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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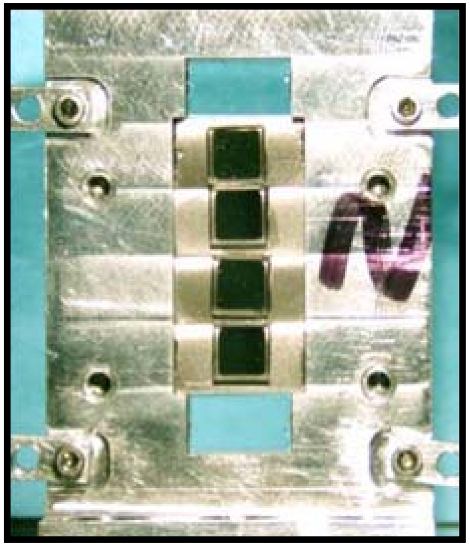
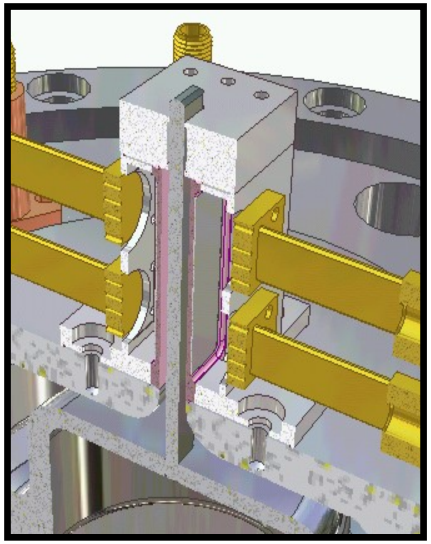
Sandia National Laboratories, Albuquerque, NM





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National Nuclear Security Administration

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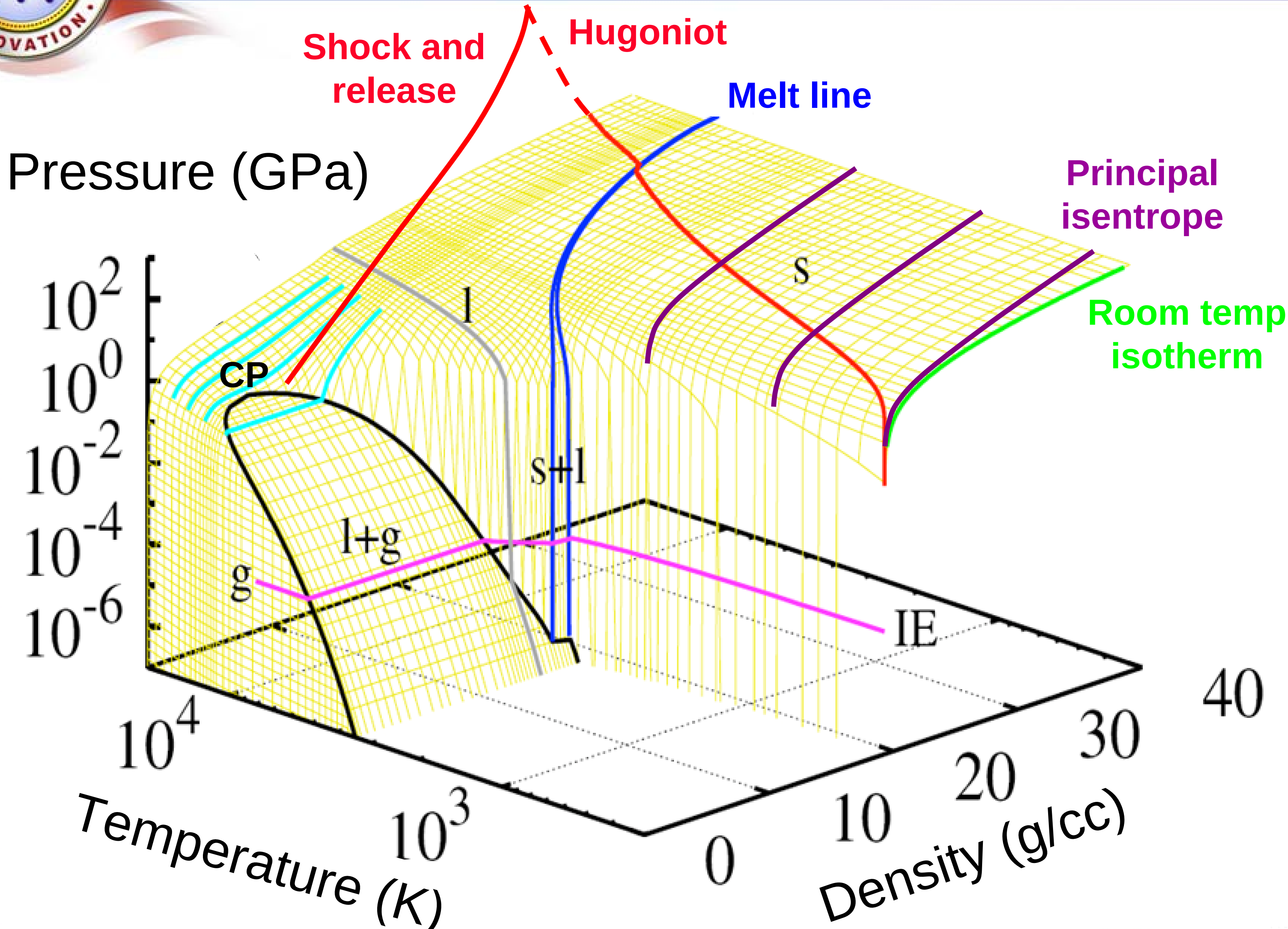
Acknowledgements

- 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



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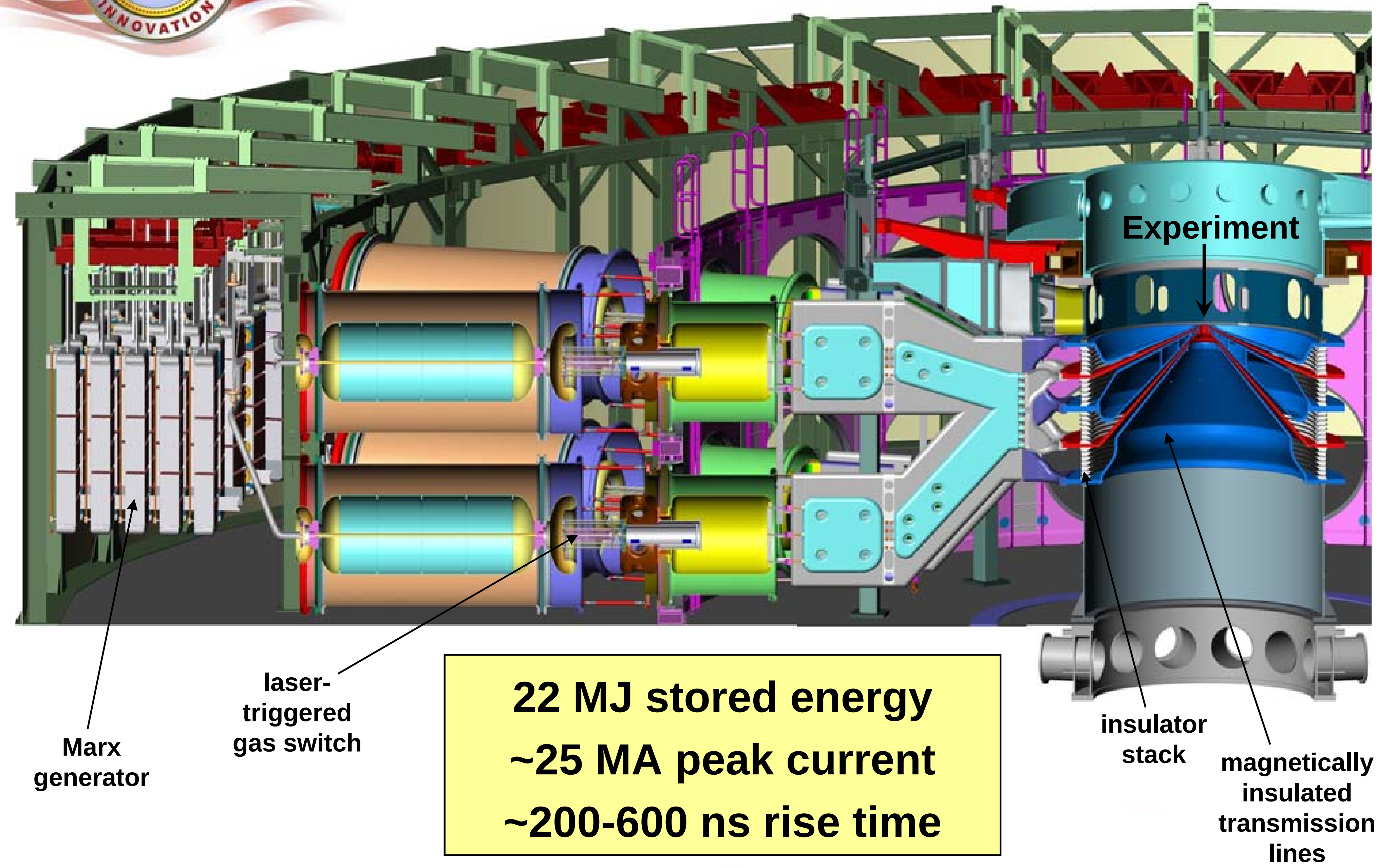
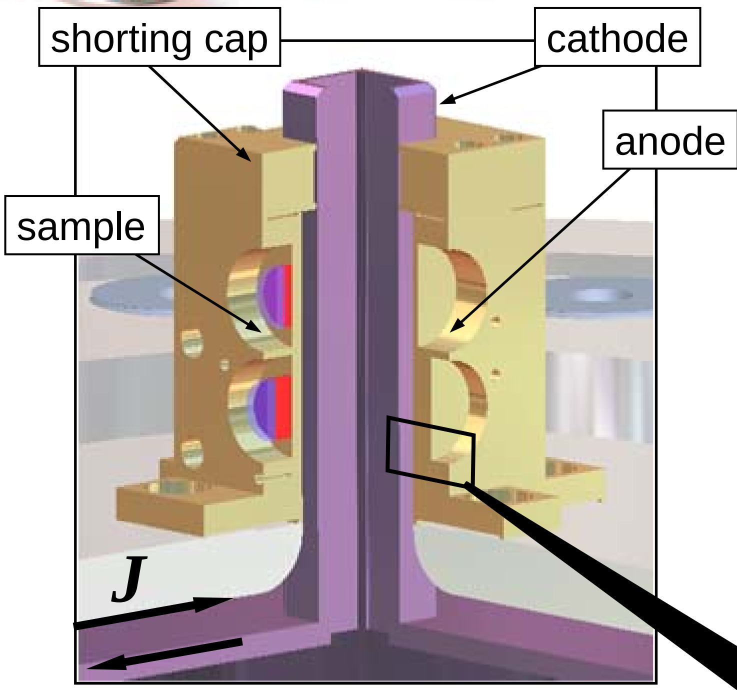
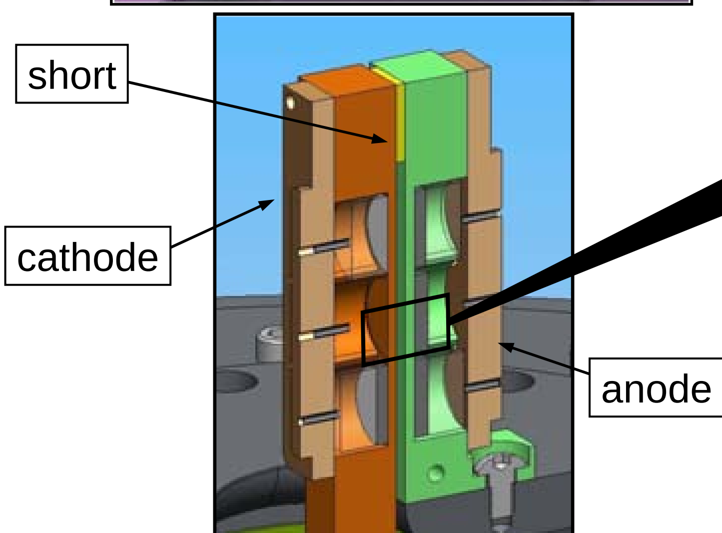
The Sandia Z Machine



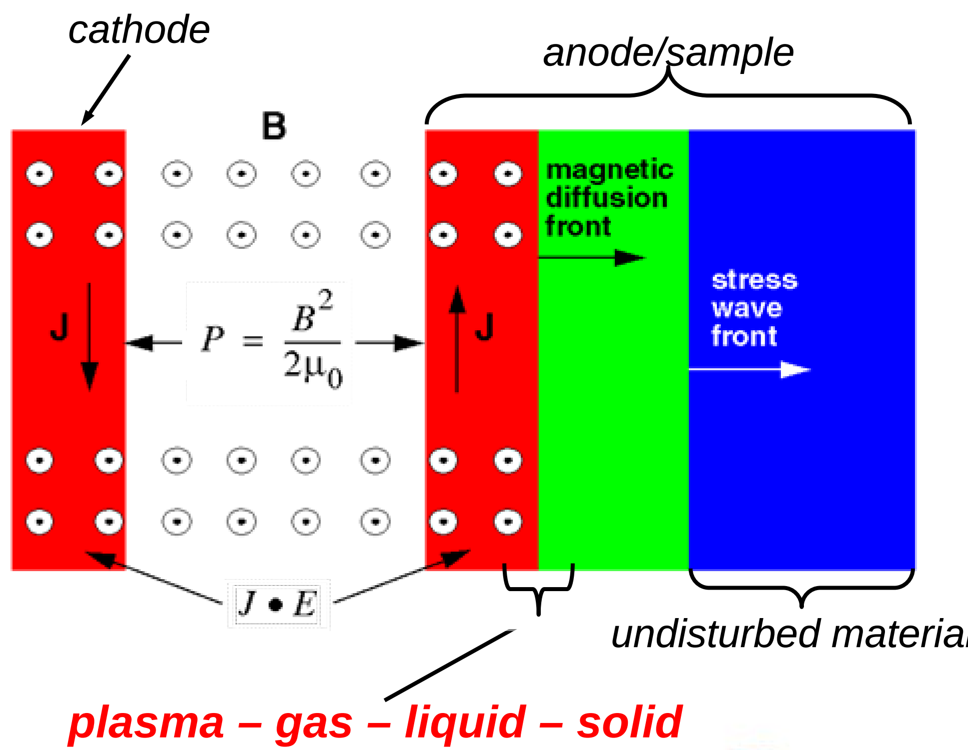
22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

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



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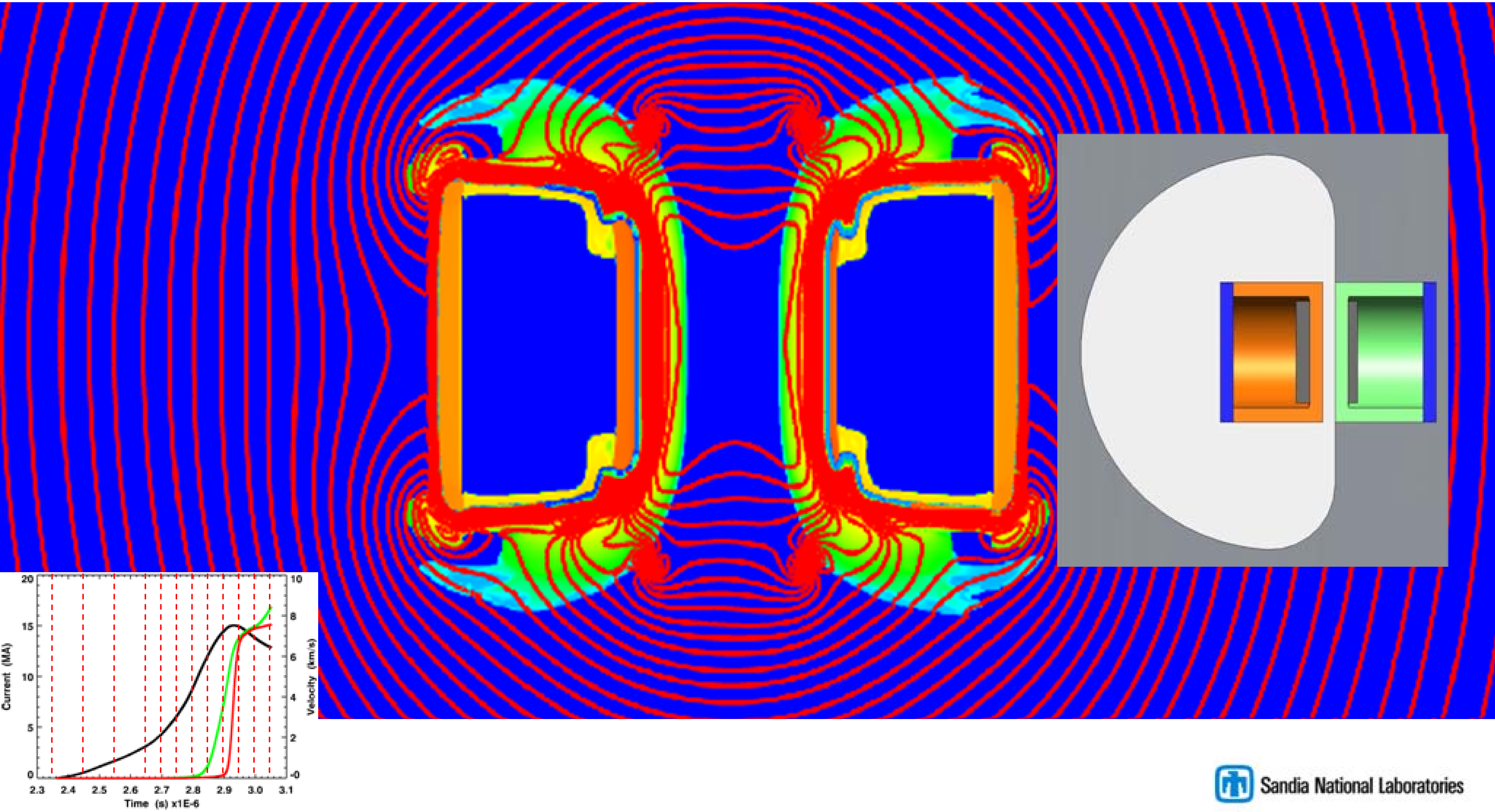
Fully self-consistent, 2-D MHD simulations required to accurately predict experimental load performance

10 mm wide stripline

t = 3050 ns



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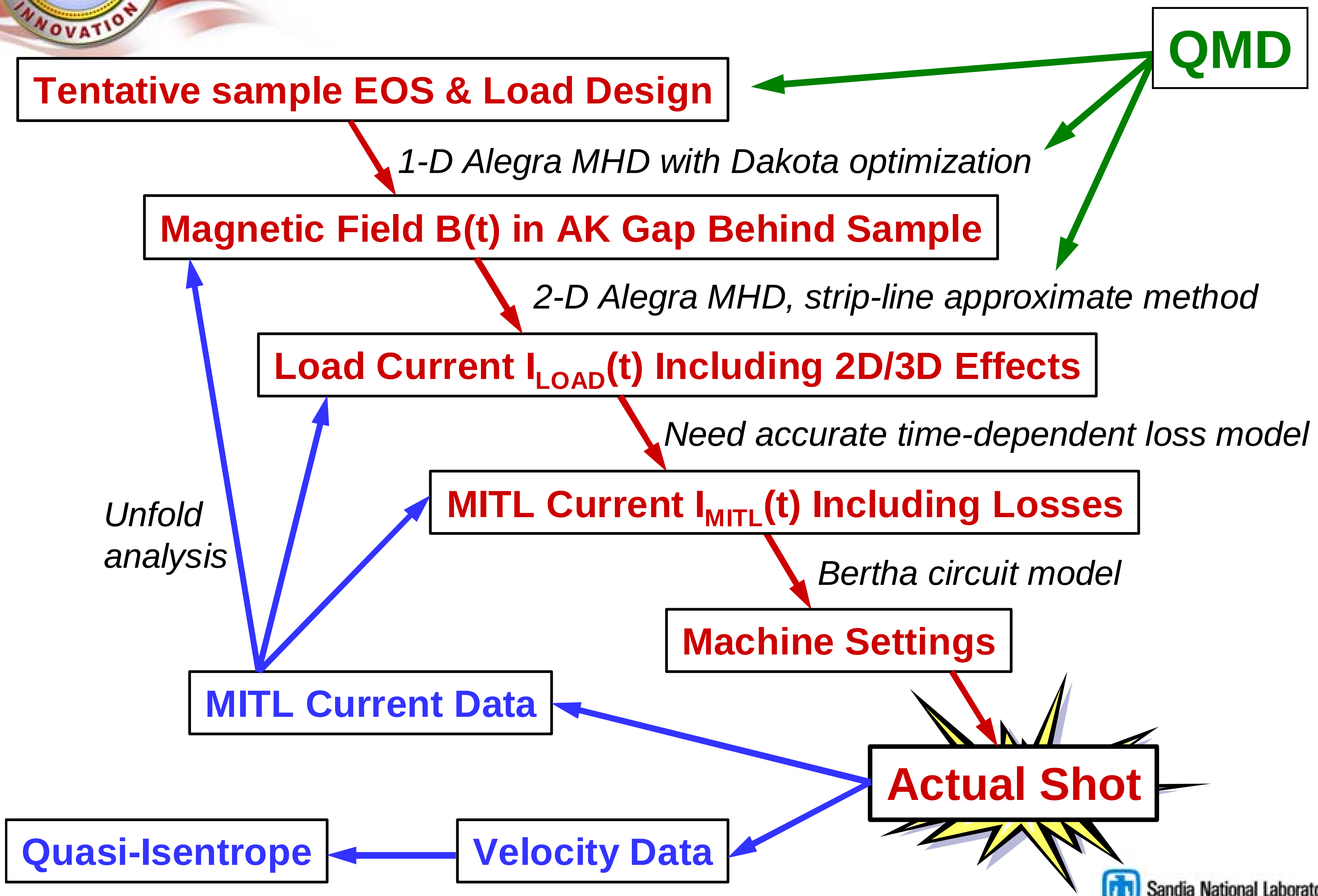
Success requires integration of theoretical, computational, and experimental capabilities



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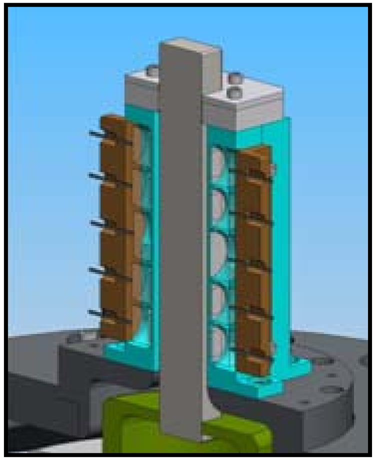
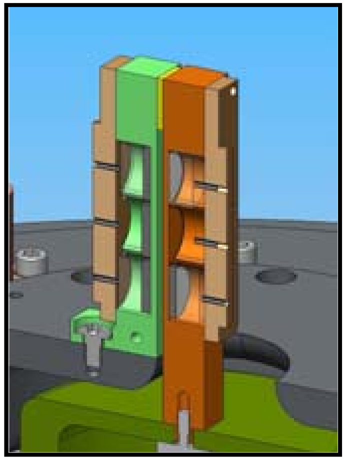
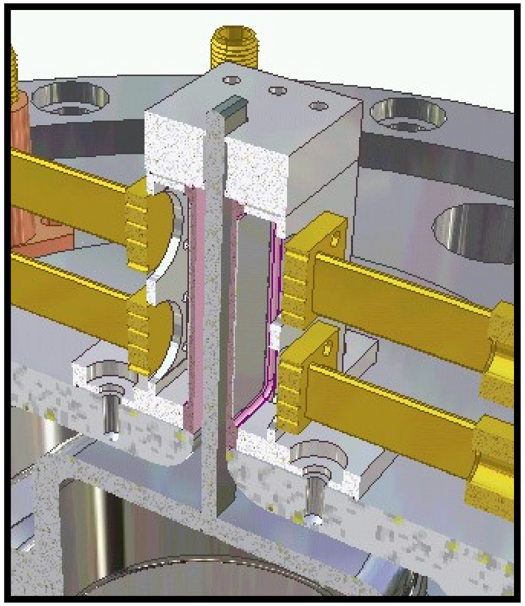
Two platforms have been developed for accurate equation of state studies – both major advances

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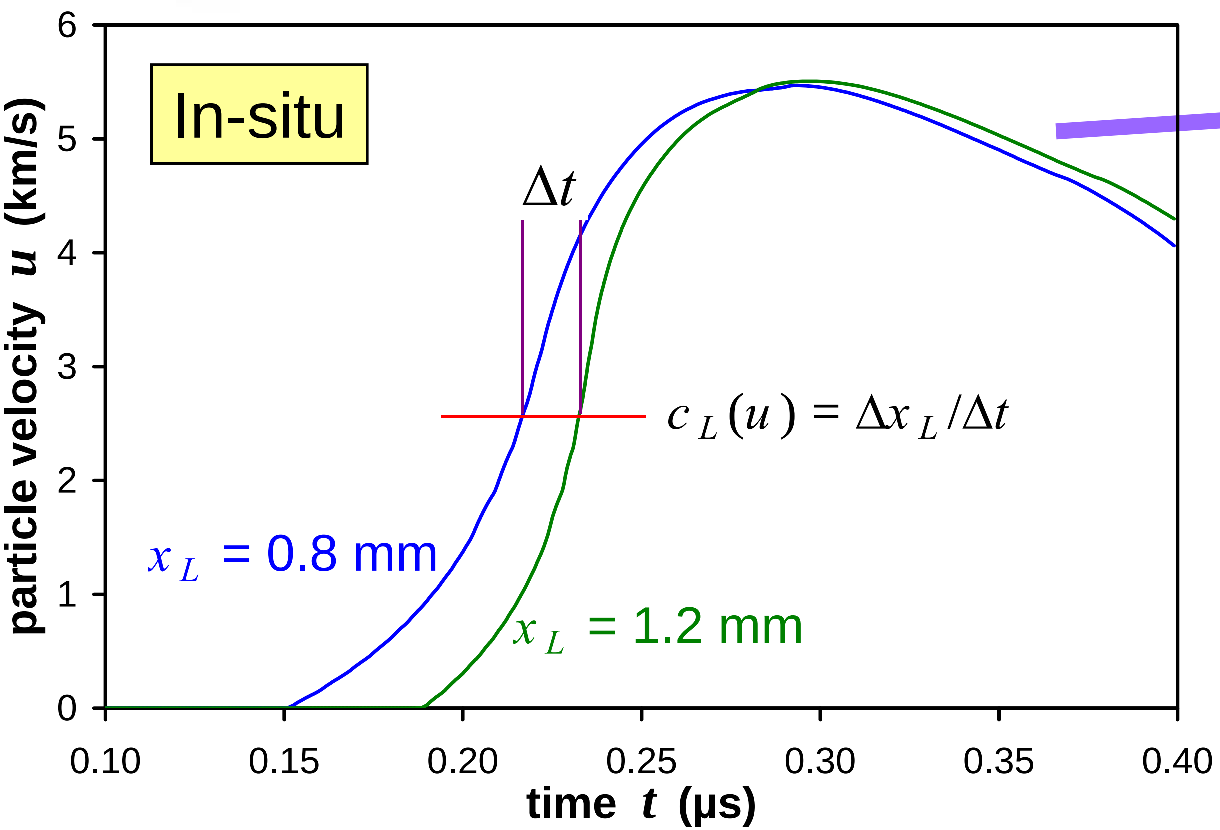
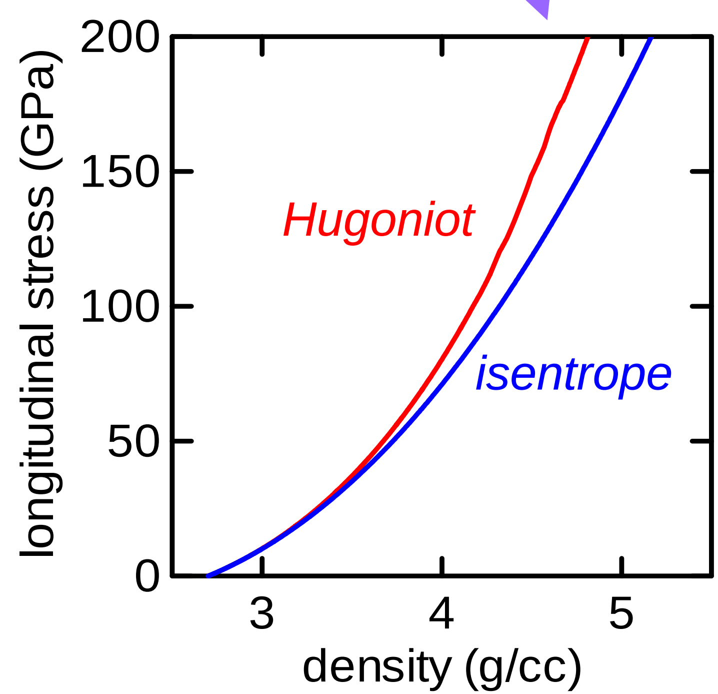
Ramp compression provides a measure of the stress-density response of a material to peak stress



conservation equations

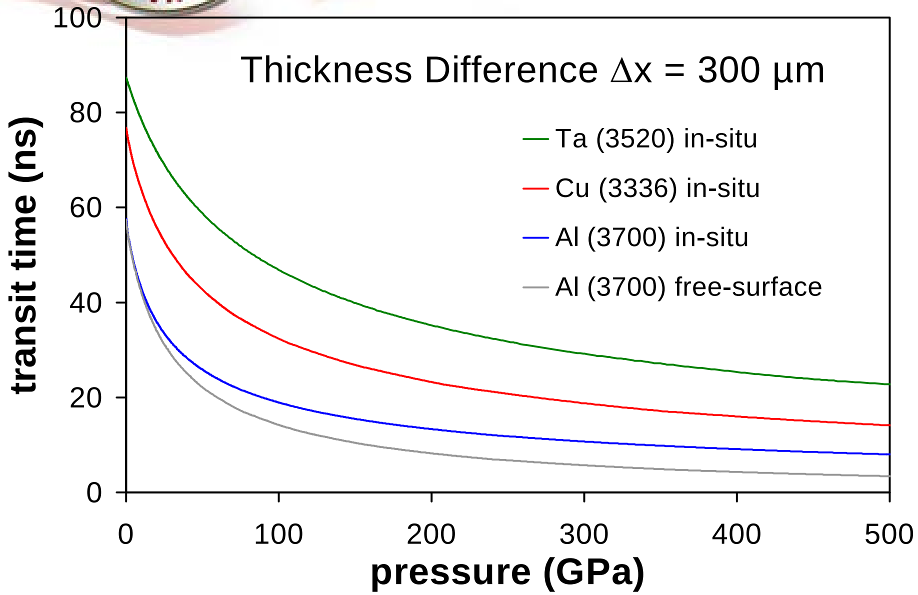
$$d\sigma_x = \rho_0 c_L du$$

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



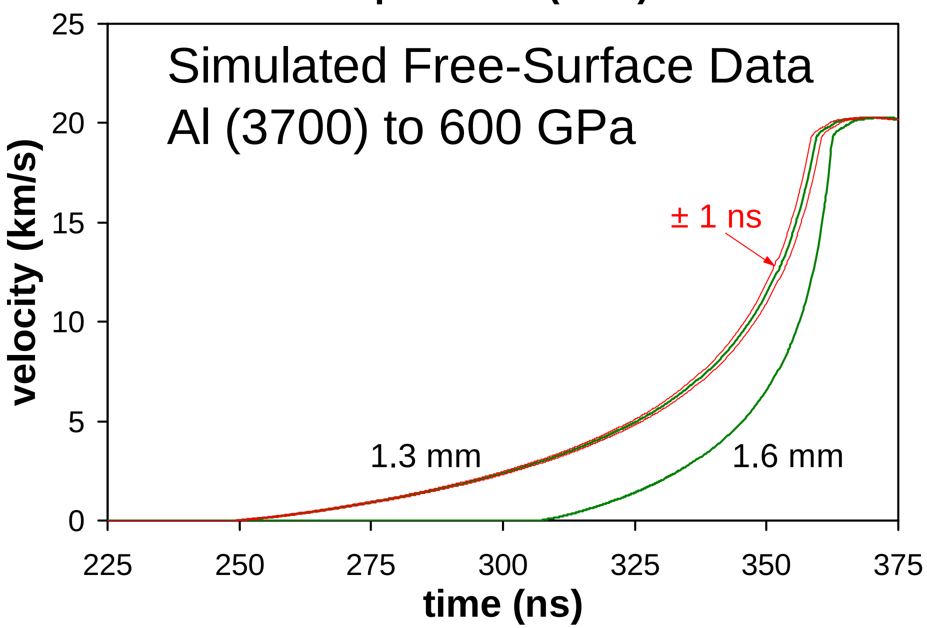
- requires simple right-going waves
- compression is usually quasi-isentropic due to dissipative phenomena (plastic work, viscosity, thermal conduction, *etc*.)

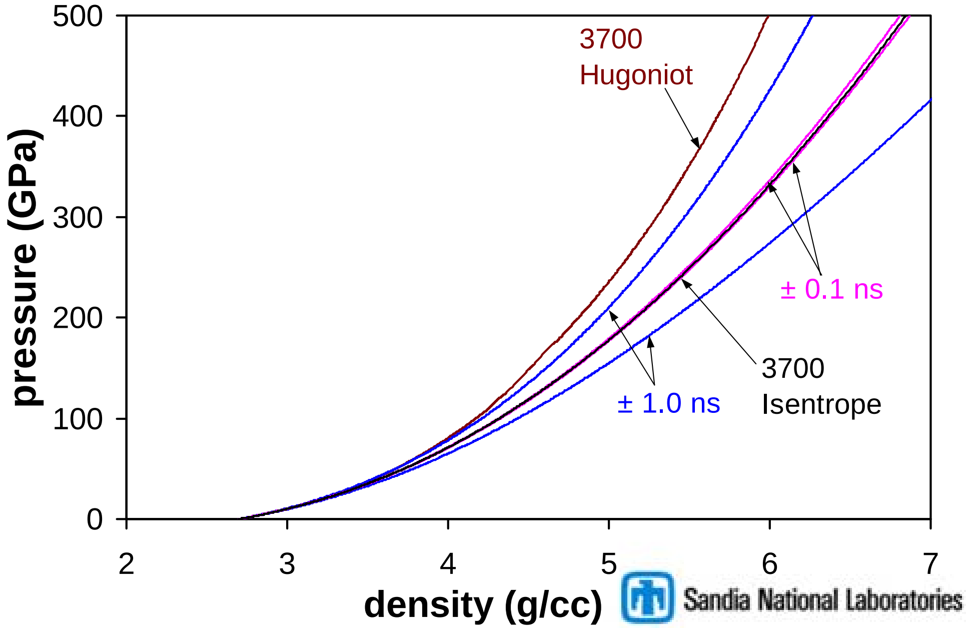
High-stress ICE experiments place stringent demands on wave profile measurements



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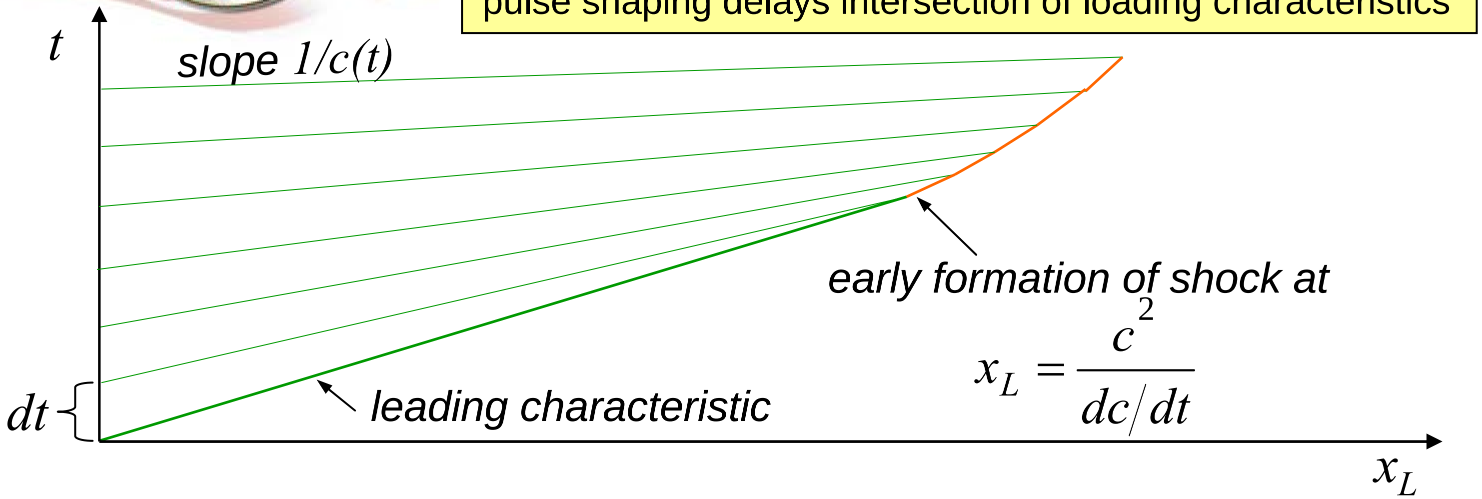
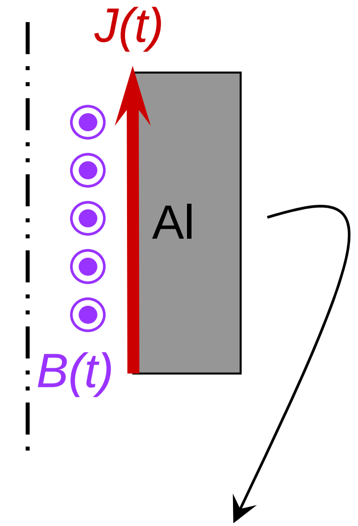
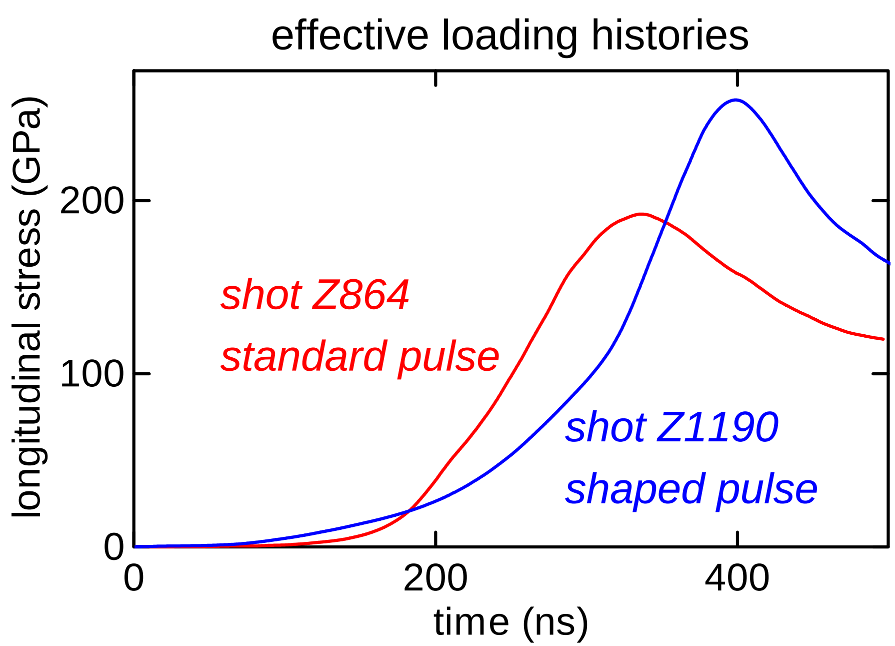
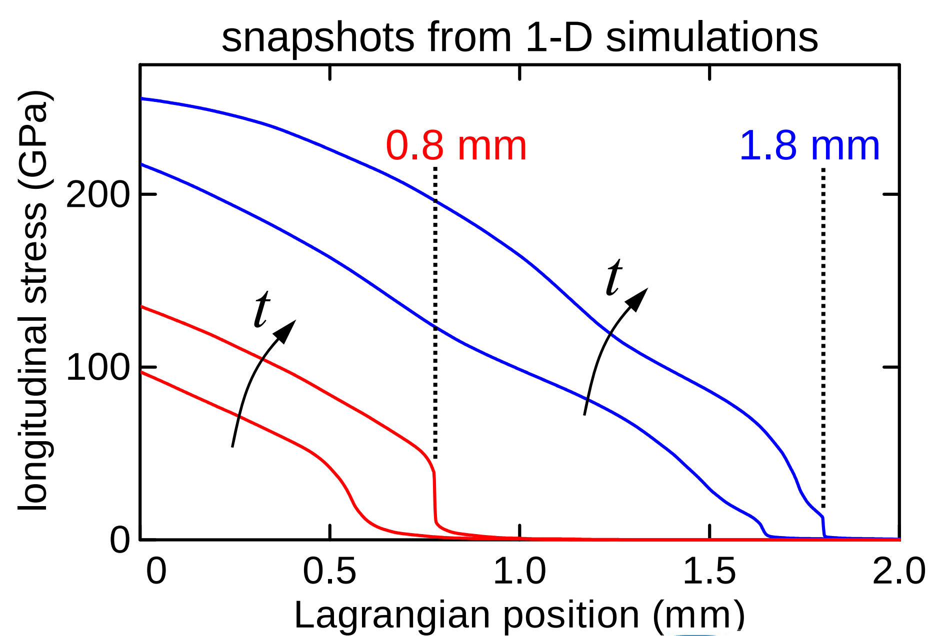
The rapid increase in sound speed requires pulse shaping to delay shock formation

pulse shaping delays intersection of loading characteristics

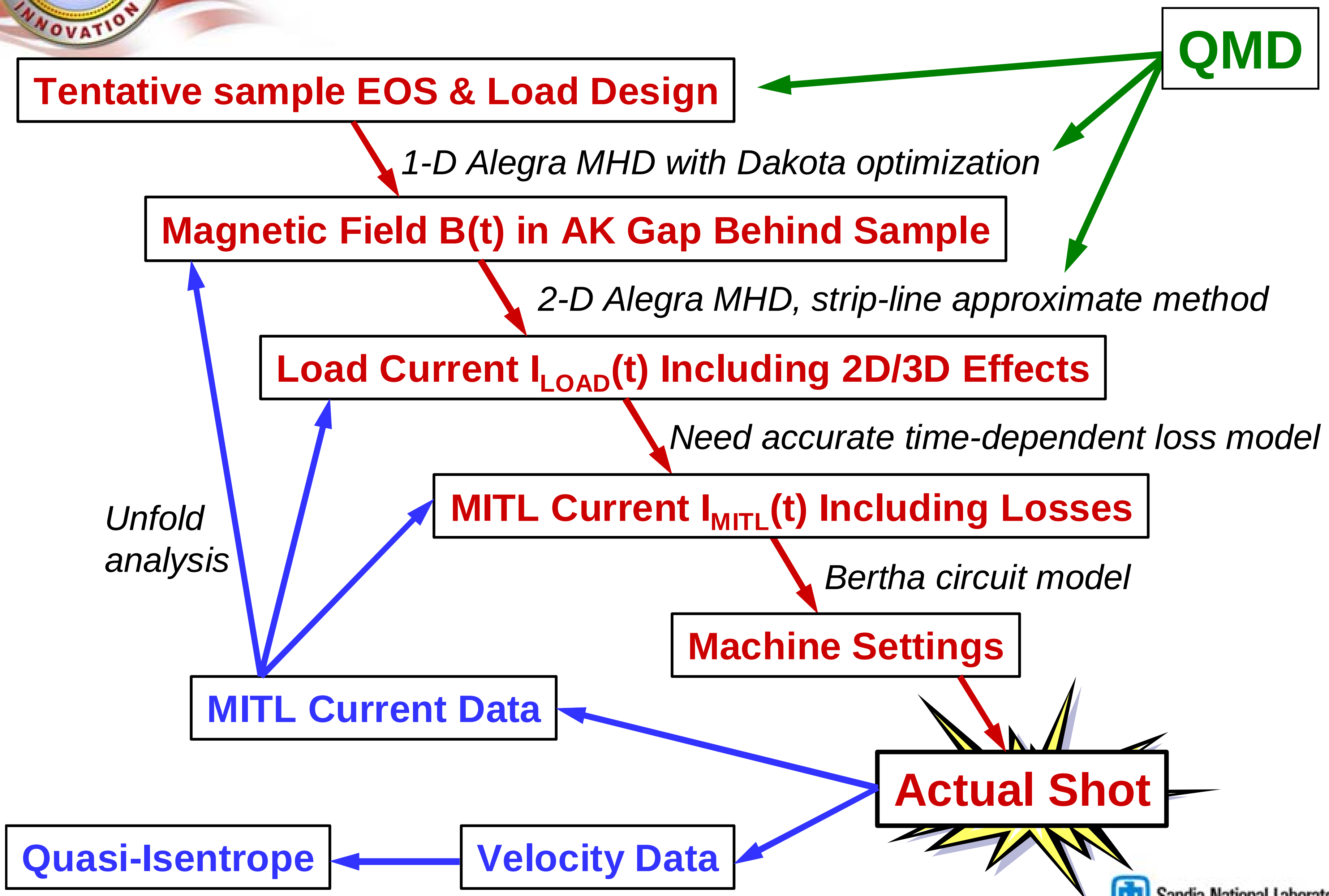








This process was followed to design an ICE experiment on Ta to 400 GPa



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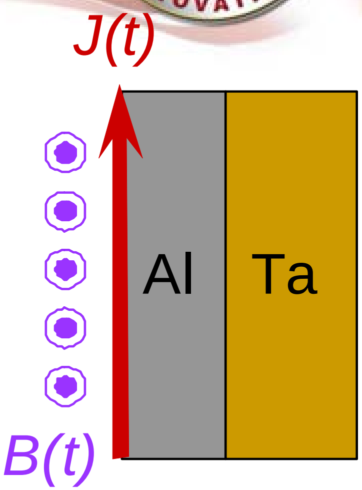
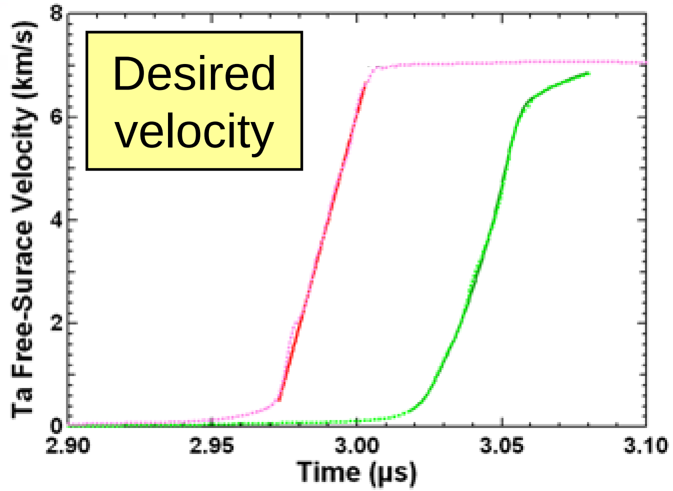
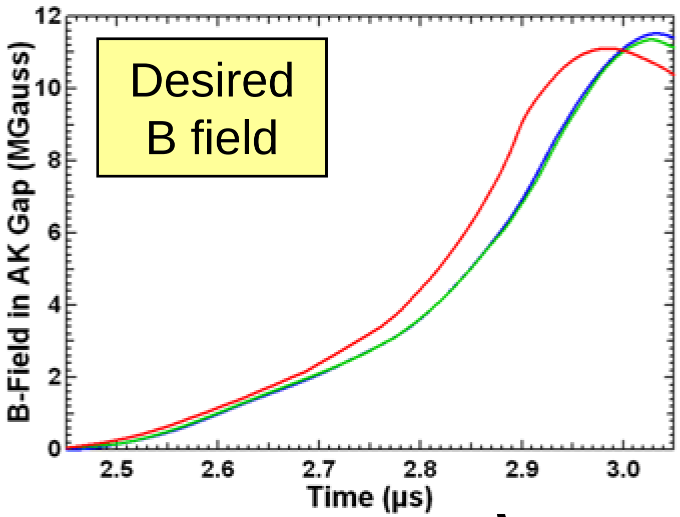
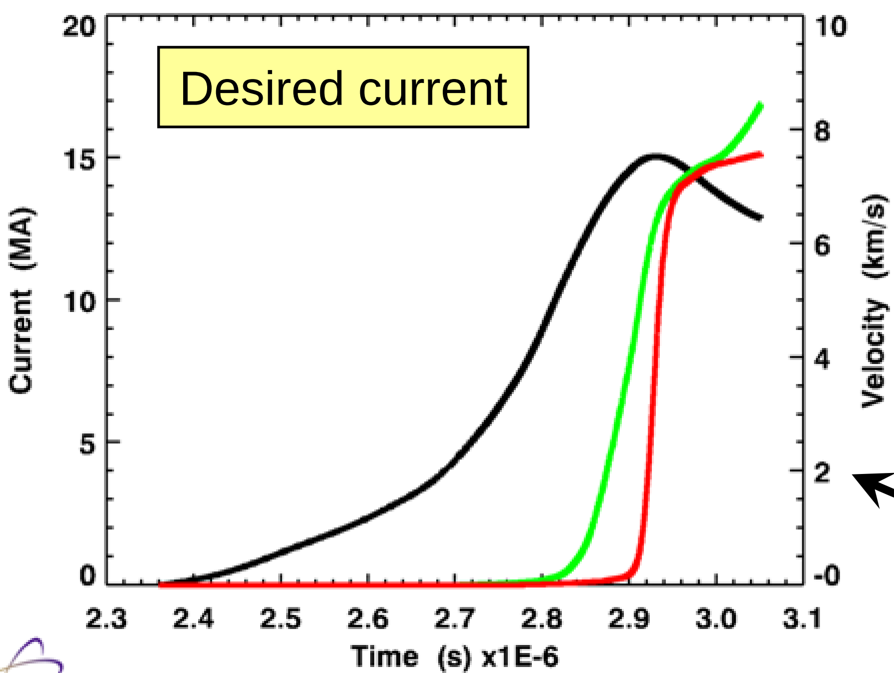
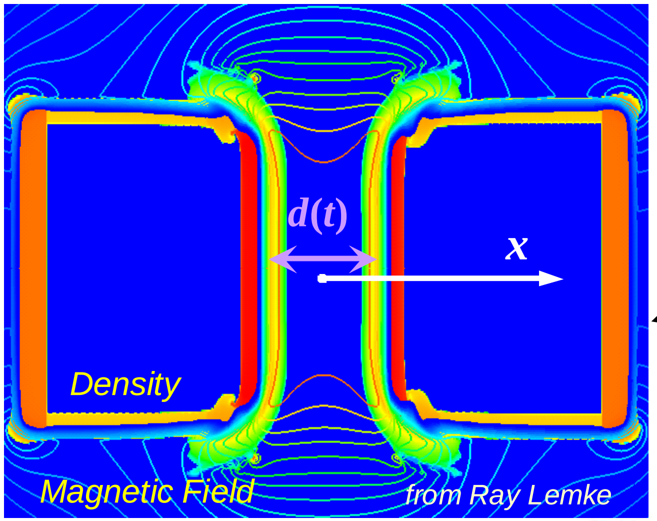
Desired current is determined through several iterative 1-D and 2-D MHD simulations



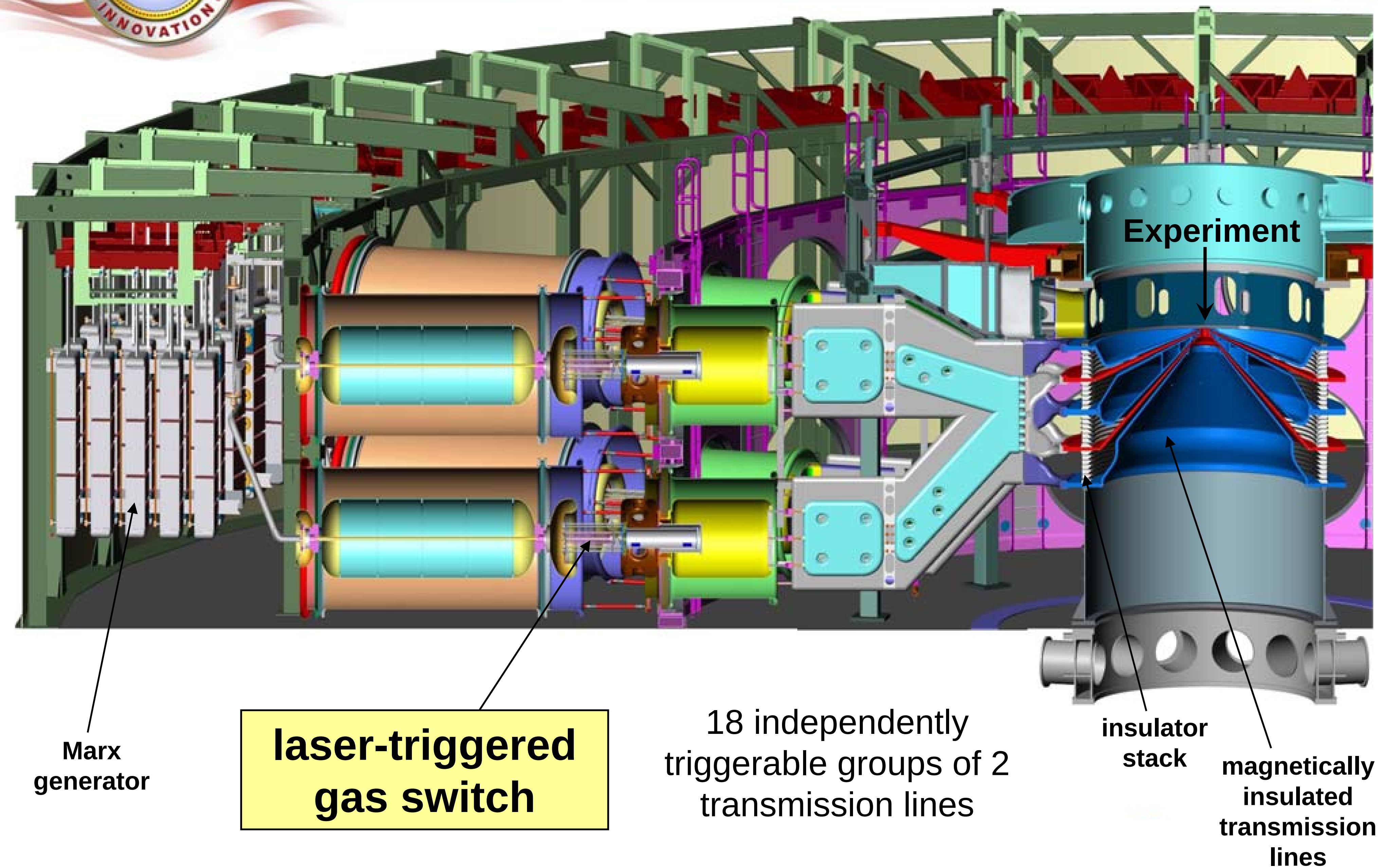








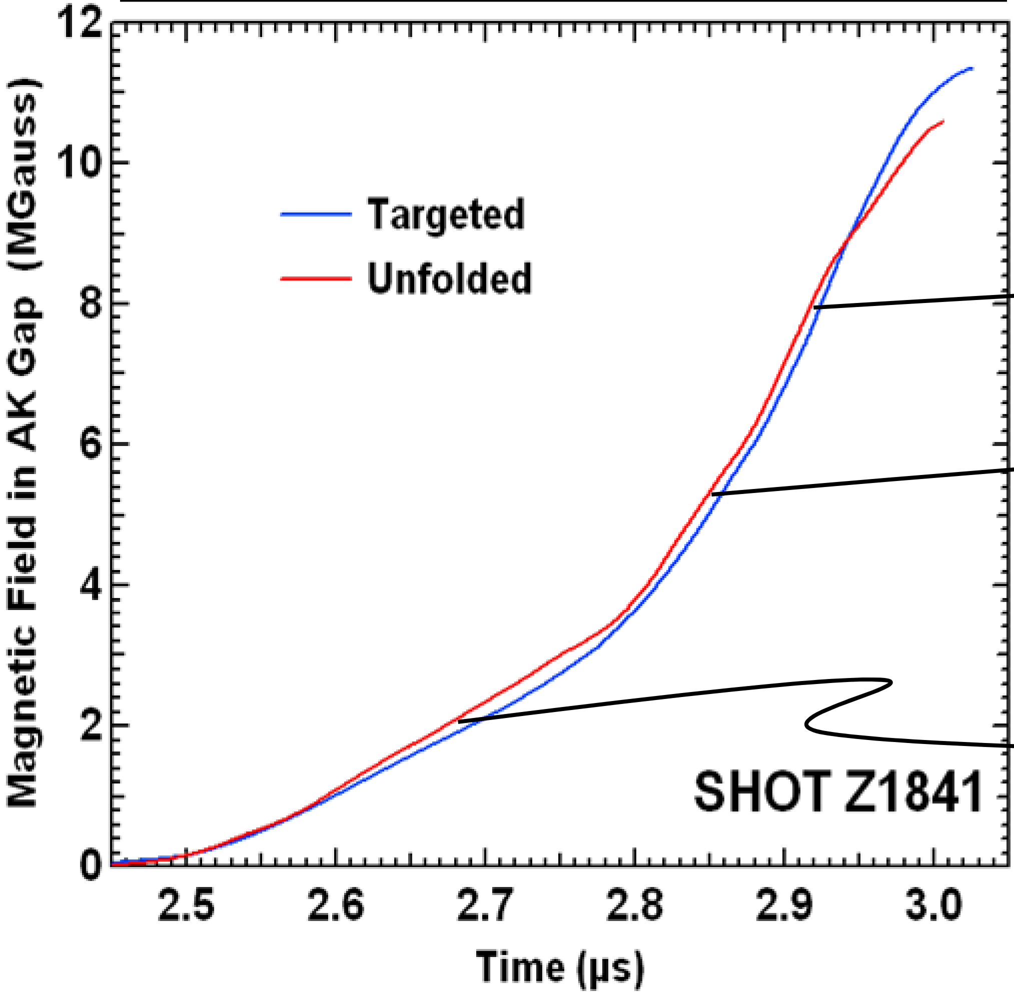
Independently triggerable gas switches provide the variability necessary for pulse shaping



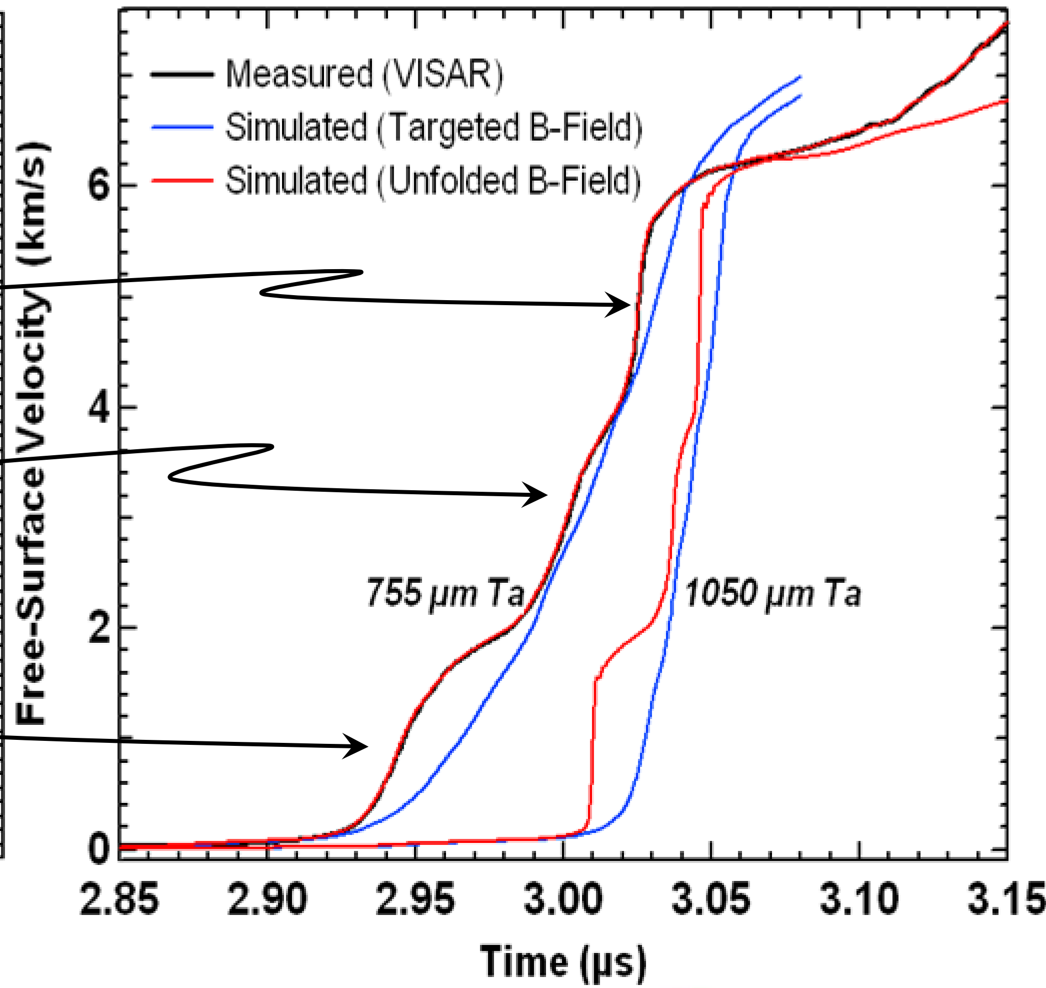
18 independently triggerable groups of 2 transmission lines

The Bertha circuit model enables fairly accurate prediction of machine performance

Current comparison



Wave profile comparison



Los Alamos

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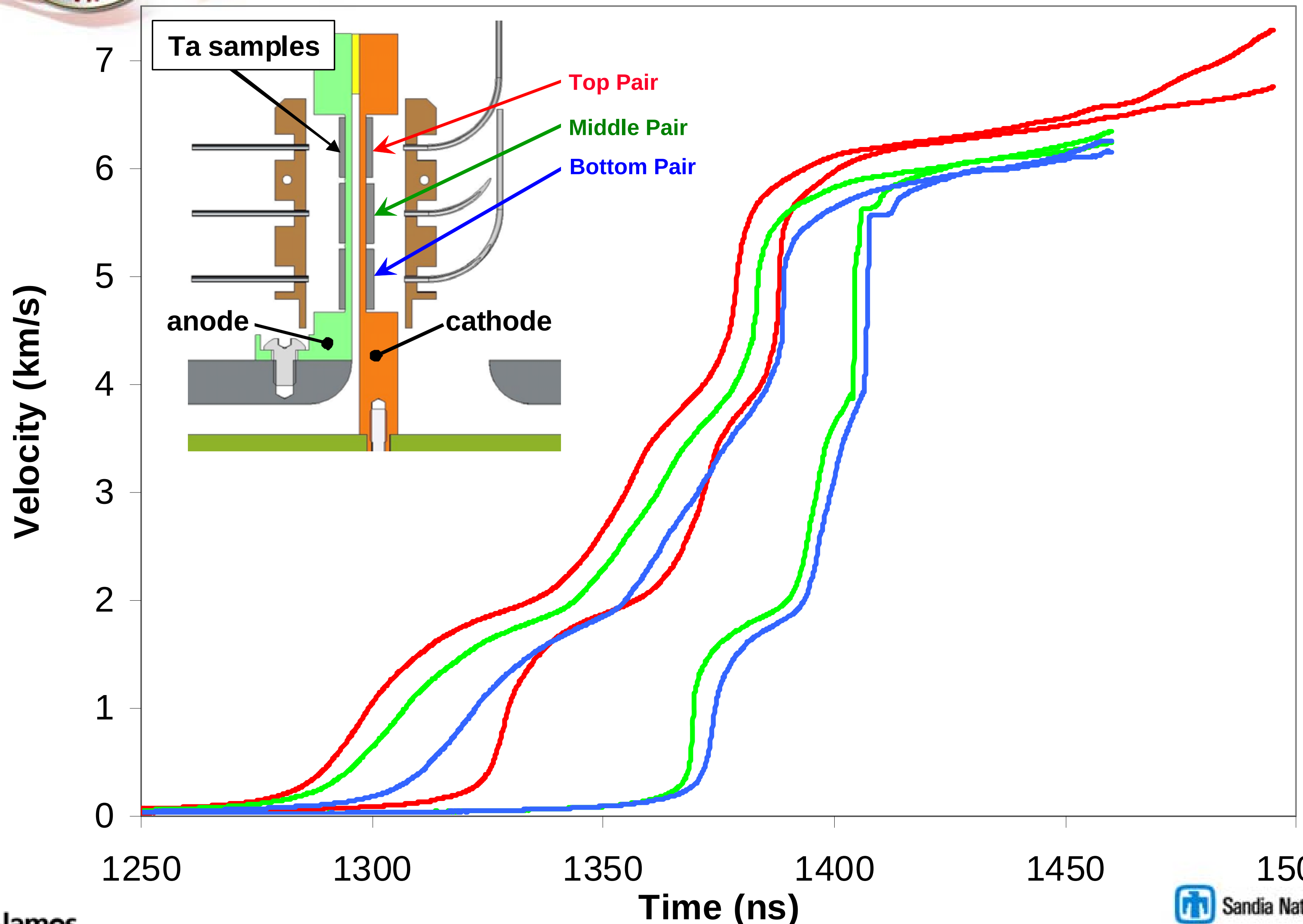
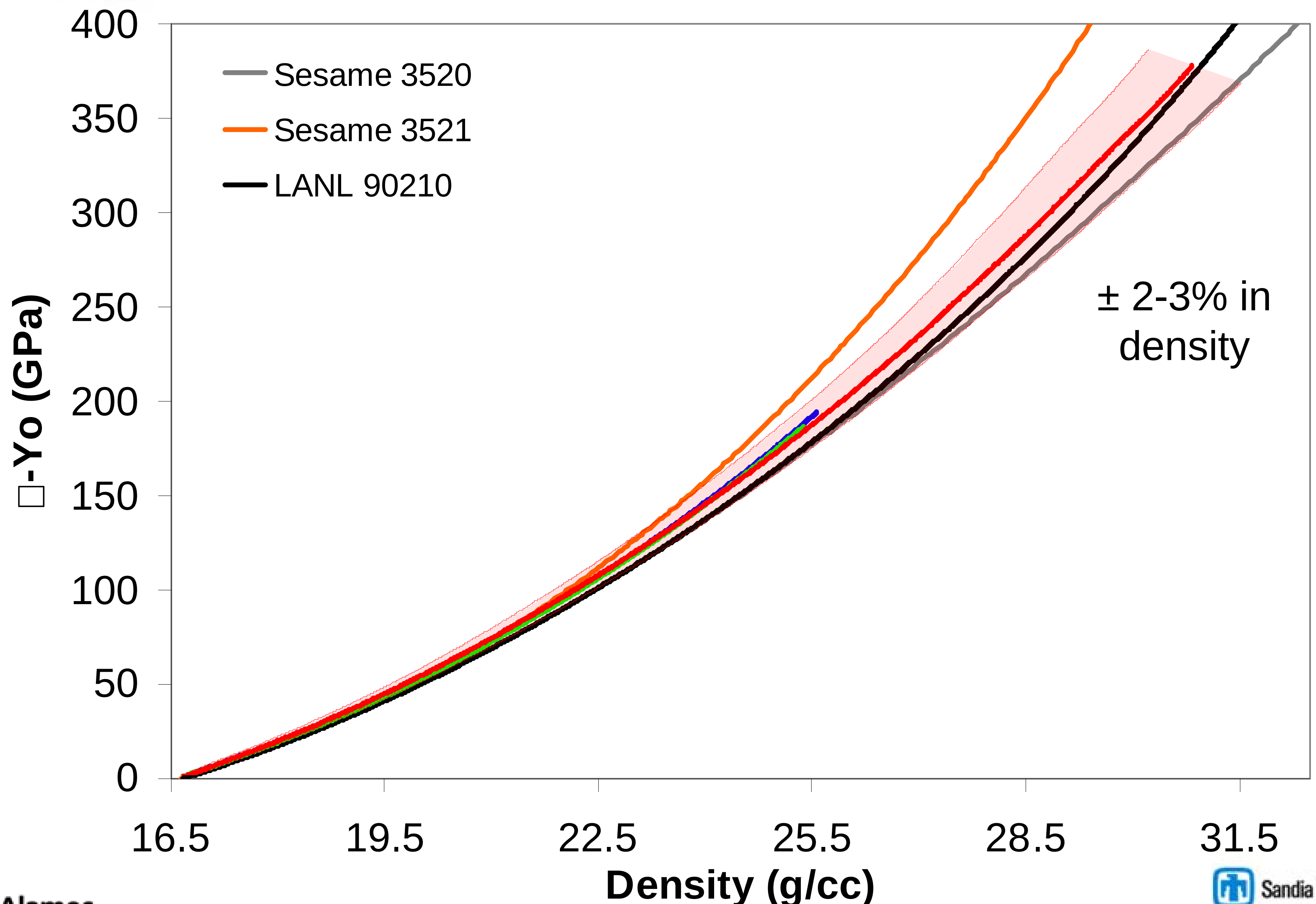
Data have been obtained which enable extraction of the Ta isentrope to nearly 400 GPa



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



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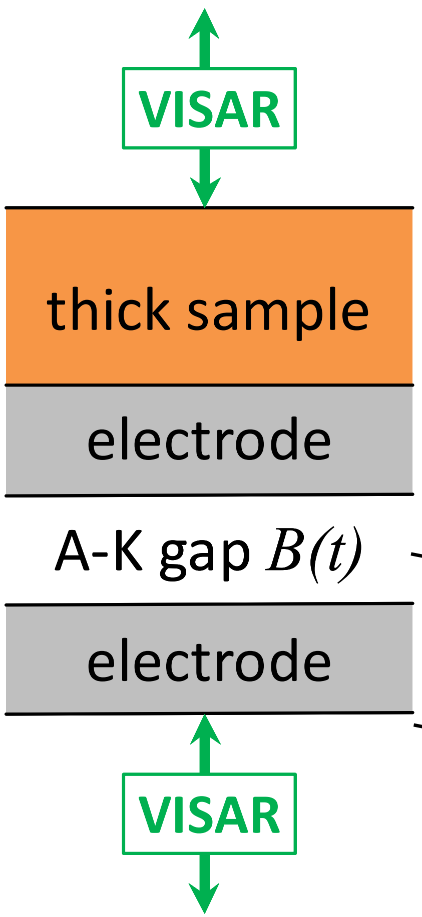
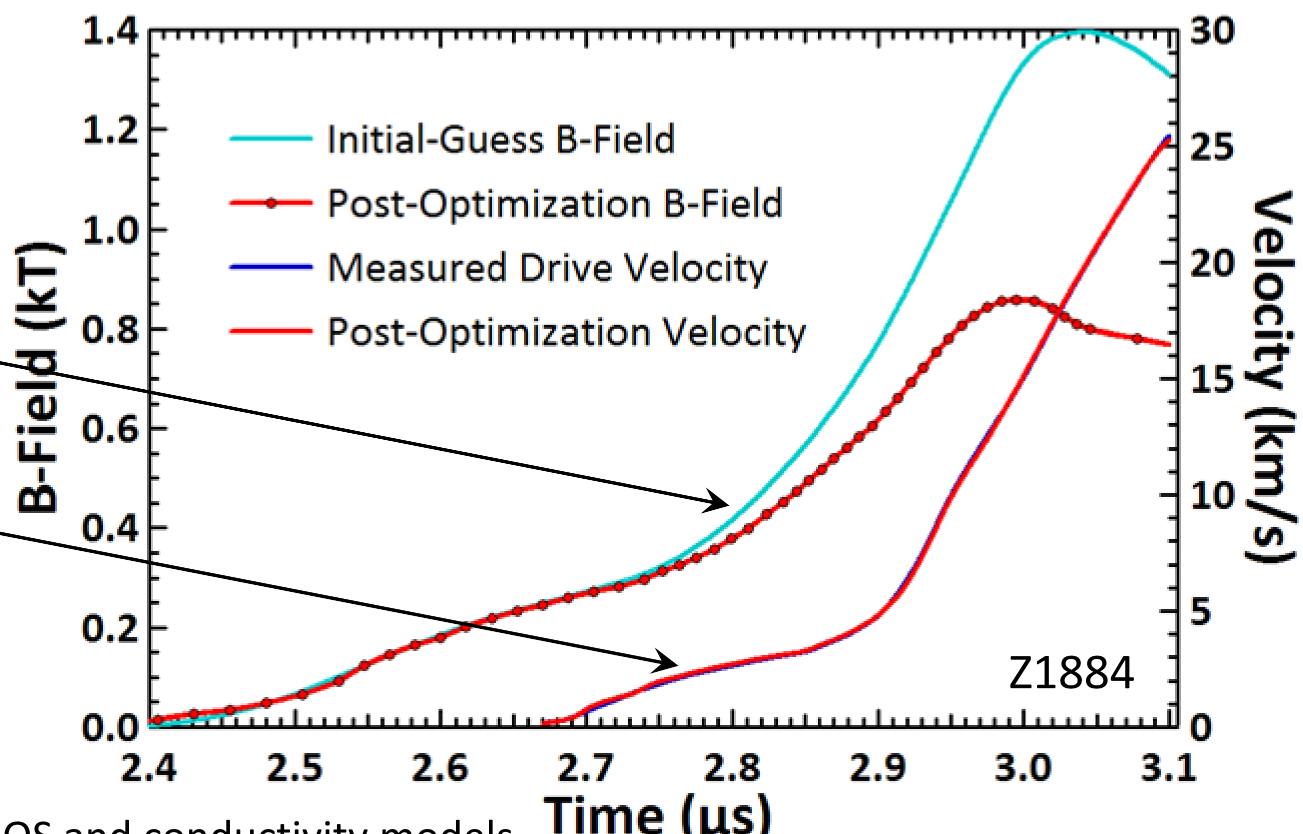
We are pursuing a single sample technique to take advantage of the relative large sample thickness

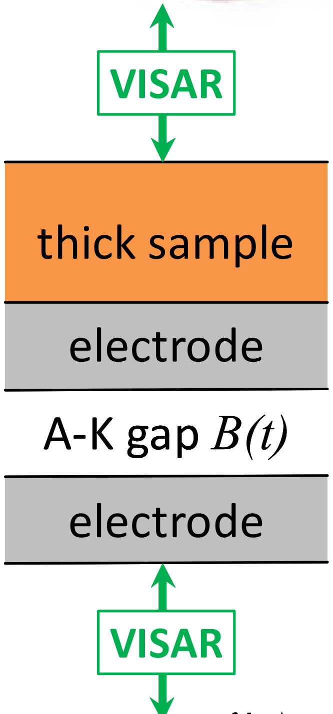
- Dakota optimization framework drives Alegra 1-D MHD simulations
- *B(t)* represented by constrained cubic spline (25-50 points) with time shift and stretch factors
- objective function is metric of isometry between simulated and experimental velocity history at electrode back surface



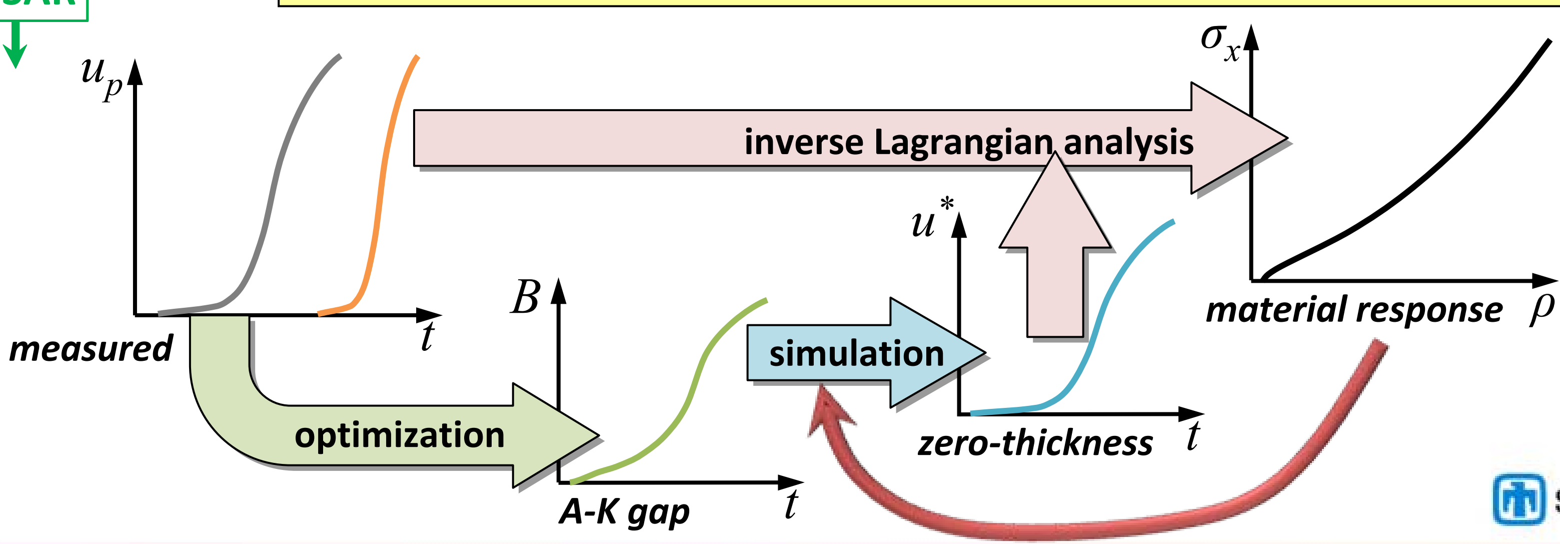


MHD simulations:
- high confidence in aluminum EOS and conductivity models
- high spatial resolution (2.5-µm cells)

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

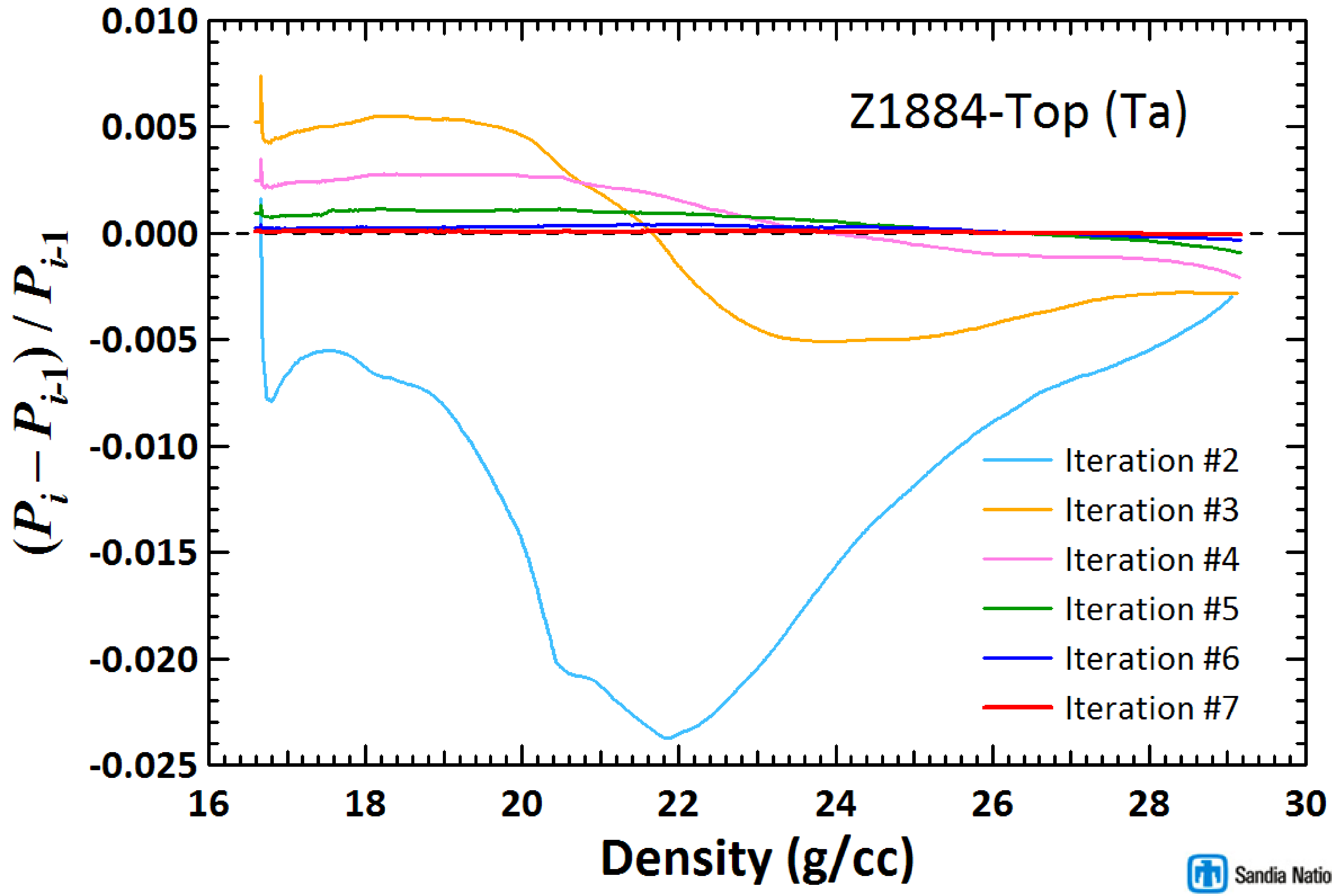


1. measure velocity at back faces of sample and opposite electrode
2. use optimization to determine $B(t)$ from electrode measurement
3. use $B(t)$ and first-guess sample EOS (Sesame table + strength) to simulate electrode/sample interface “zero-thickness” velocity
4. perform inverse Lagrangian analysis 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

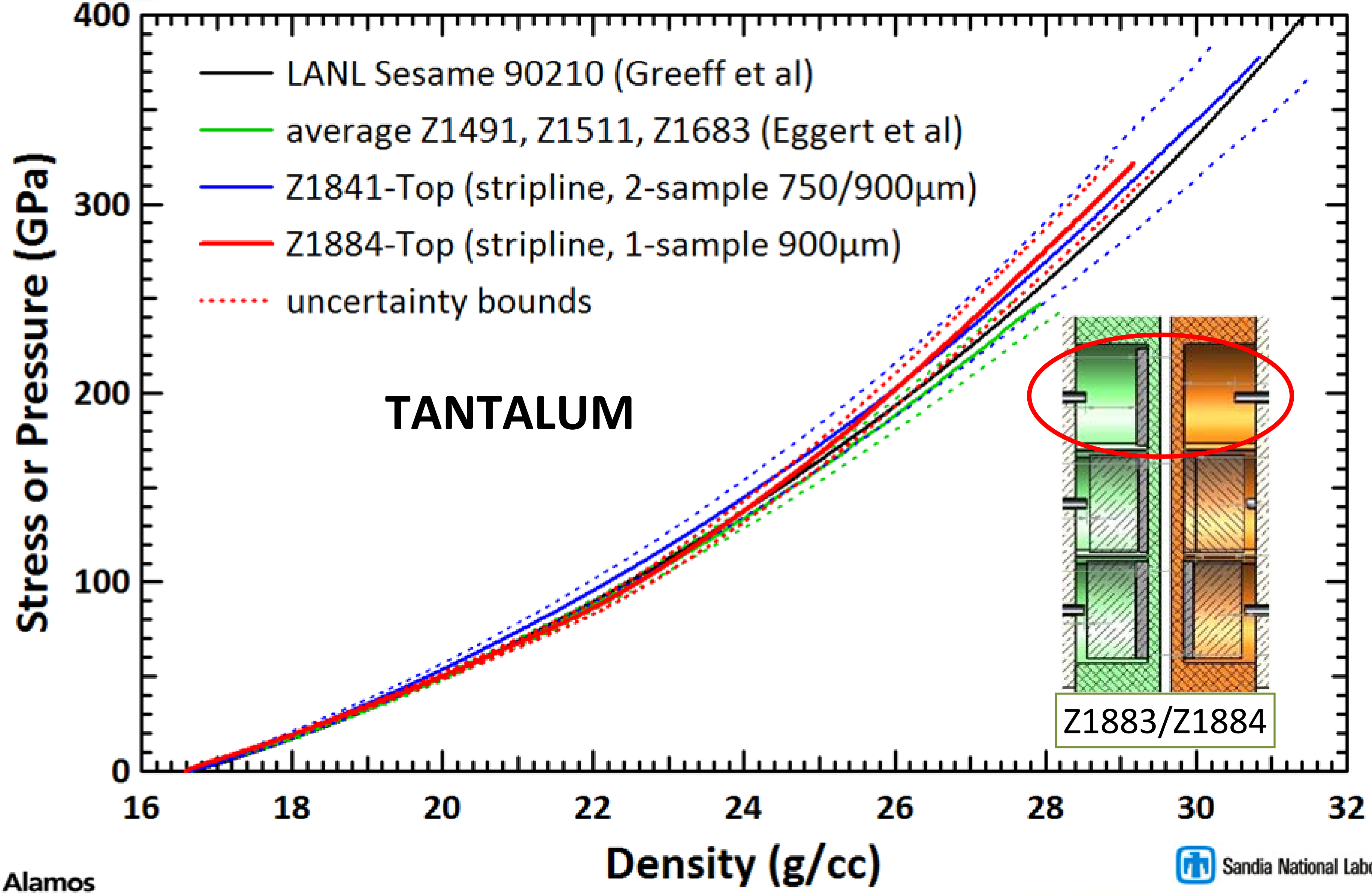


Outer loop of single-sample approach converges

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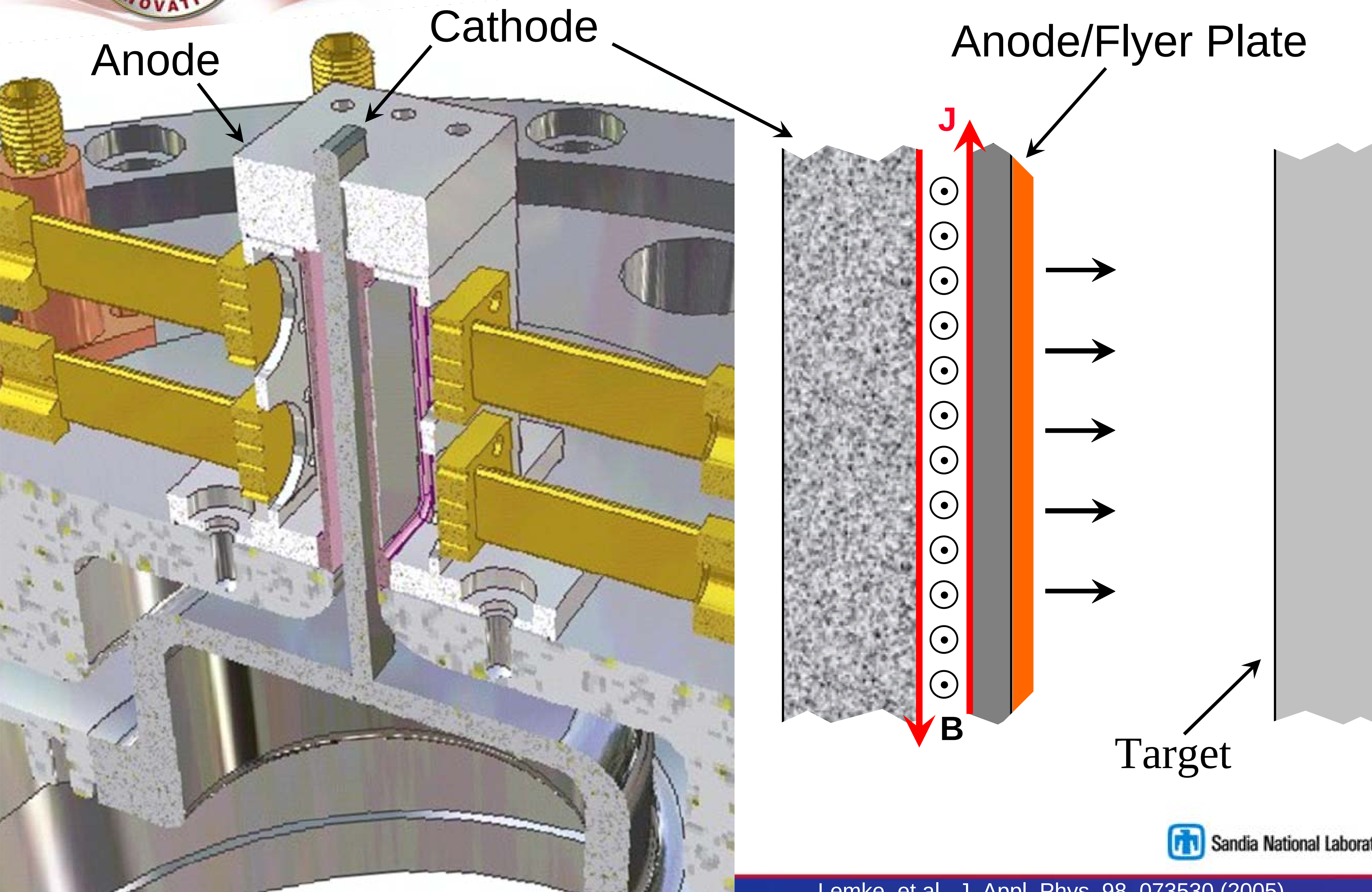
With proper pulse shape and design the anode can be launched as an effective high-velocity flyer plate



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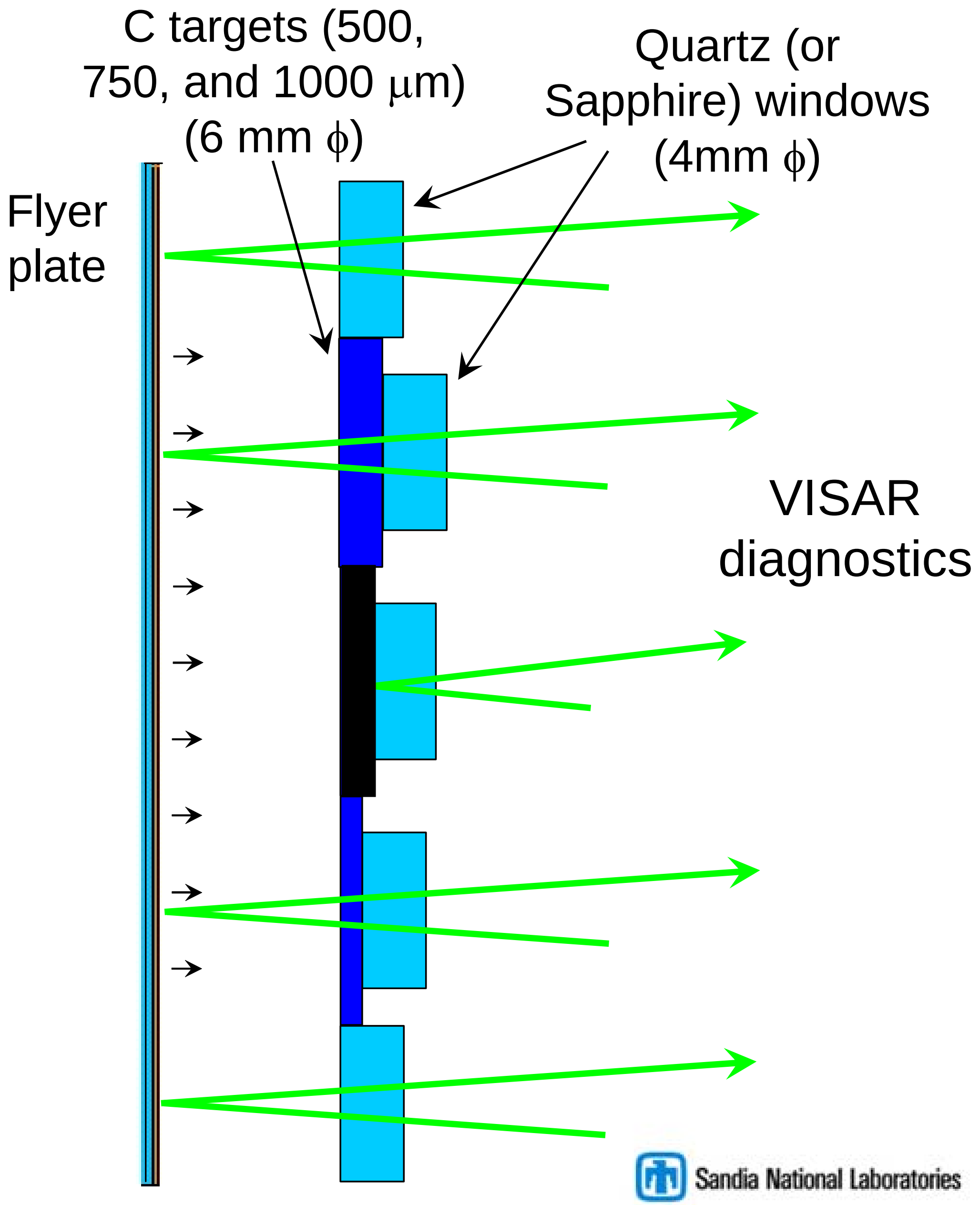
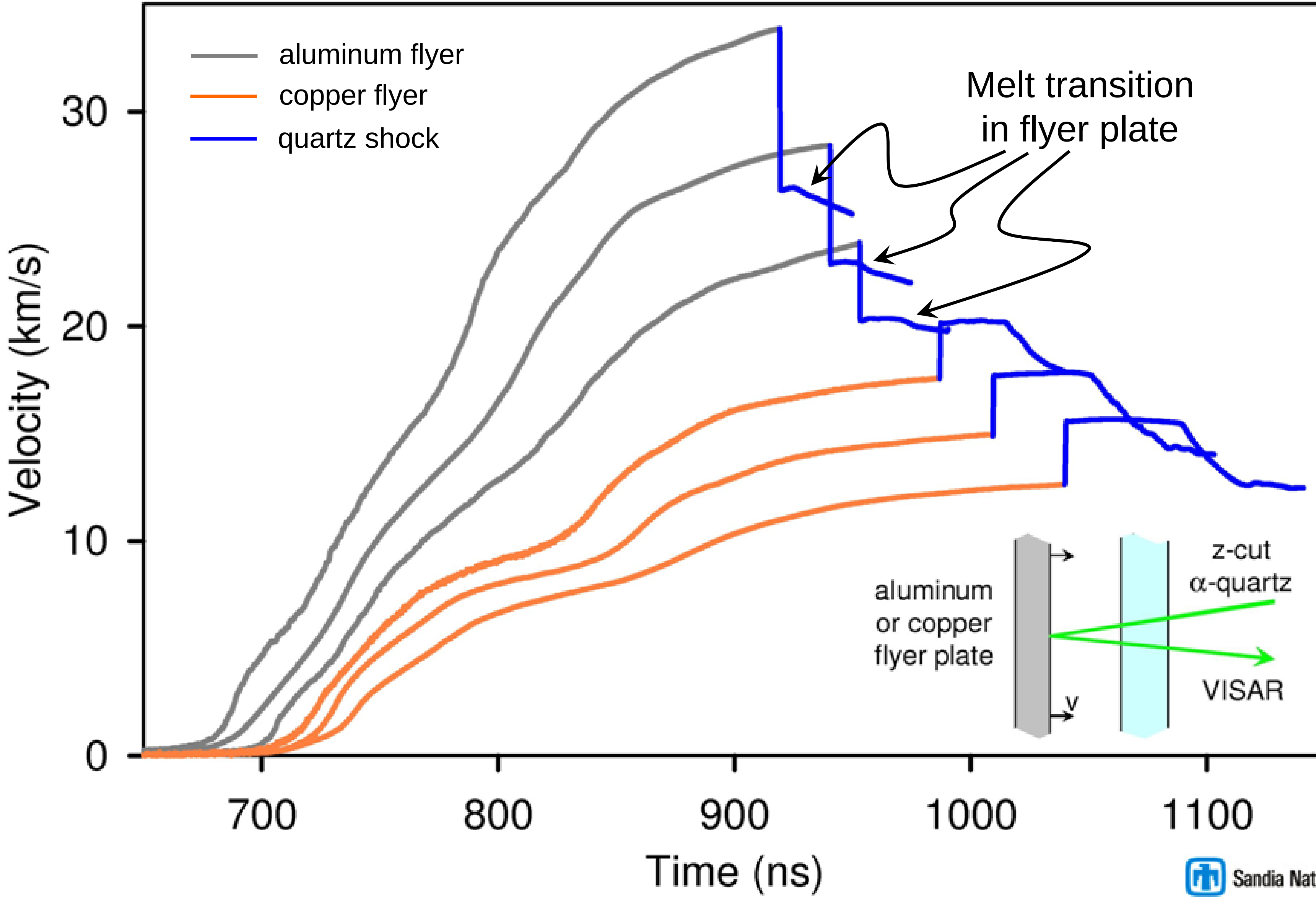
Lemke, et al., J. Appl. Phys. 98, 073530 (2005)

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

Typical configuration



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



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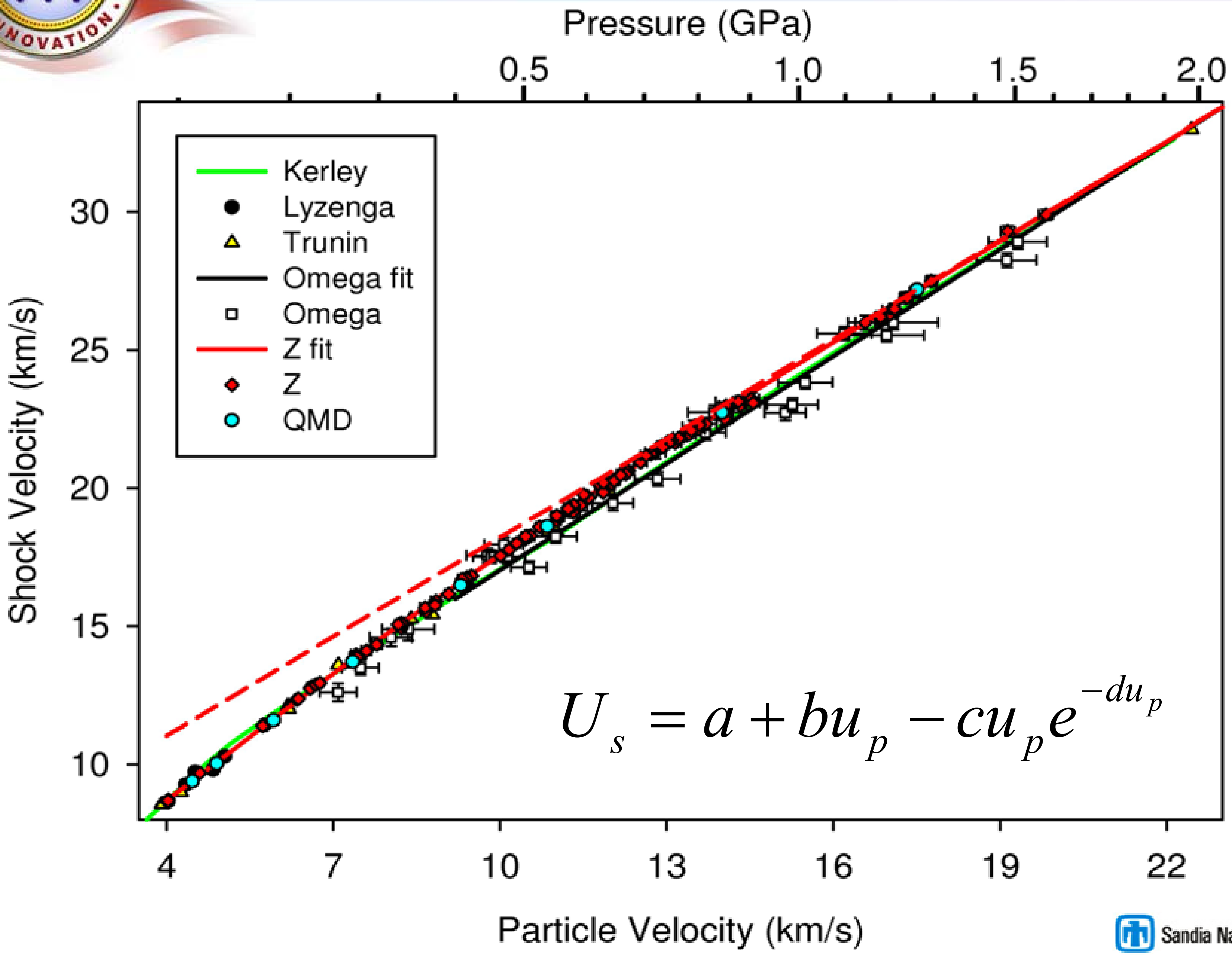
U_s-u_p Hugoniot for α-Quartz



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

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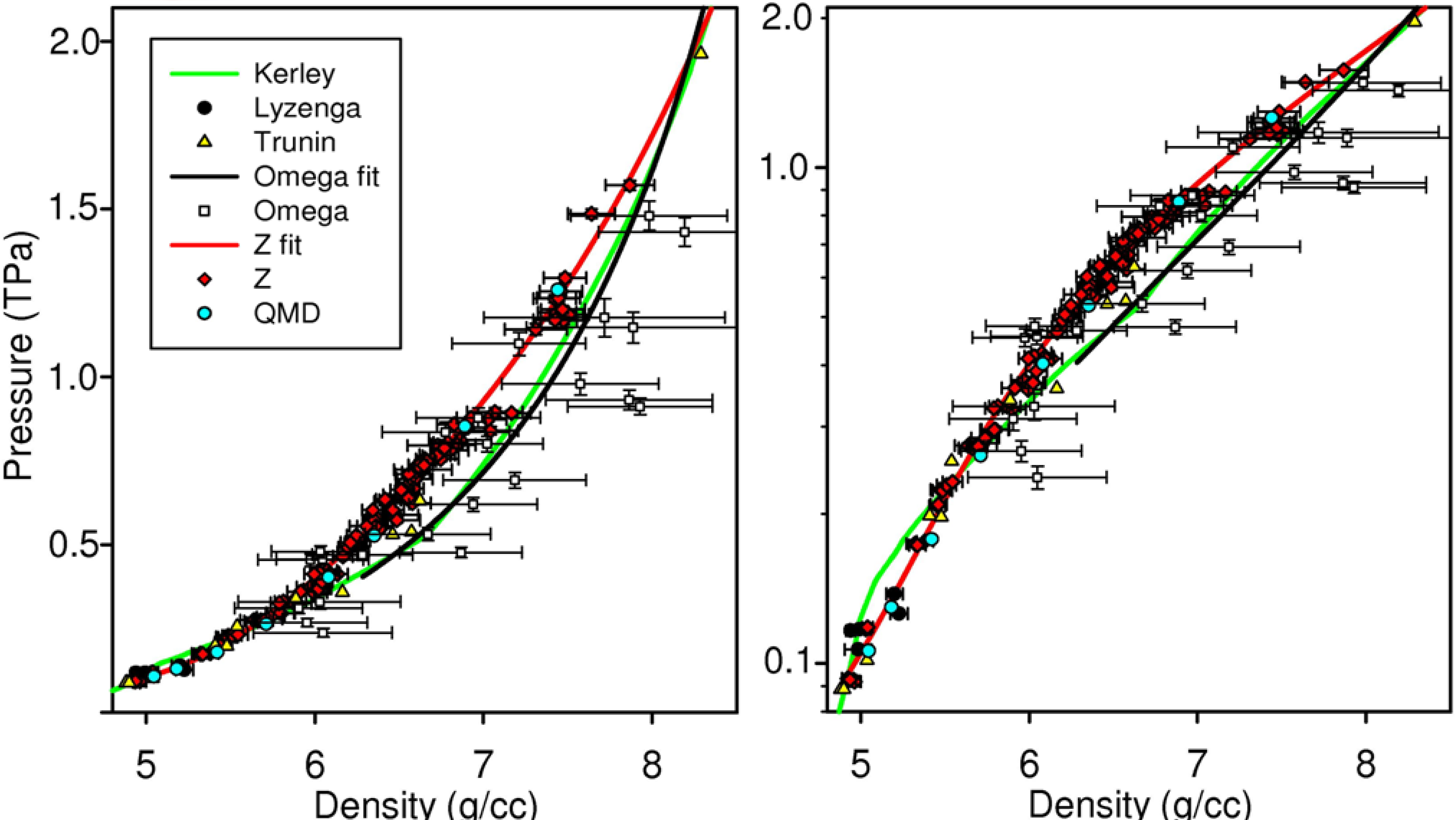
Pressure – density Hugoniot for α-Quartz



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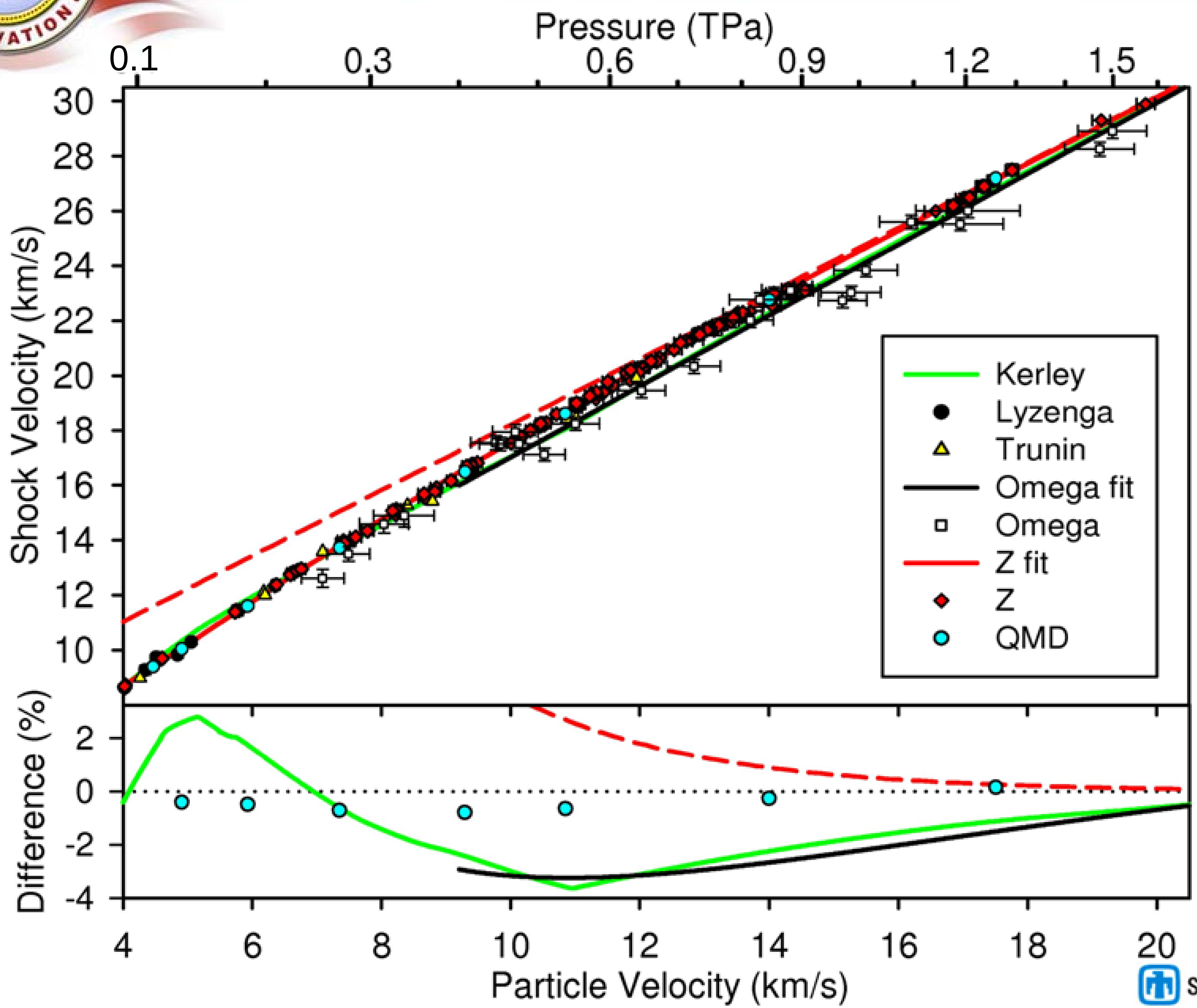
U_s residuals with respect to the Z-fit indicate dissociative effects extend to much higher pressure



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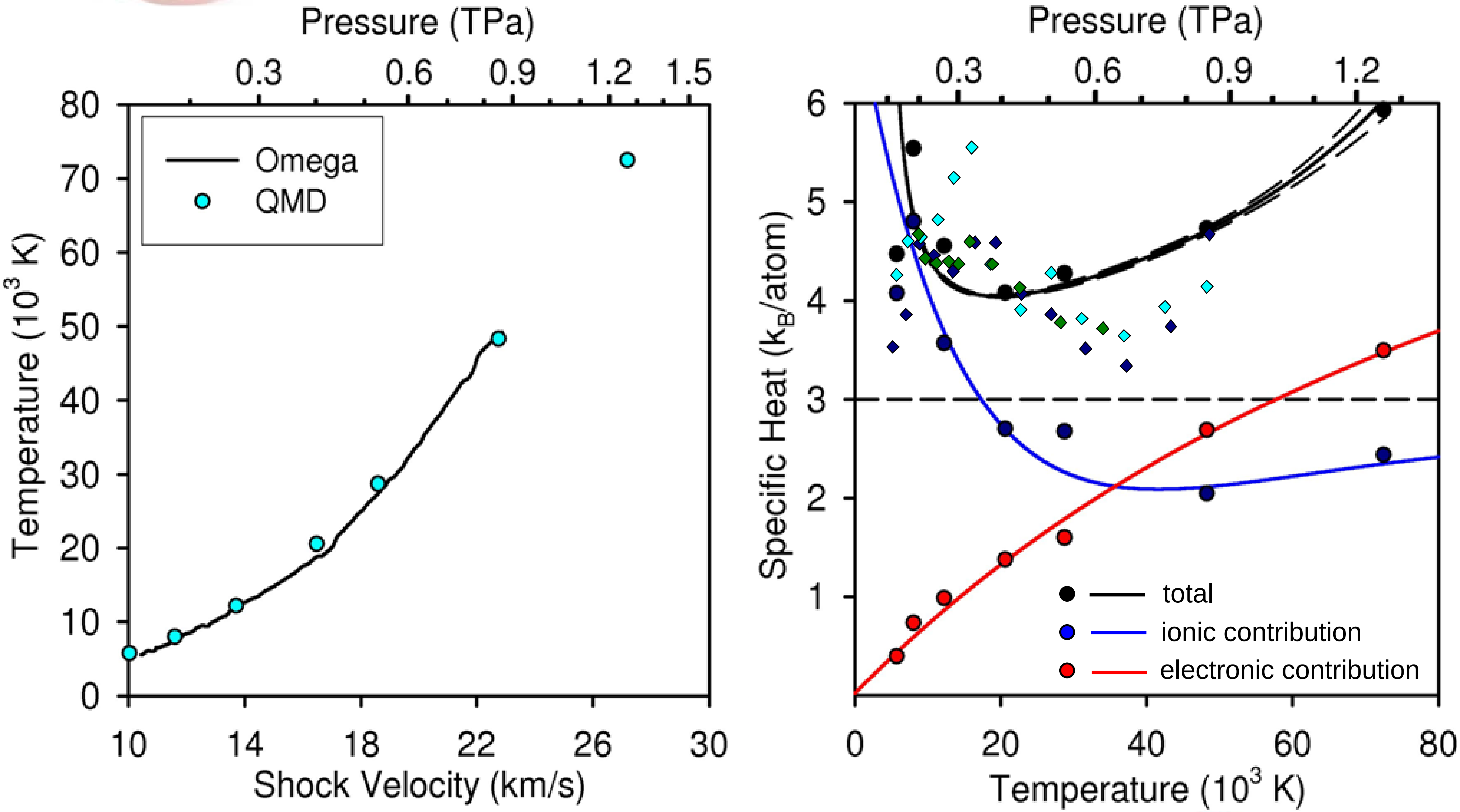
QMD calculations provide unique insight into the dynamics of the fluid at multi-Mbar pressures



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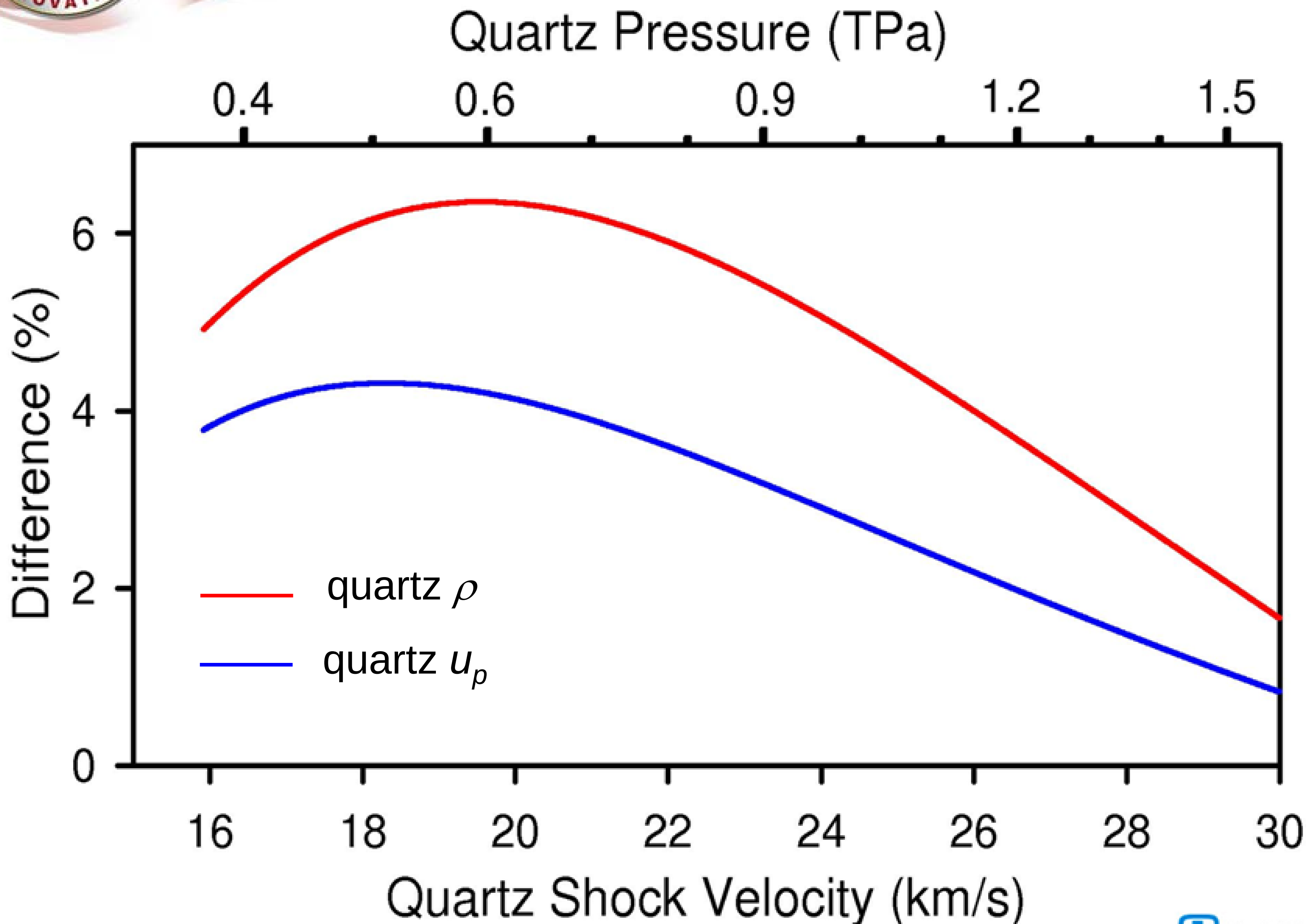
Differences in Z- and Ω-fits will have a significant impact on quantities inferred from quartz U_s



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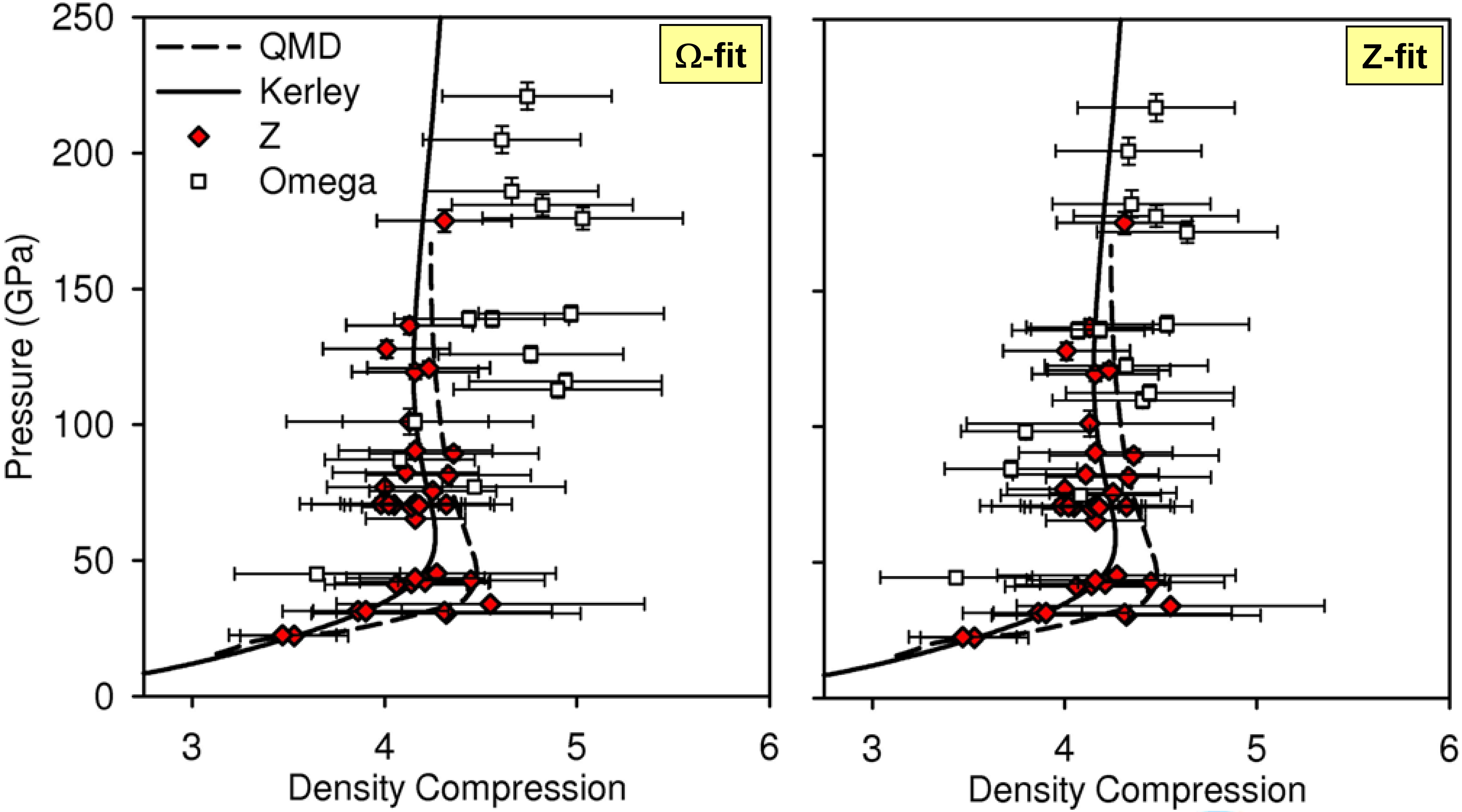
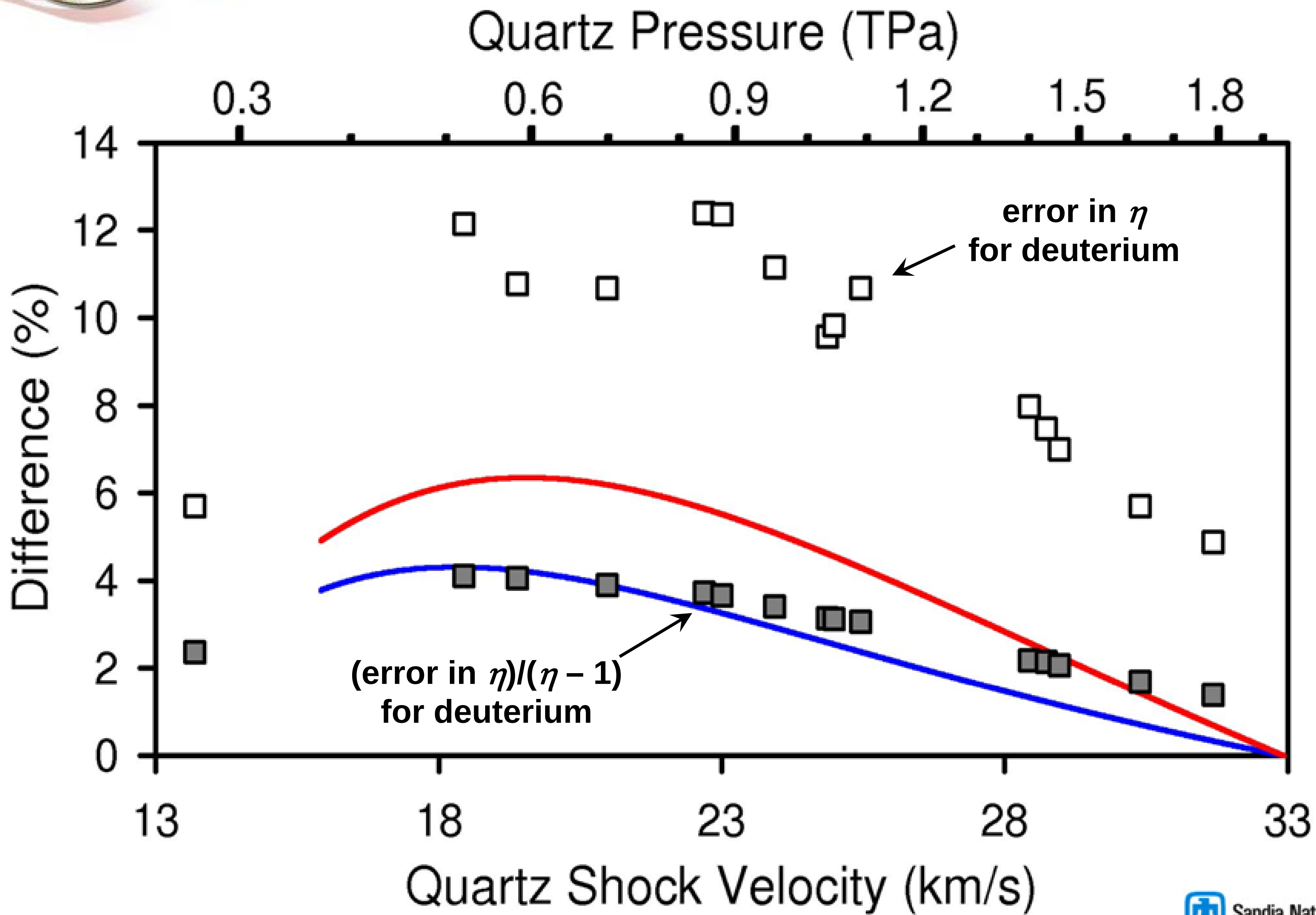
Knudson, et al., PRL 103, 225501 (2009)

Recently published deuterium data becomes significantly stiffer upon reanalysis



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



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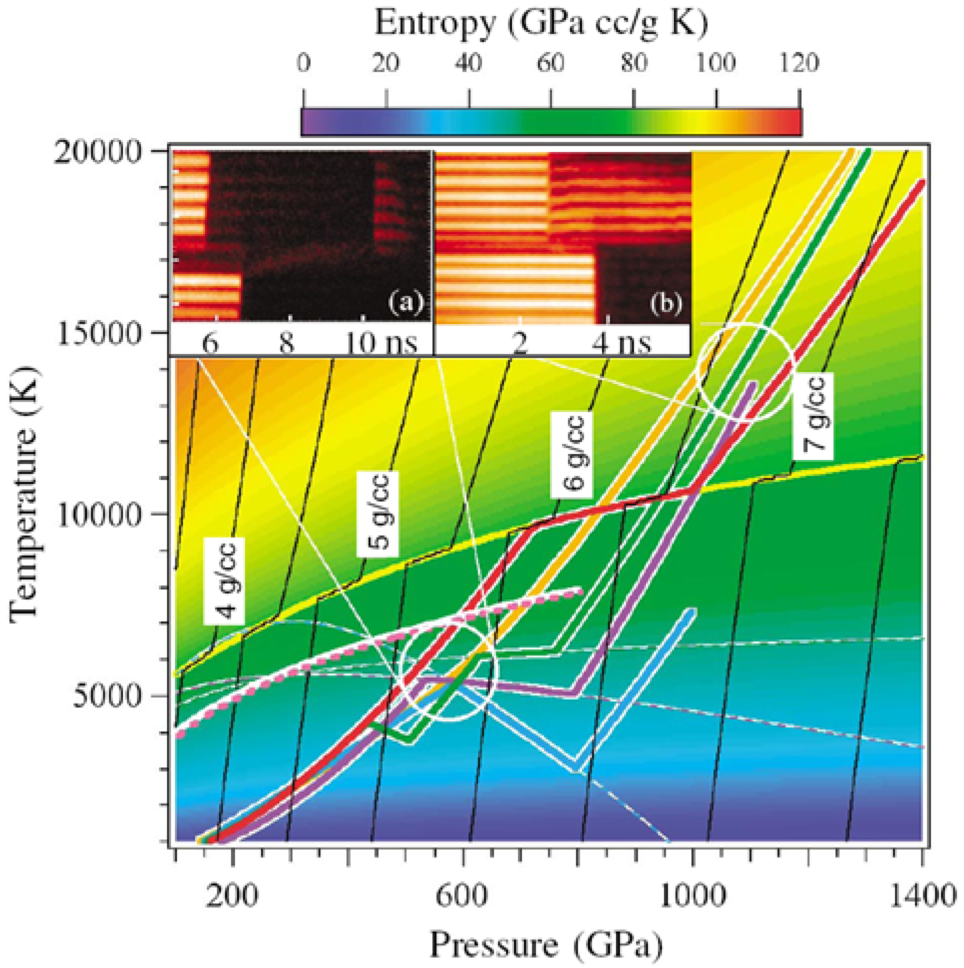
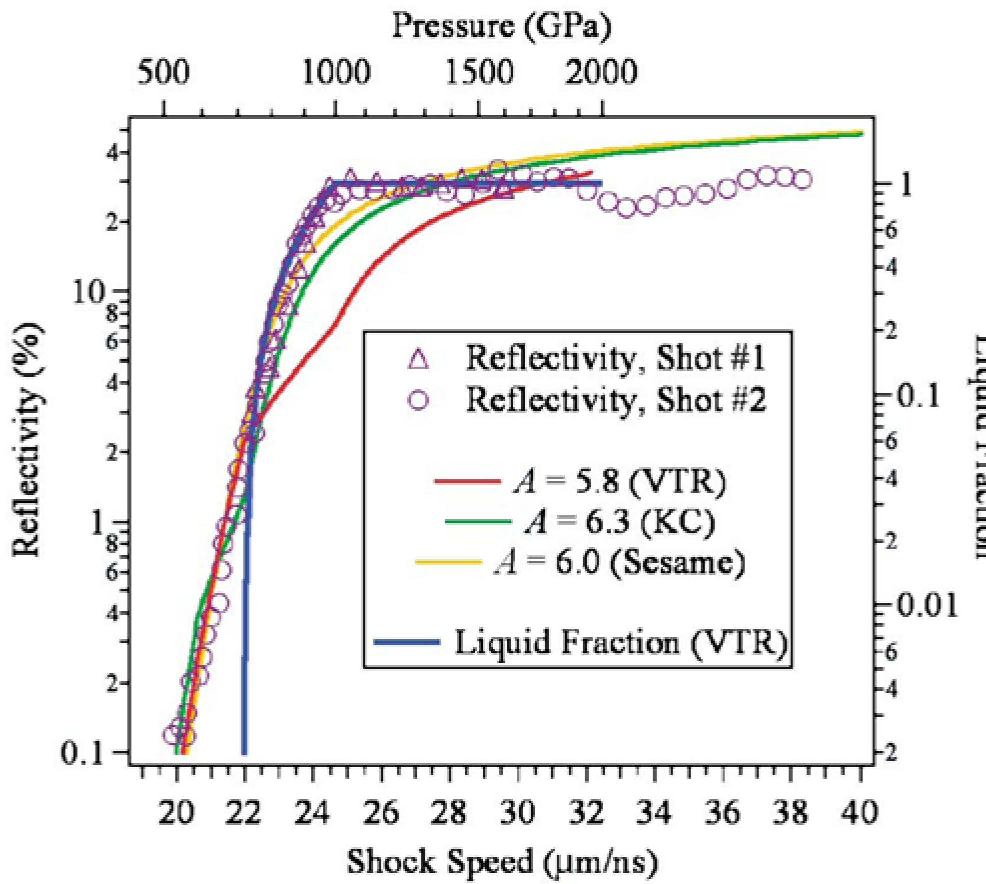
Existing models for diamond exhibit a broad range of predicted melt behavior – melt poorly understood

Several chemical picture models for diamond



Reflectivity study on Omega suggests complete melt near 1100 GPa



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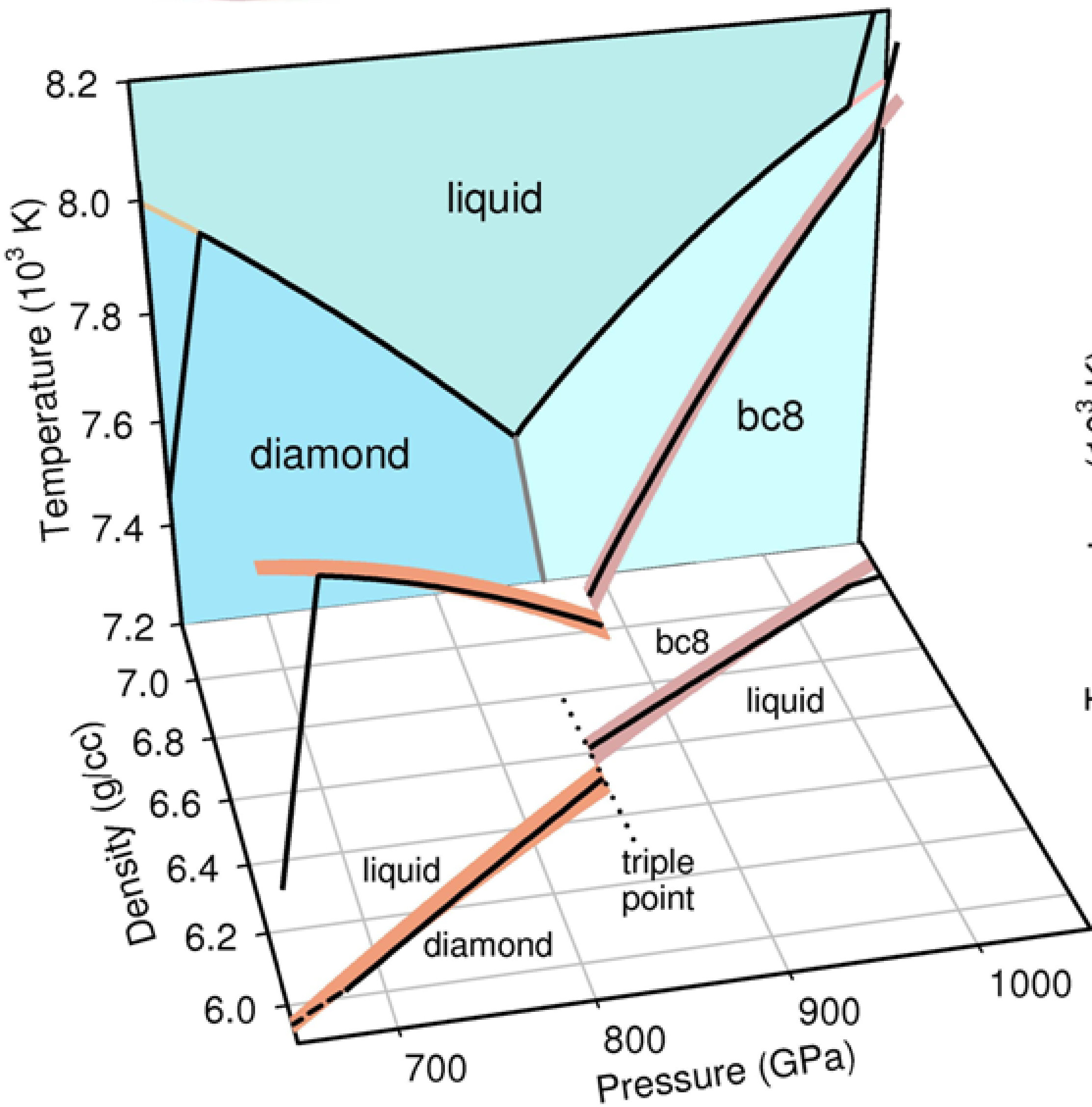
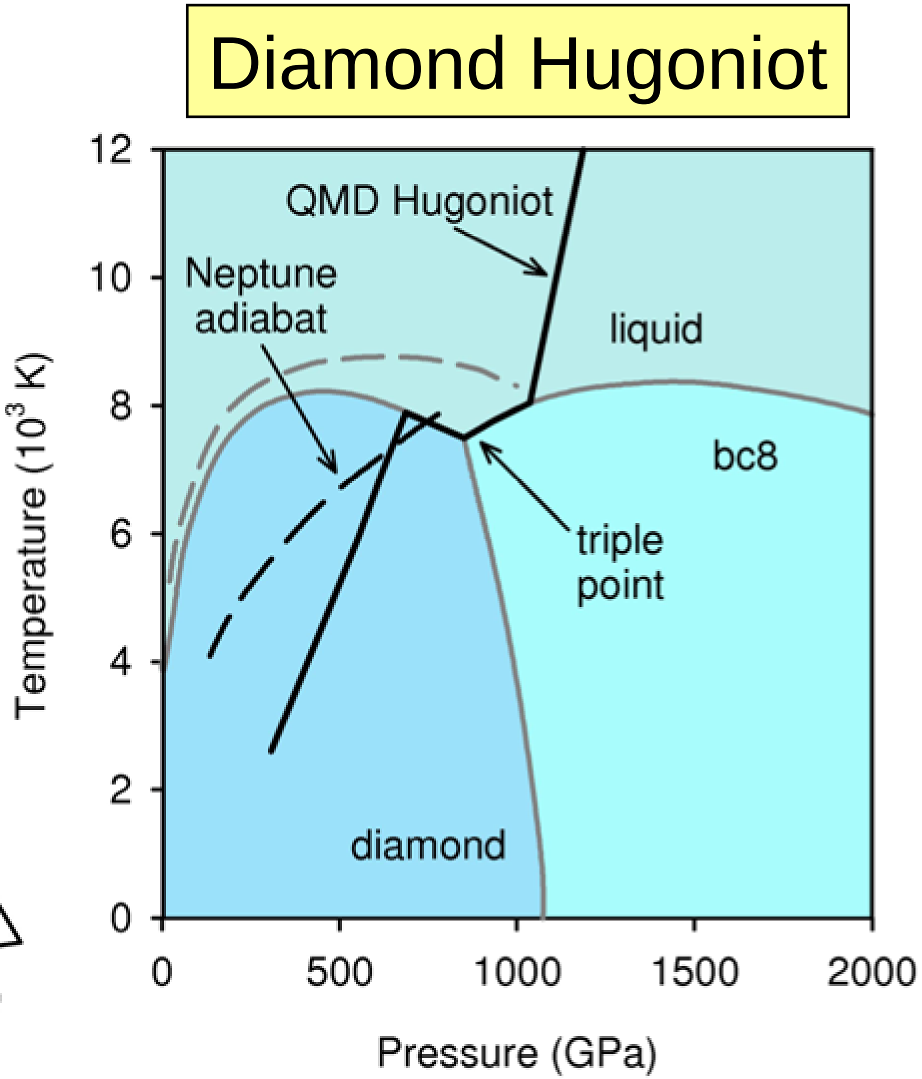
Quantum Molecular Dynamics calculations provided estimates for melt and predicted a triple point (TP)





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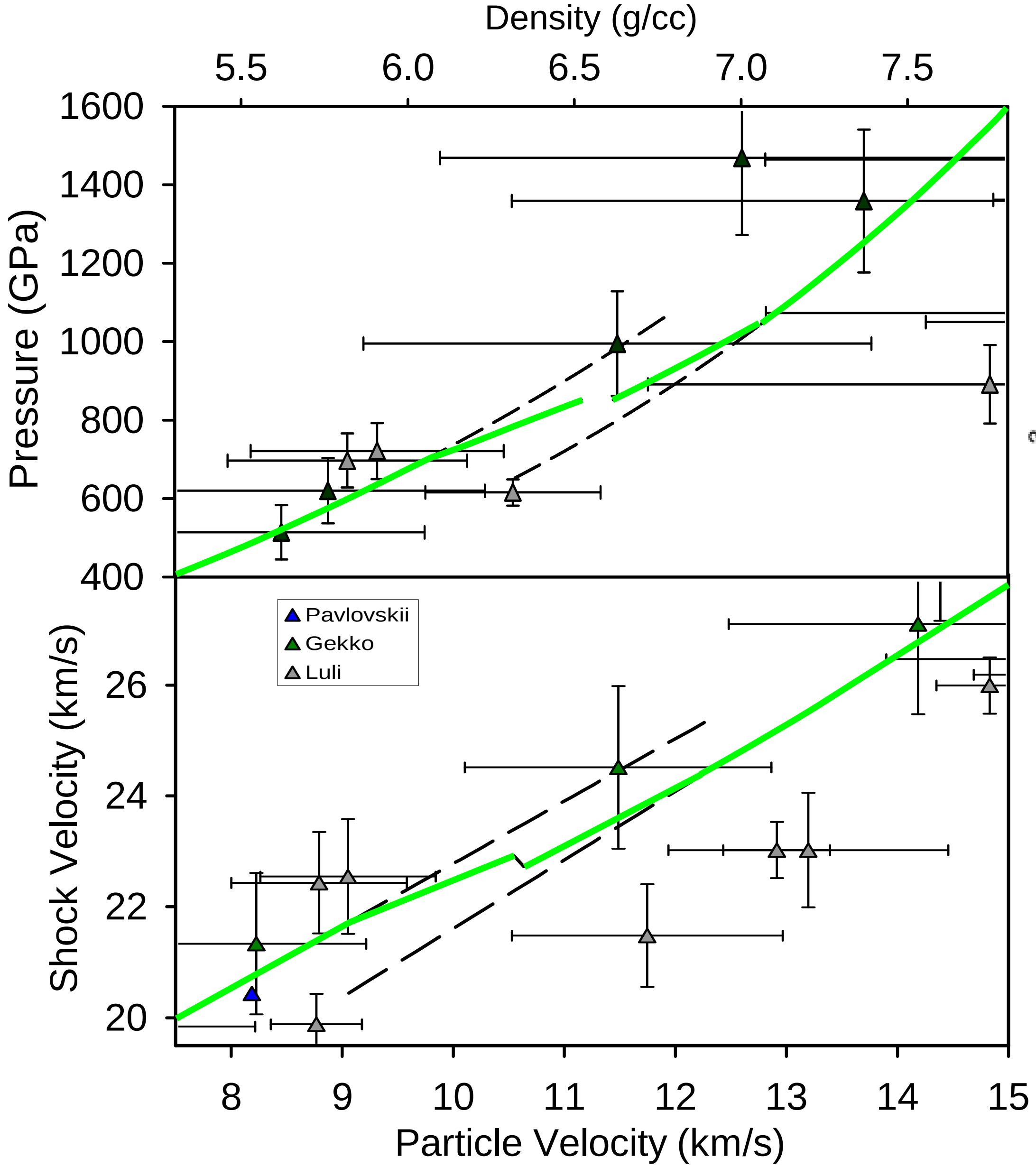
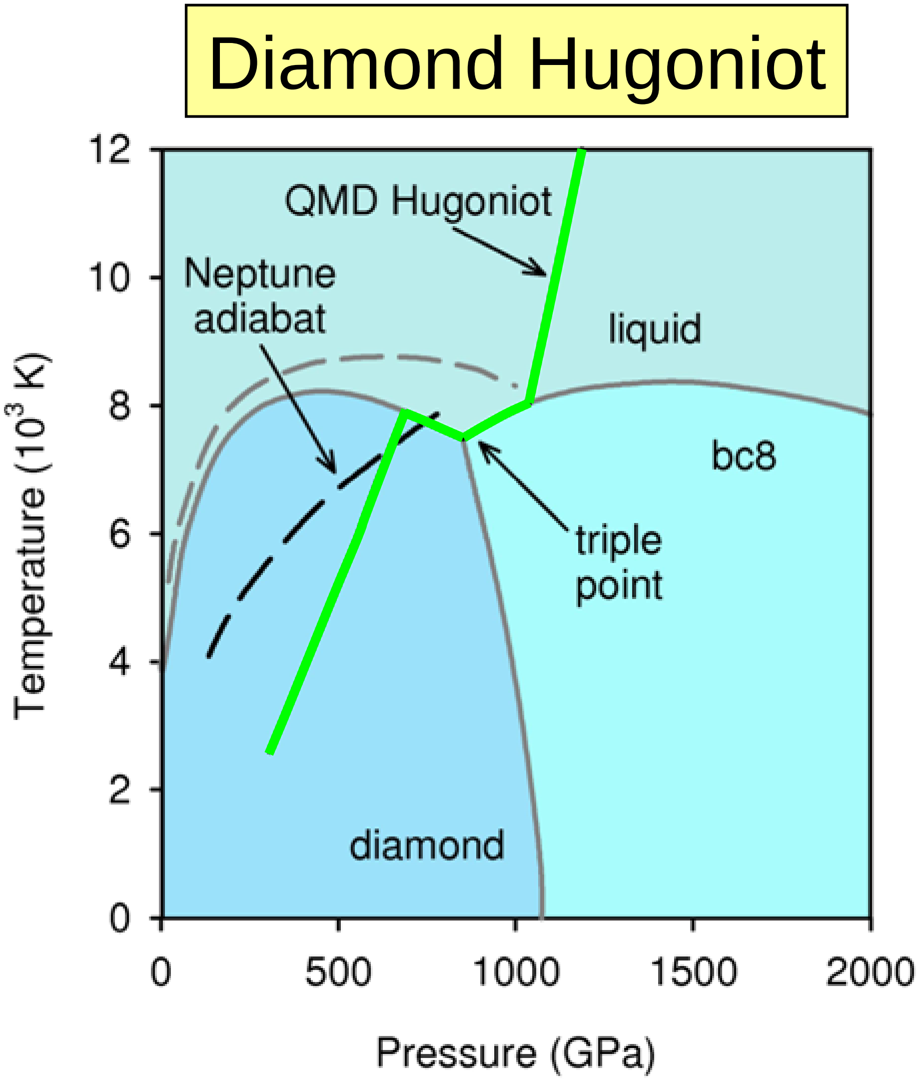
The proposed TP is manifest on the Hugoniot by significant changes in compressibility





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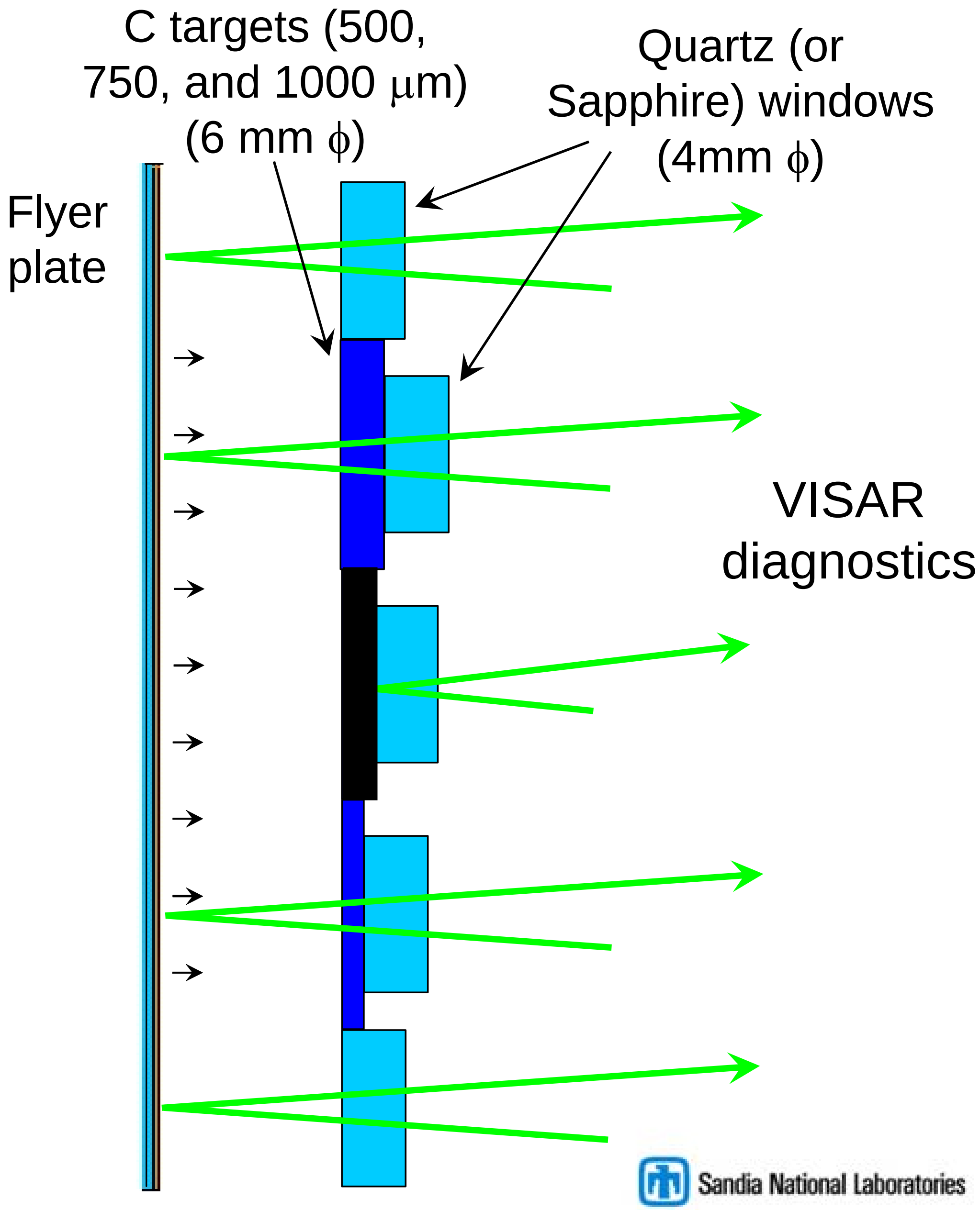
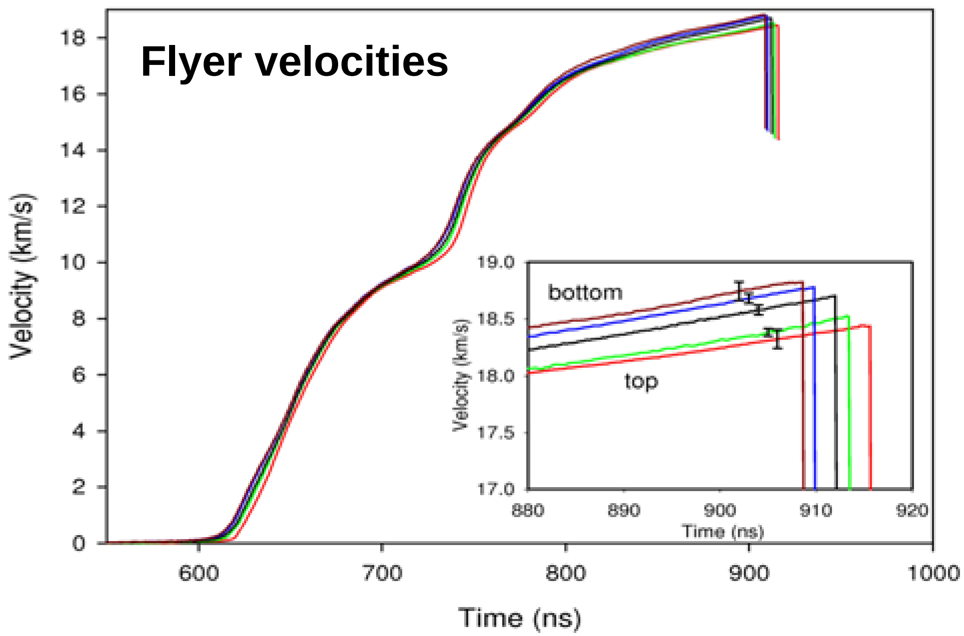
Correa, et al., PNAS **103**, 1204 (2006)

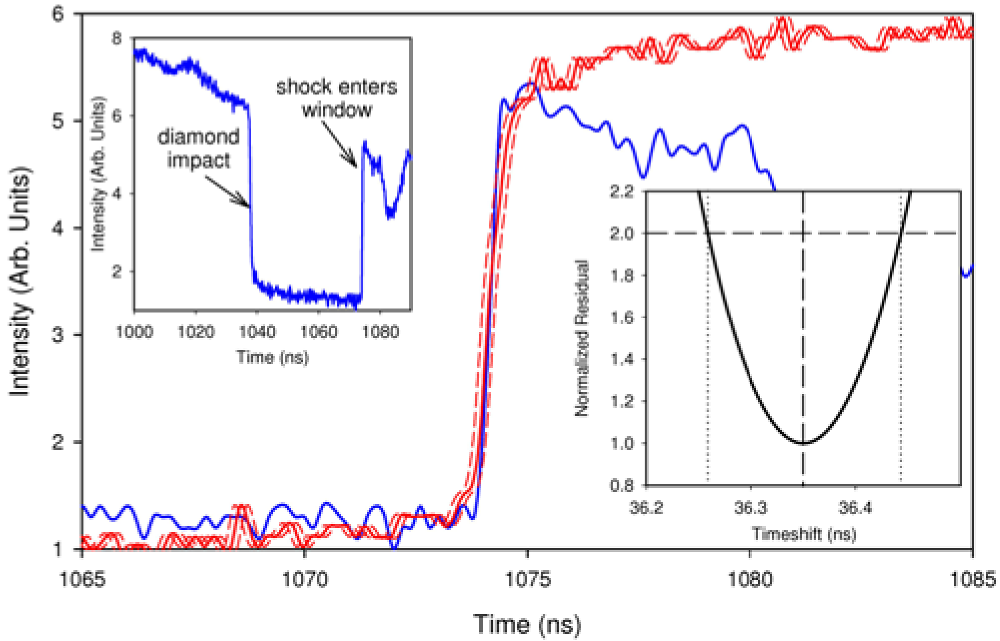
Relatively large flyer plates enabled multiple, redundant measurements increasing accuracy

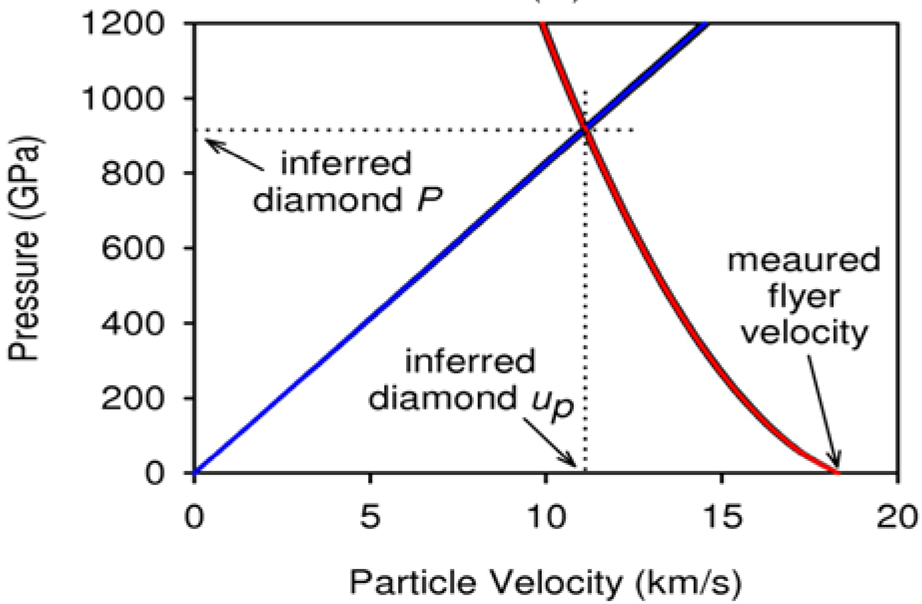
Diamond experimental configuration



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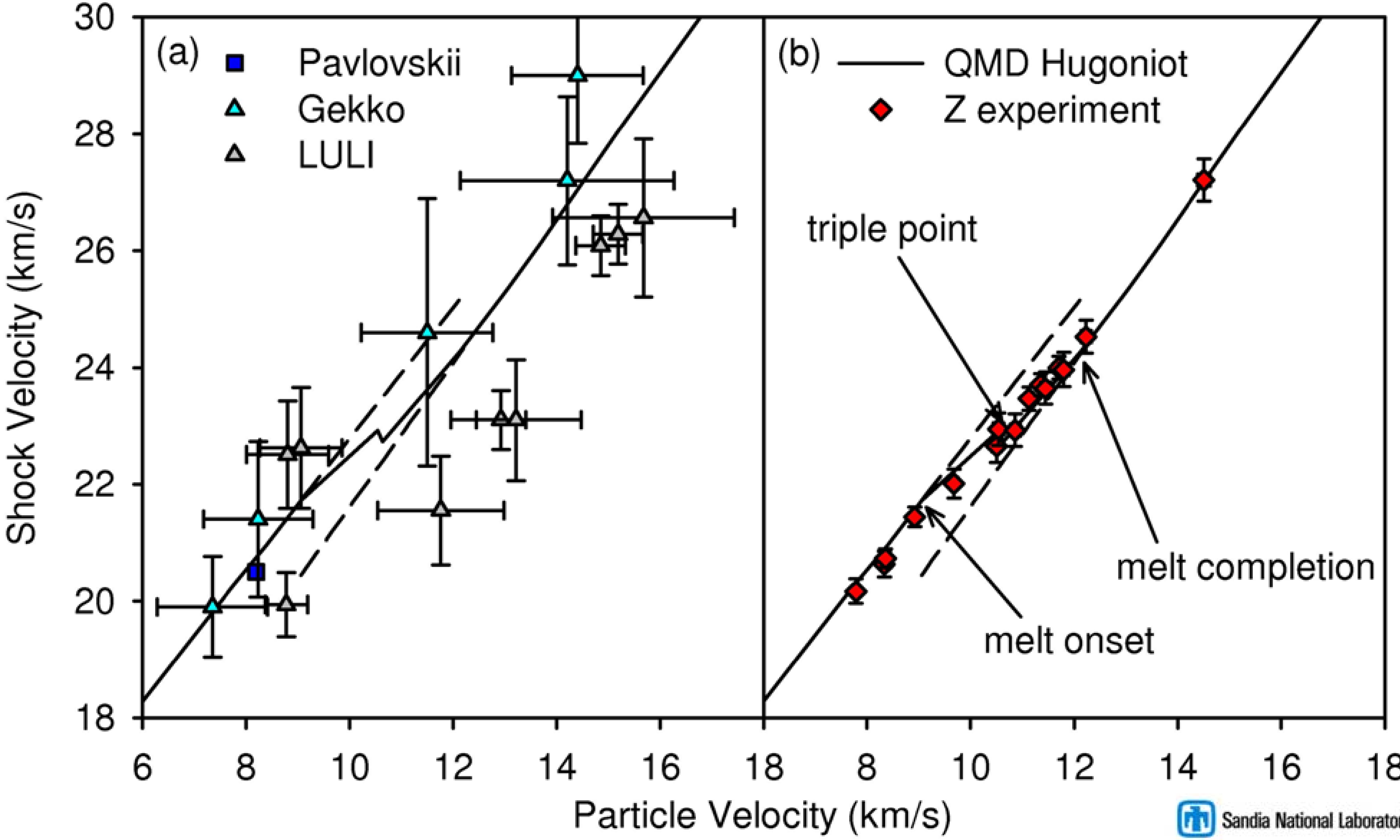
Knudson, et al., Science **322**, 1822 (2008)

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



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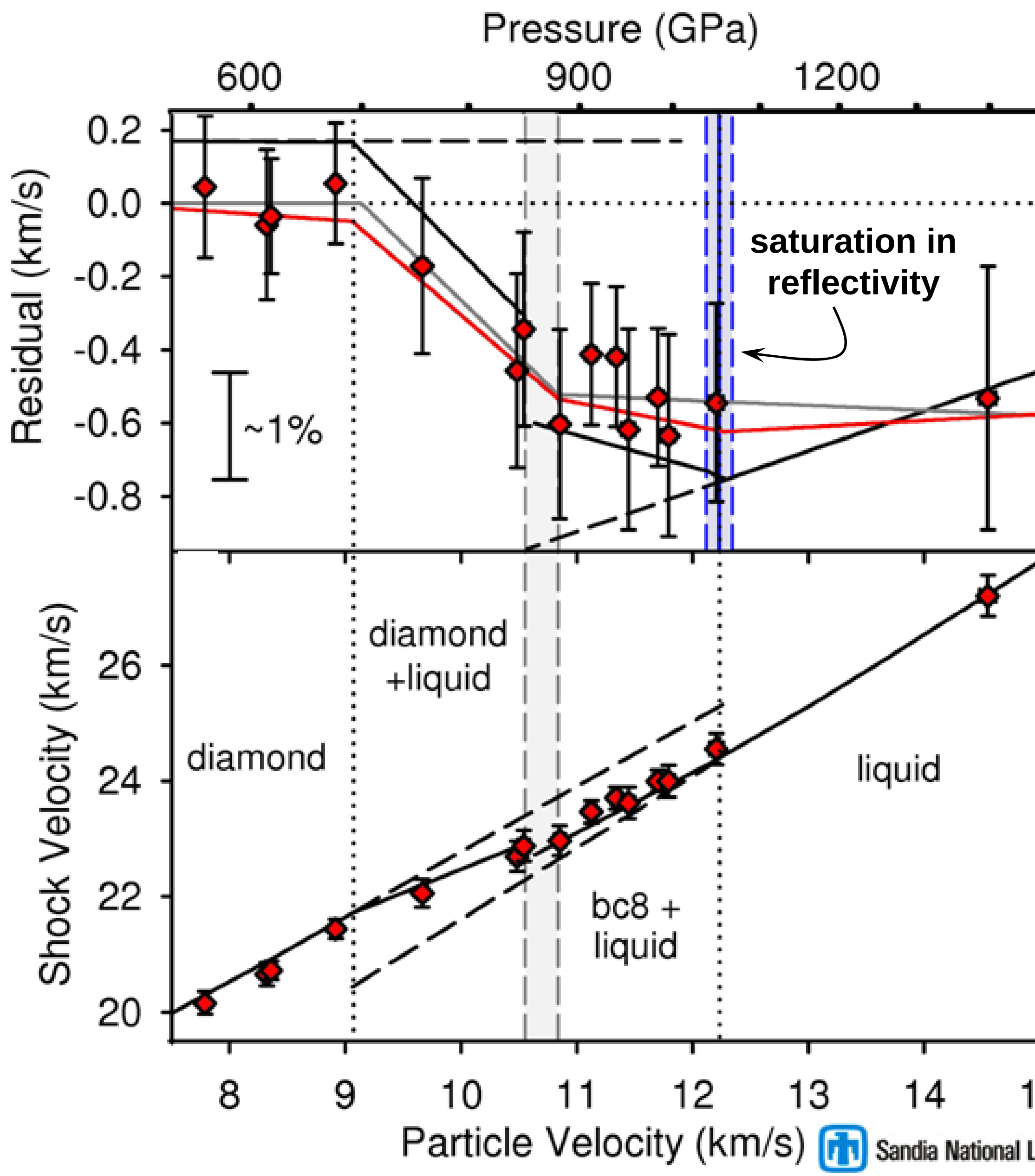
Four piece linear fit leads to consistency with the reflectivity measurements of Bradley, et al.

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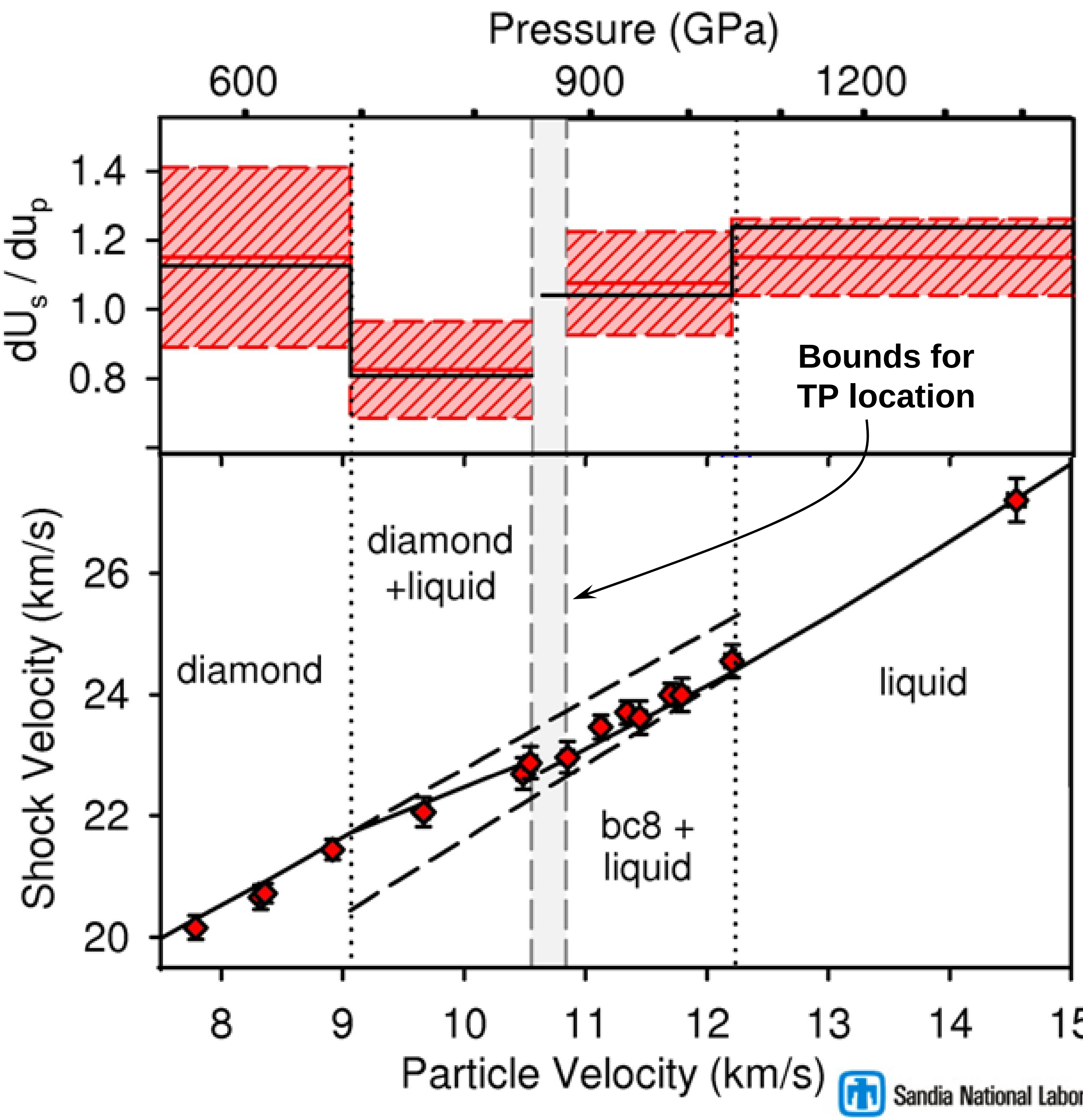
Location of breakpoints and slopes are in excellent agreement with the QMD predictions

- 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 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