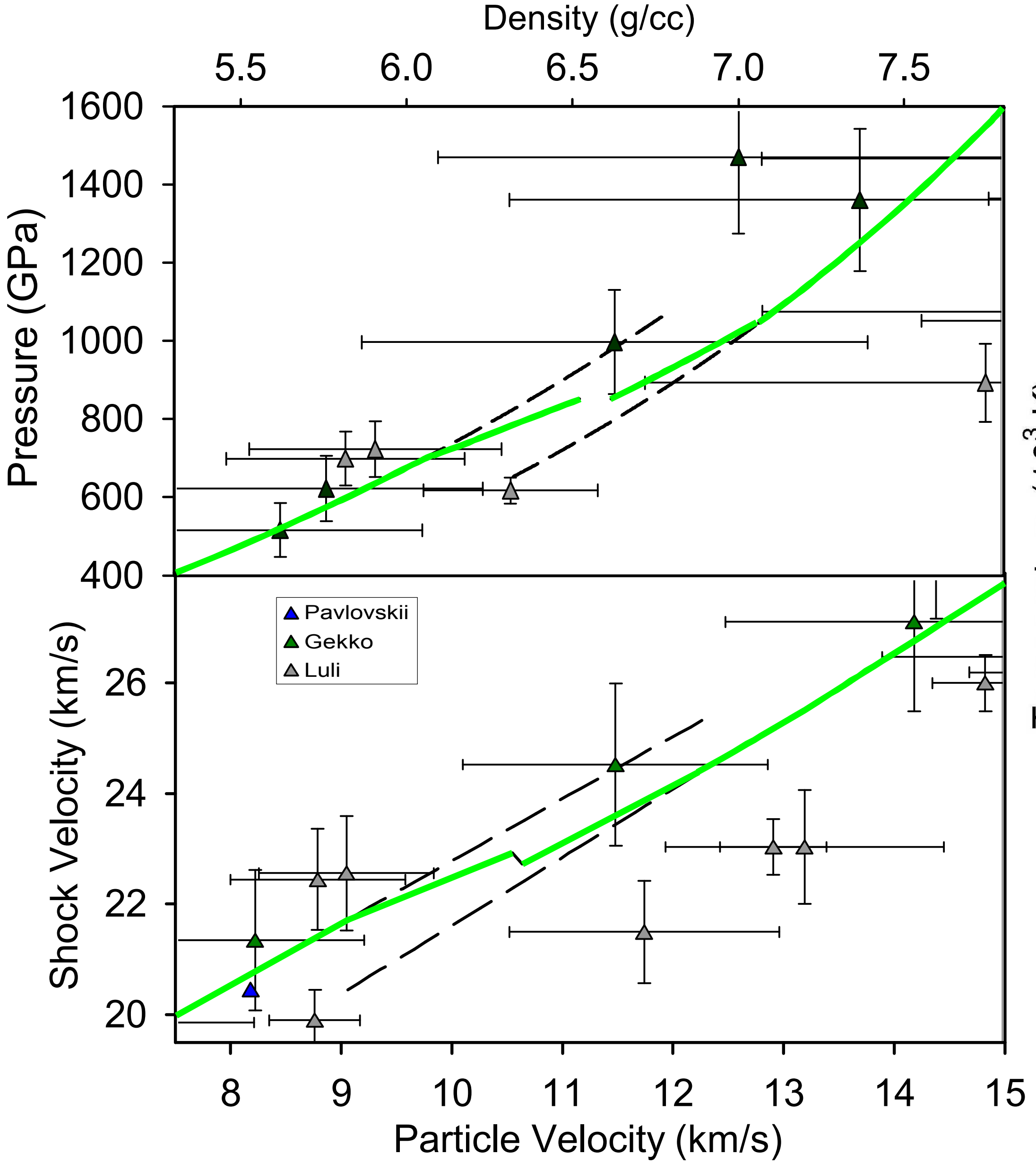
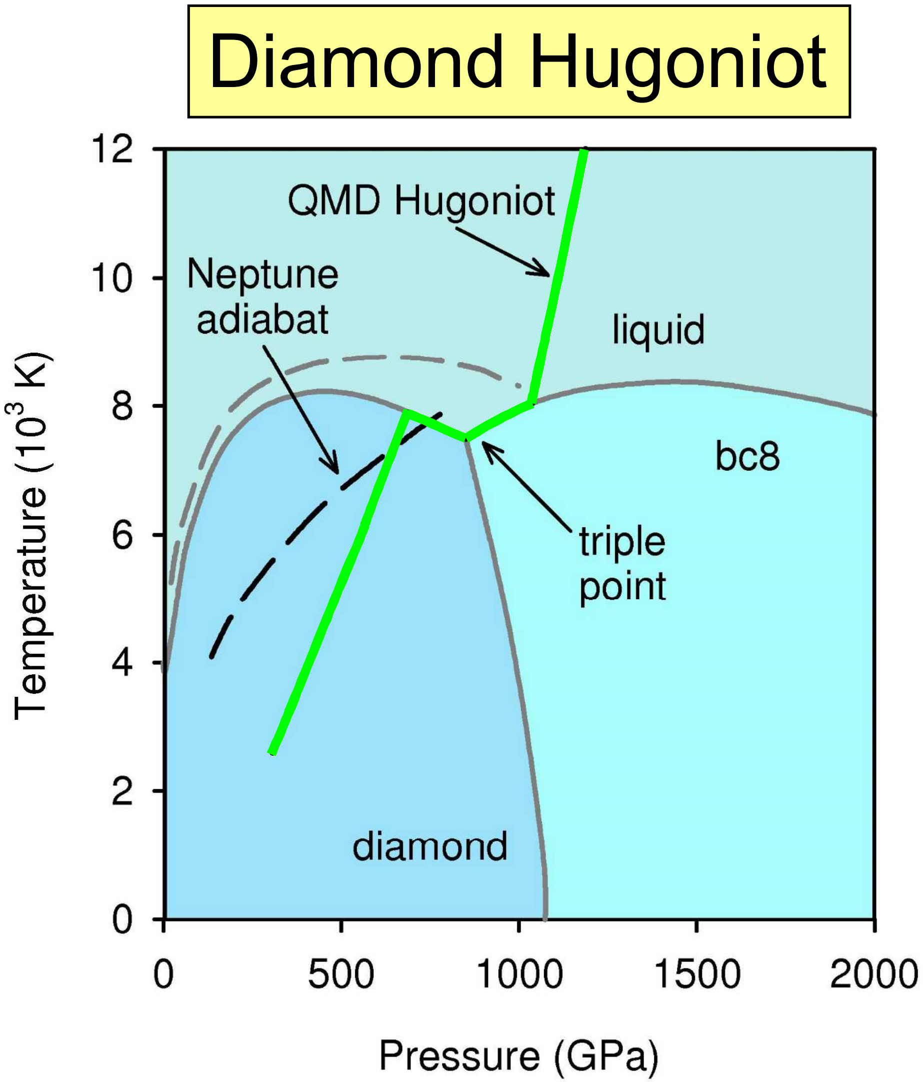
Correa, et al., PNAS **103**, 1204 (2006)

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





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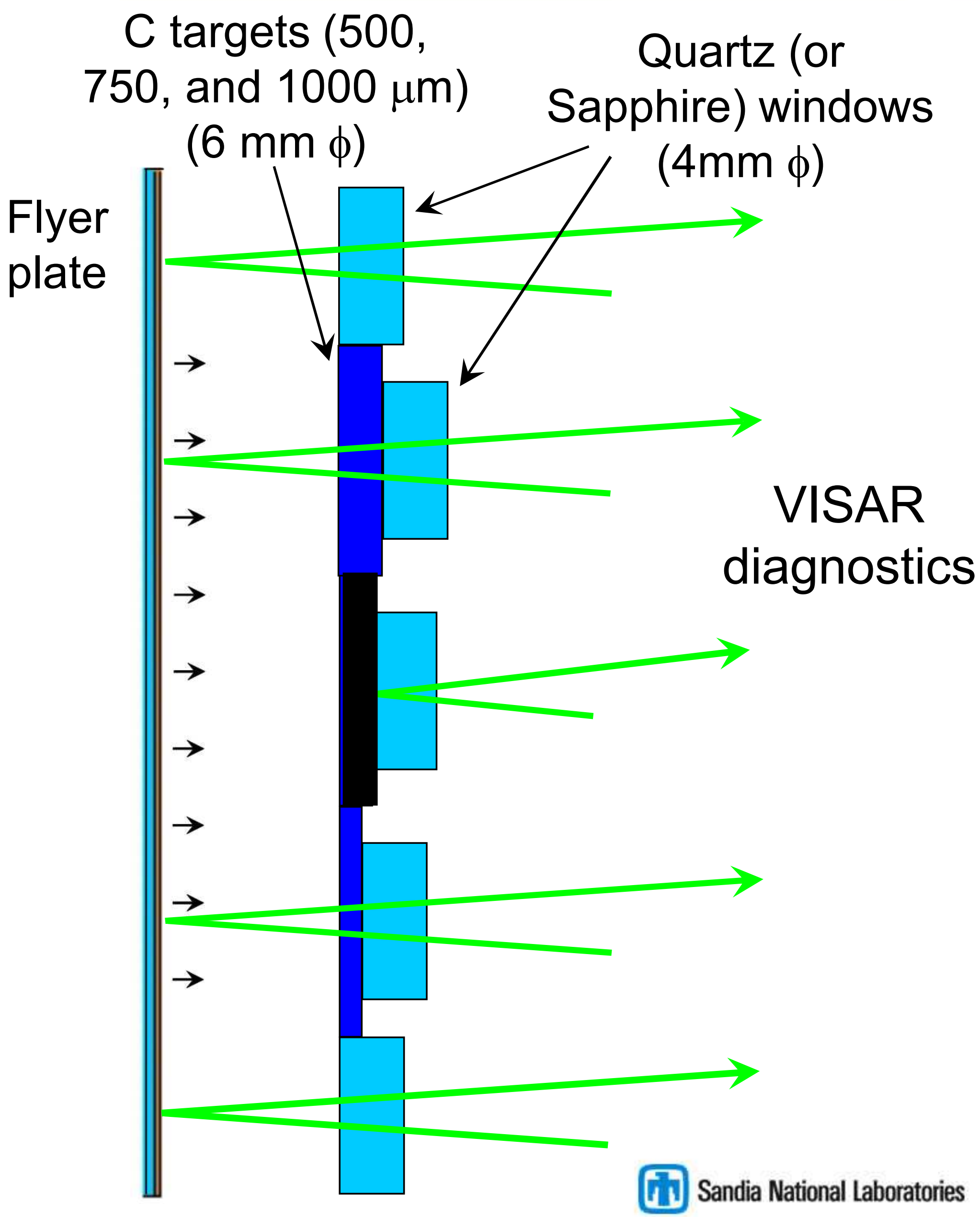
Relatively large flyer plates enabled multiple, redundant measurements increasing accuracy

Diamond experimental configuration



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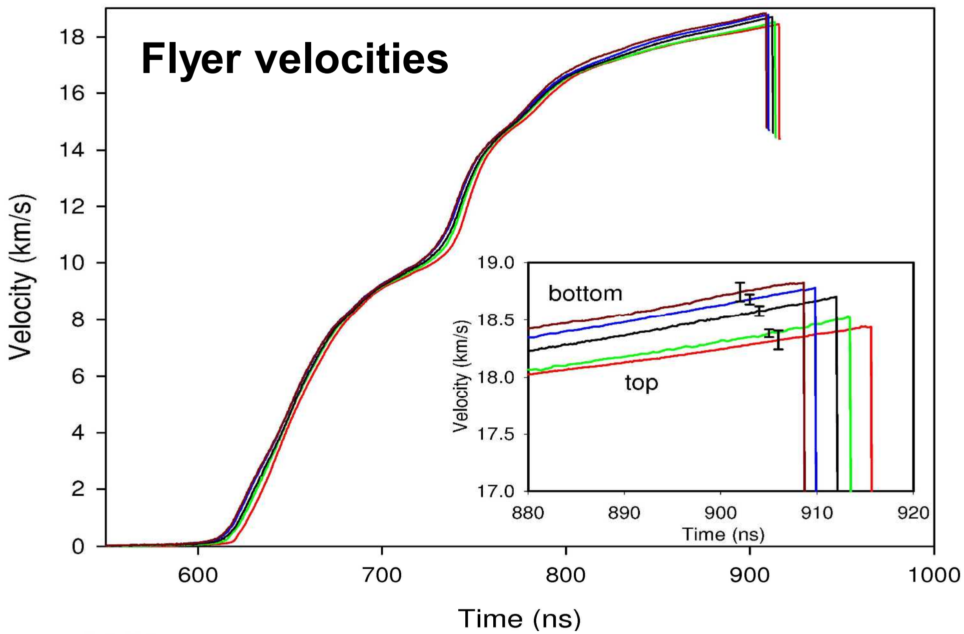
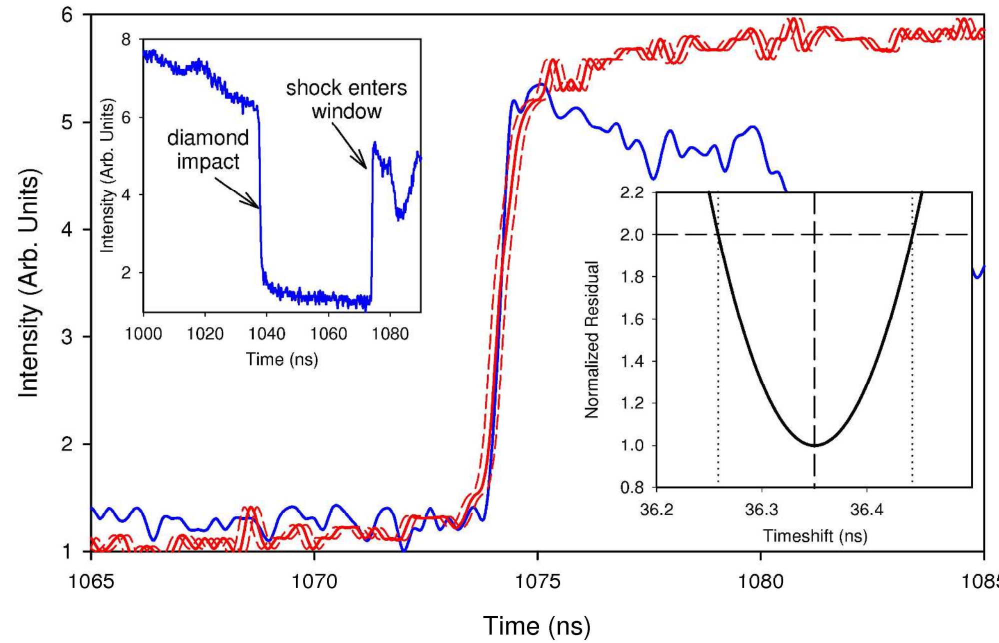
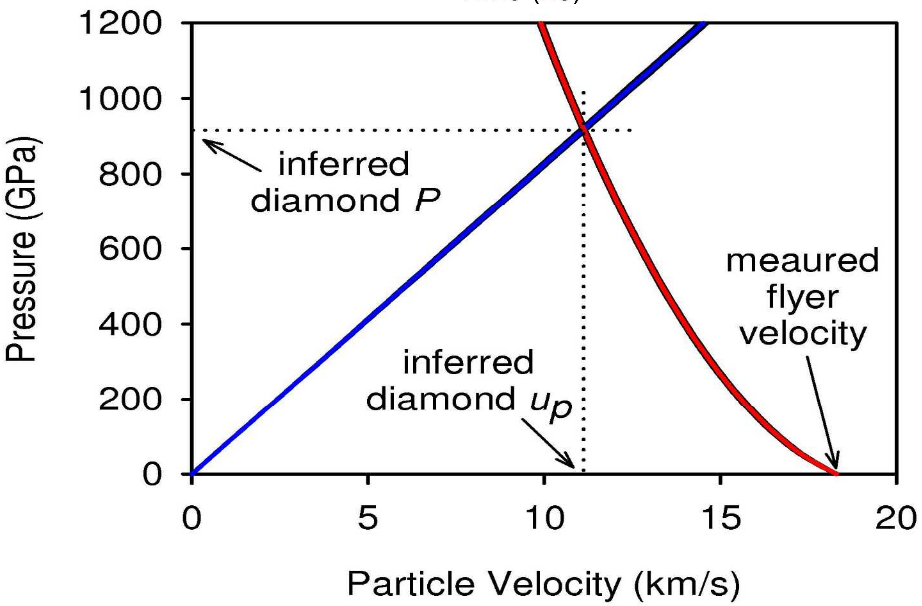
The Z platform provided extremely accurate measurements of the diamond Hugoniot







- Multiple samples and diagnostics allowed for redundant measurements for increased accuracy
- Transparency of the diamond samples allowed for in-line measurement of impact velocity and shock transit time
- Impact velocity and shock speed measurement provides tight constraint on the inferred particle velocity and density

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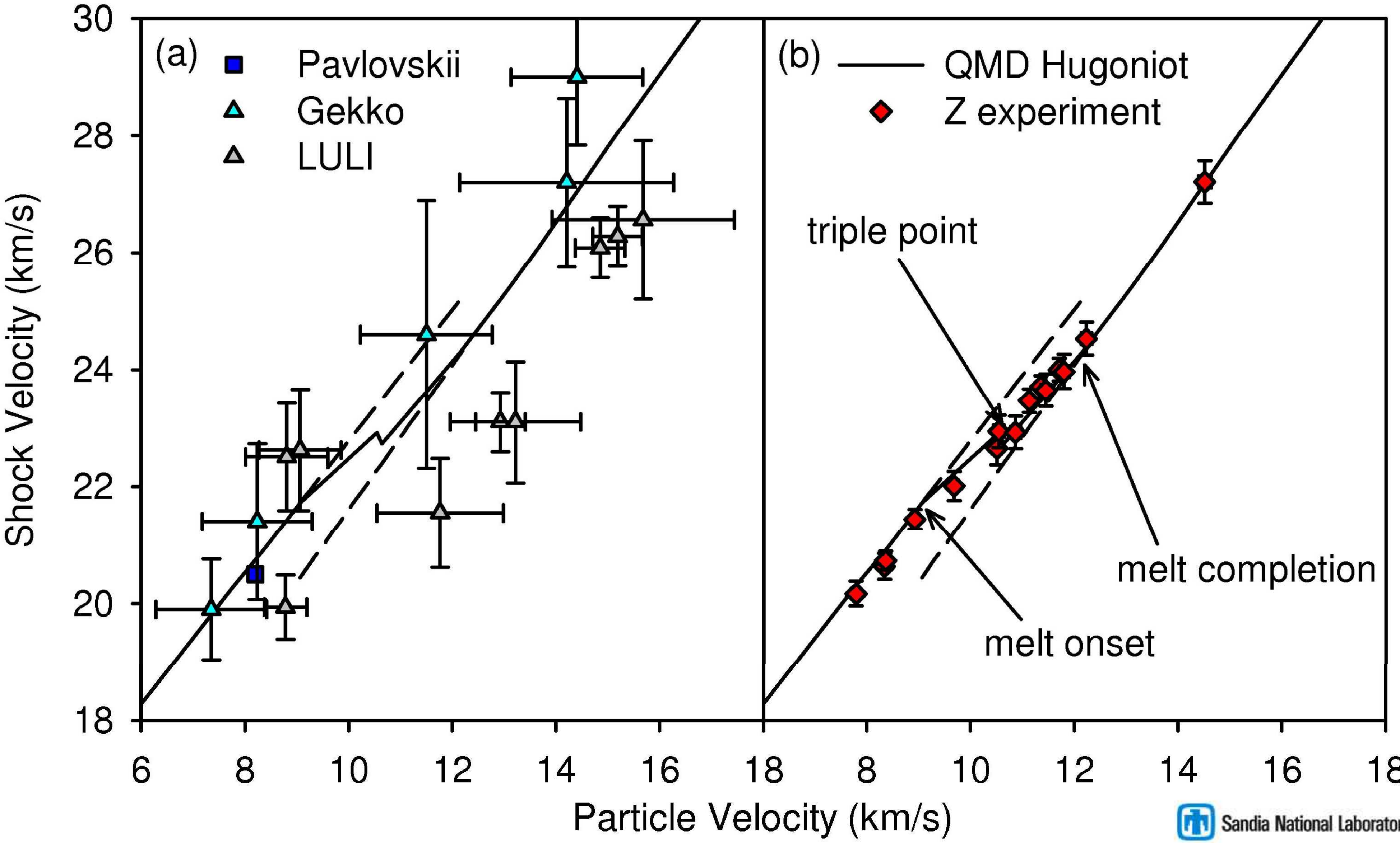
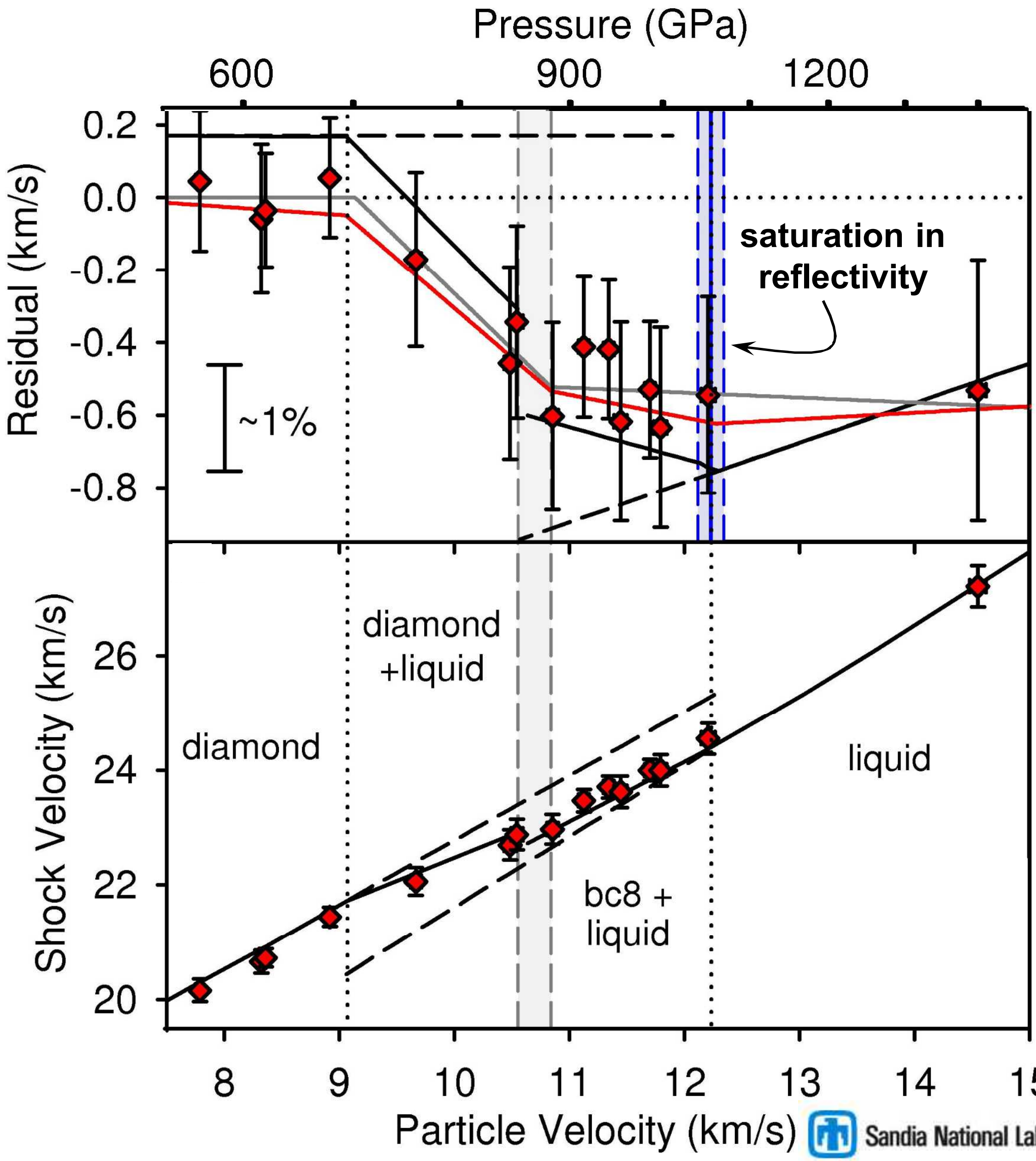
This accuracy allowed for quantitative comparison with QMD predictions and evidence of the TP



Knudson, et al., Science **322**, 1822 (2008)

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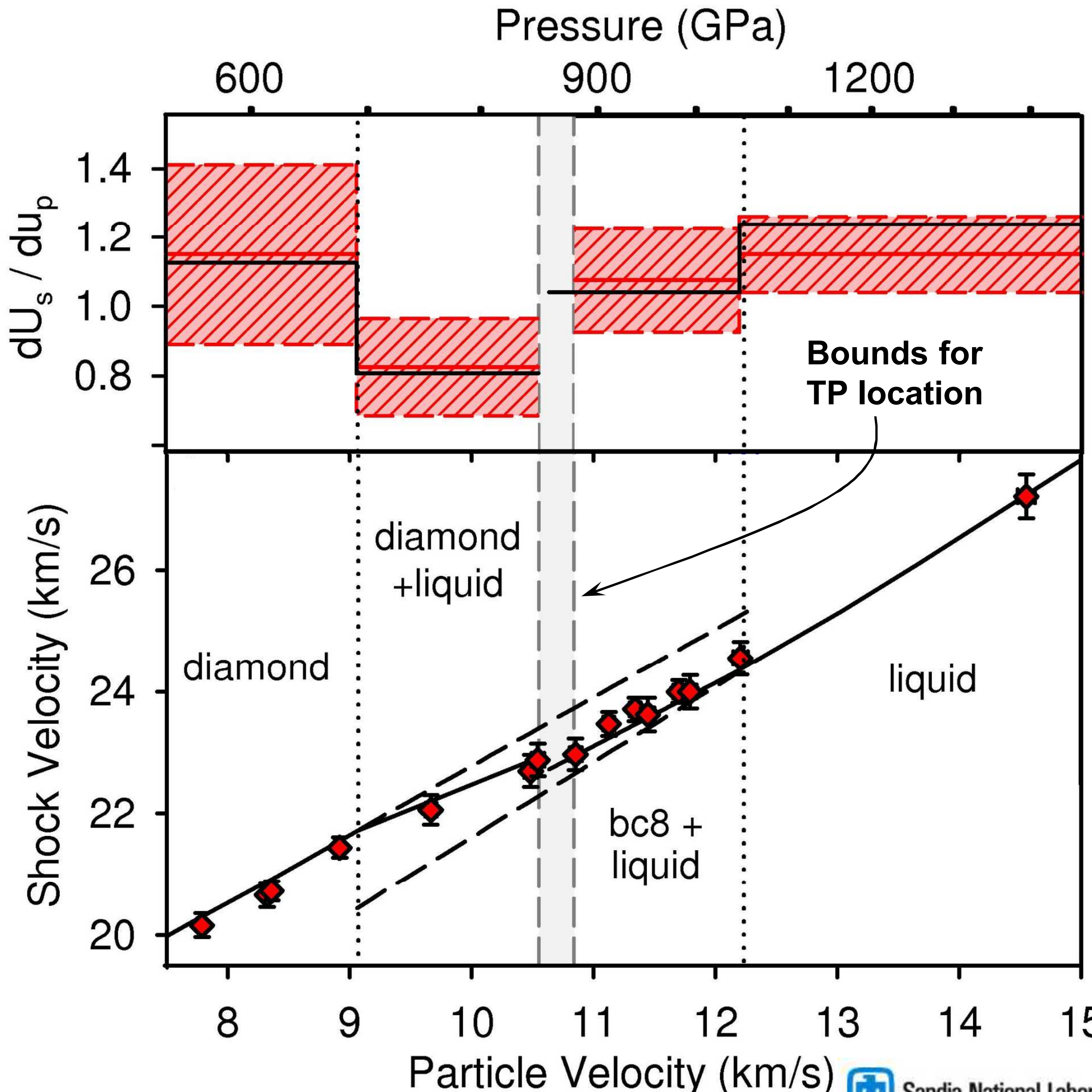
Location of breakpoints and slopes are in excellent agreement with the QMD predictions

- 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 provides validation
  - Strongly suggests the presence of a higher pressure solid phase of carbon above ~860 GPa



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Conclusion

- Magnetic ramp compression is enabling new regions of a material's phase diagram to be explored under dynamic compression
- Obtaining unprecedented accuracy in the multi-Mbar pressure regime both on and off-Hugoniot
- Future direction will be to couple advanced capabilities to ramp compression facilities
  - Pre-heat capability
  - Sample recovery
  - Advanced diagnostics
    - » pyrometry
    - » x-ray diffraction