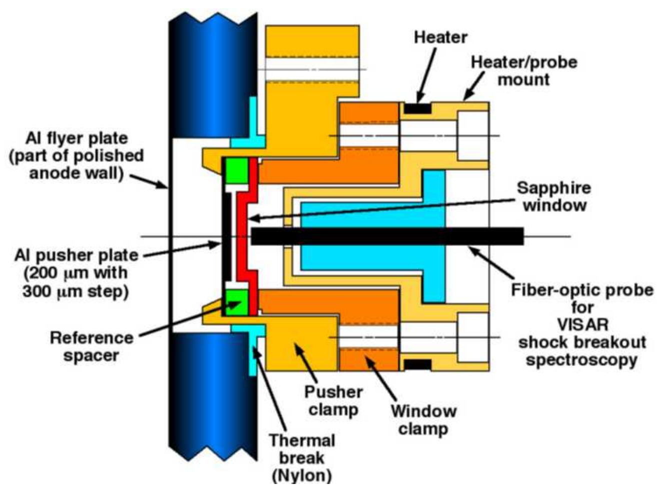
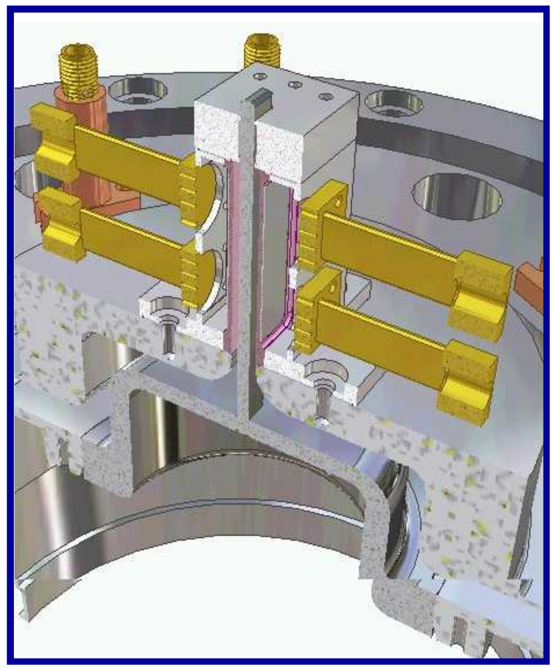
SAND2005-0074C

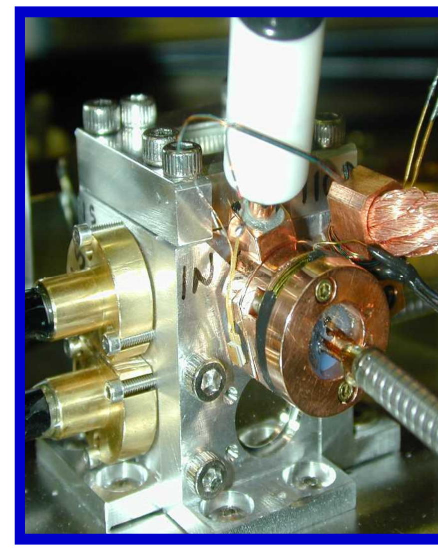
Shock Response of Deuterium Subjected to High-Velocity Plate Impact

Gordon Conference on Research at High Pressure

Kimball Union Academy, Meriden, NH June 28, 2004







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- Dave Hanson, Mike Desjarlais, Clint Hall, Chris Deeney, Bob Johnston, Jim Bailey, Greg Dunham, Ray Lemke, Randy Hickman, Josh Mason, Alan Carlson (SNL)
- Bill Anderson (LANL)
- Jerry Kerley, Dennis Hayes, Jim Asay (Consultants)

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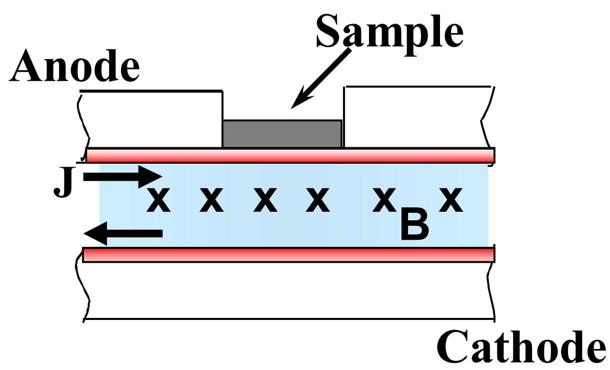
Outline

- Summary of magnetic flyer technique on Z
- Independent, self-consistent measurements show agreement with ab-initio models to 1 Mbar
  - Primary Hugoniot
  - Reverberation
  - Re-shock Pressure
  - Hugoniot Temperature
  - Re-shock Temperature
- Release response of aluminum calibrated for impedance matching technique
  - Main source of potential systematic uncertainty
- Conclusions & Future directions

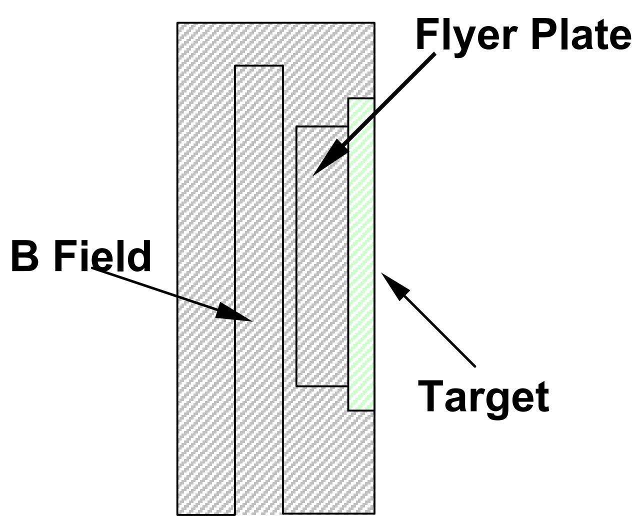
We've developed techniques on Z for accurate EOS studies—both major advances



Isentropic Compression Experiments (ICE)*

Magnetically produced Isentropic Compression Experiments (ICE) to provide measurement of continuous compression curves
- previously unavailable at Mbar pressures

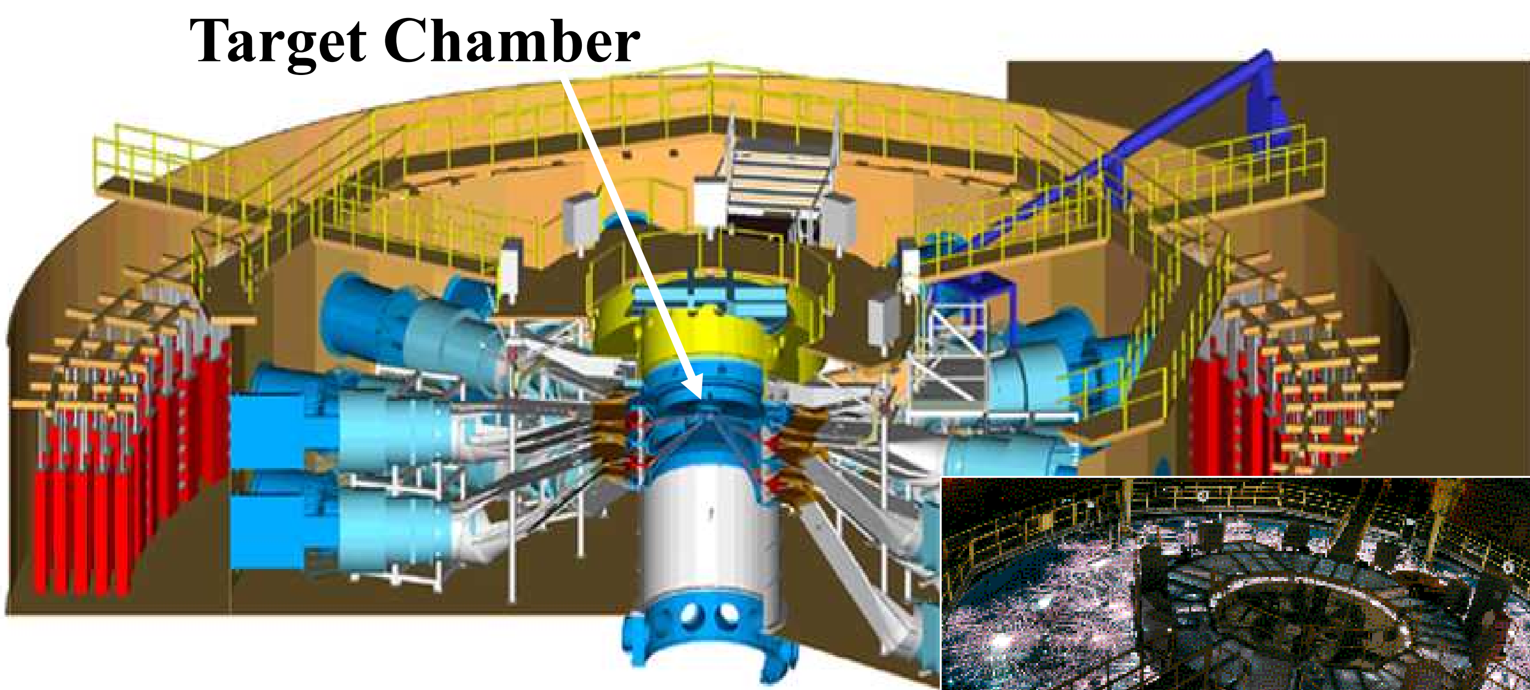
* Developed with LLNL

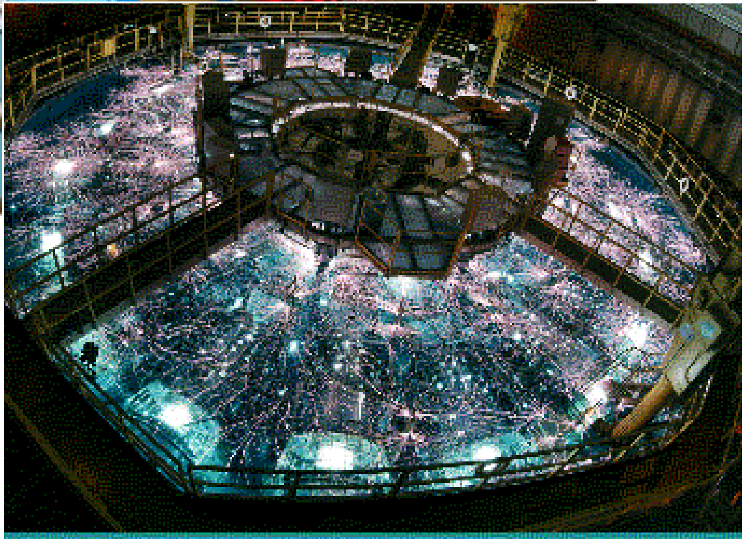


Magnetically launched flyer plates

Magnetically driven flyer plates for shock Hugoniot experiments at velocities to ~ 27 km/s
- exceeds gas gun velocities by ~ 3X and pressures by ~ 4X with similar accuracy

Sandia Z accelerator



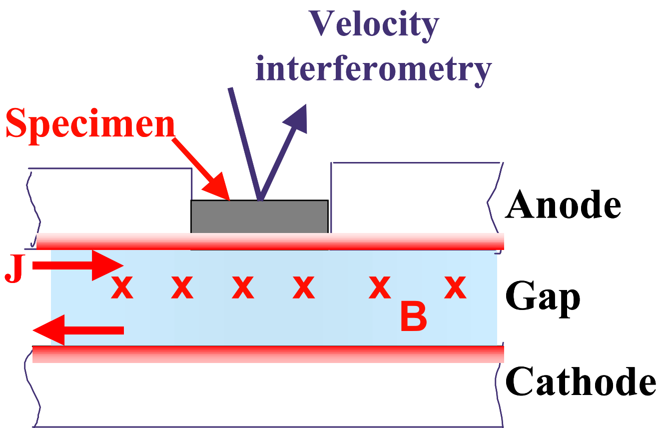


11.5 MJ stored energy

~22 MA peak current

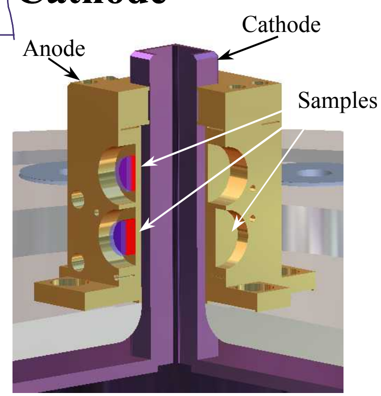
~200 ns rise time

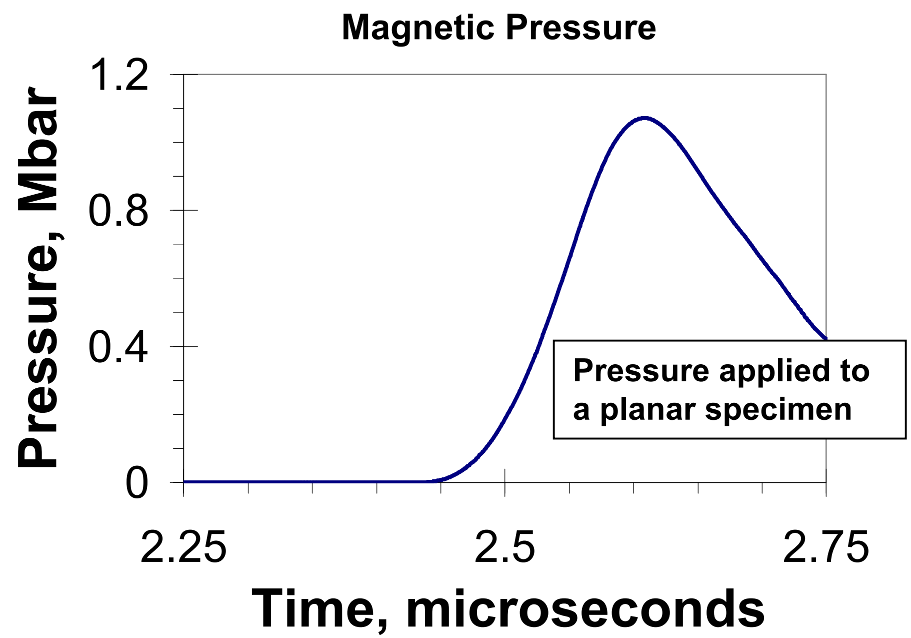
Z generates large amplitude ramp waves for studying quasi-isentropic compression



$$B = \mu_0 J$$

$$P = B^2 / 2\mu_0$$





- Shockless loading for 200-300 ns
- Multiple experiments/shot (4-12)
- Same loading history (A-B comparison)
- Versatile (simultaneous Lo/Hi T)

C.A. Hall, et al., Rev. Sci. Instrum. **72**, 1 (2001)

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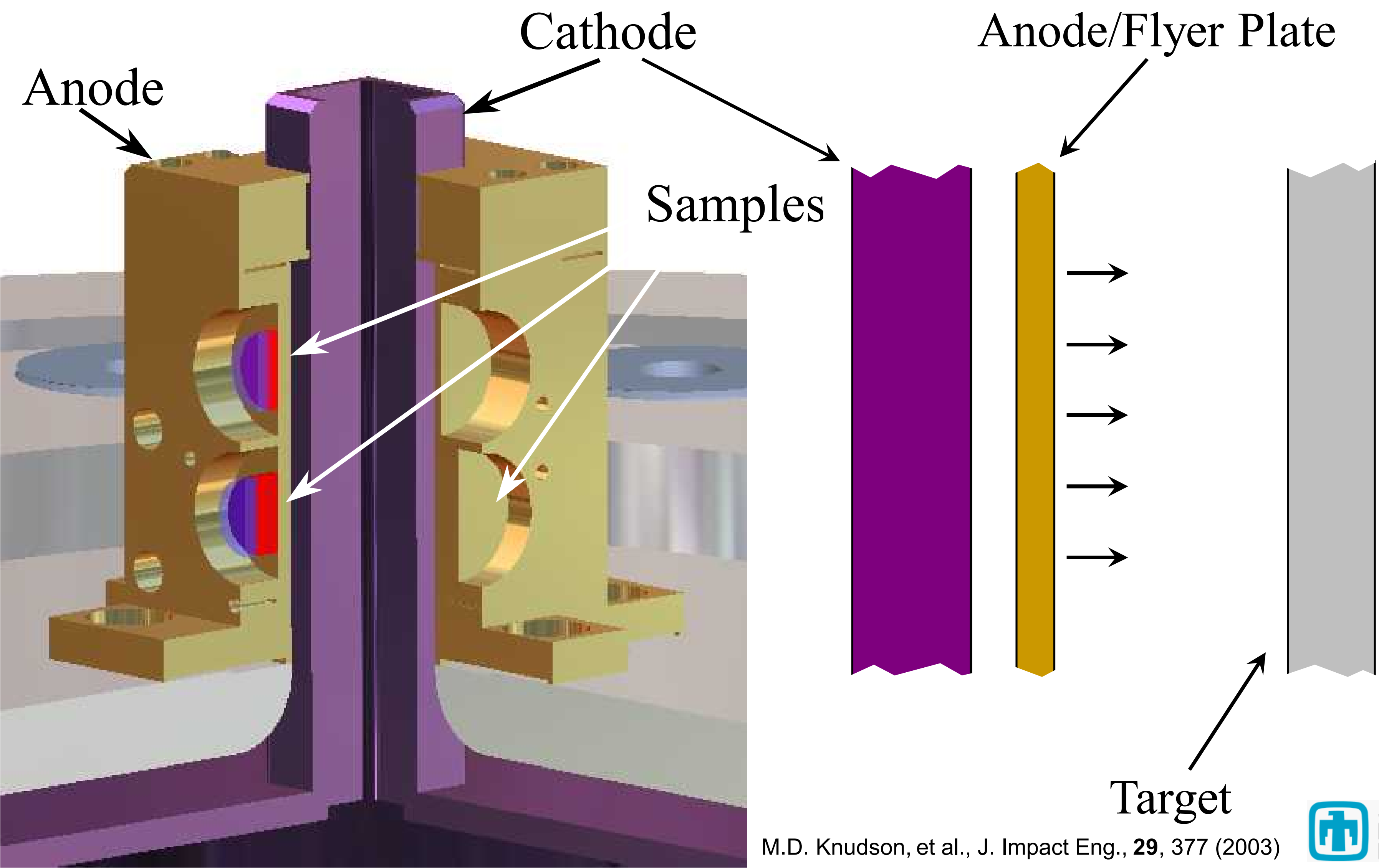
Ultra-high velocity flyer plates have been developed for EOS data at multi-Mbar pressures



M.D. Knudson, et al., J. Impact Eng., **29**, 377 (2003)

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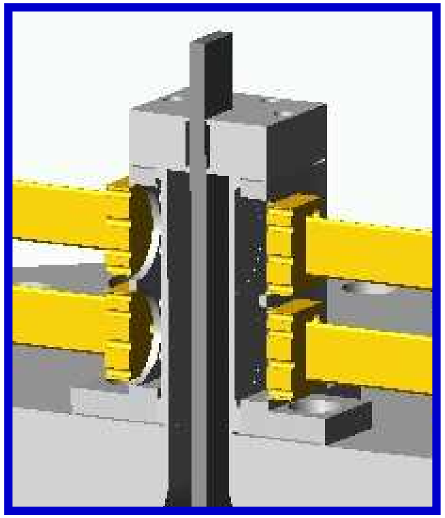
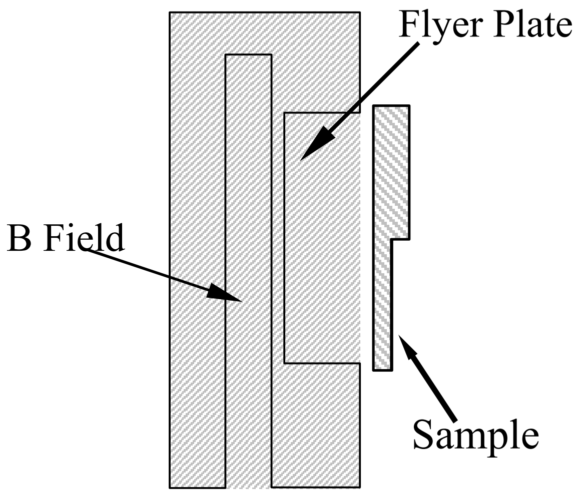
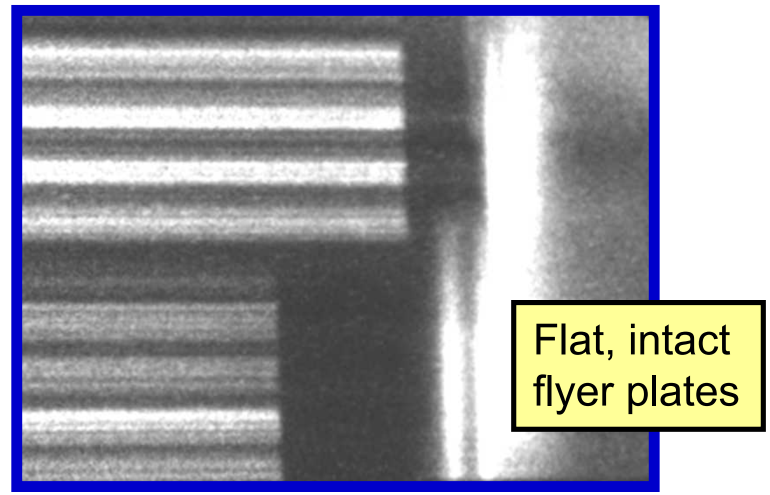
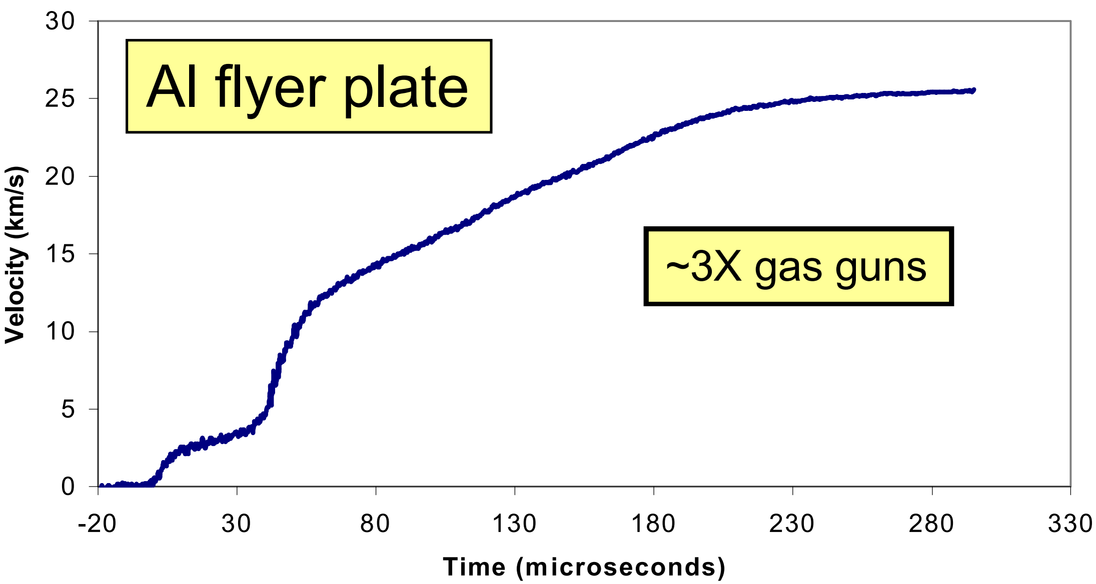
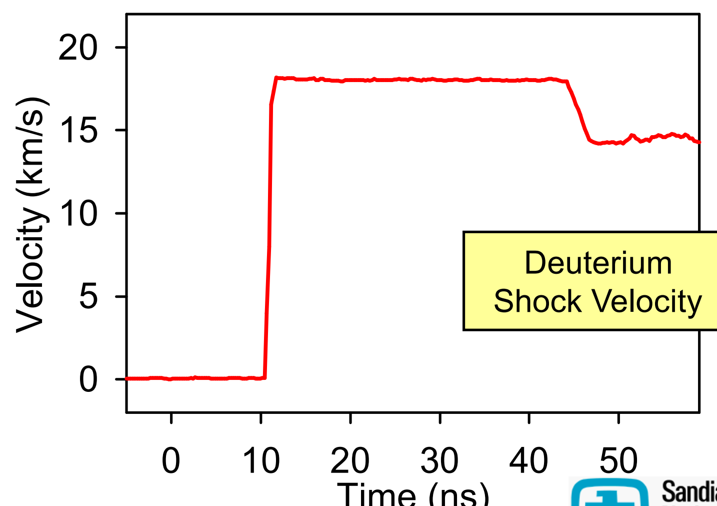
Ultra-high velocity flyer plates are being developed for EOS data at multi-Mbar pressures



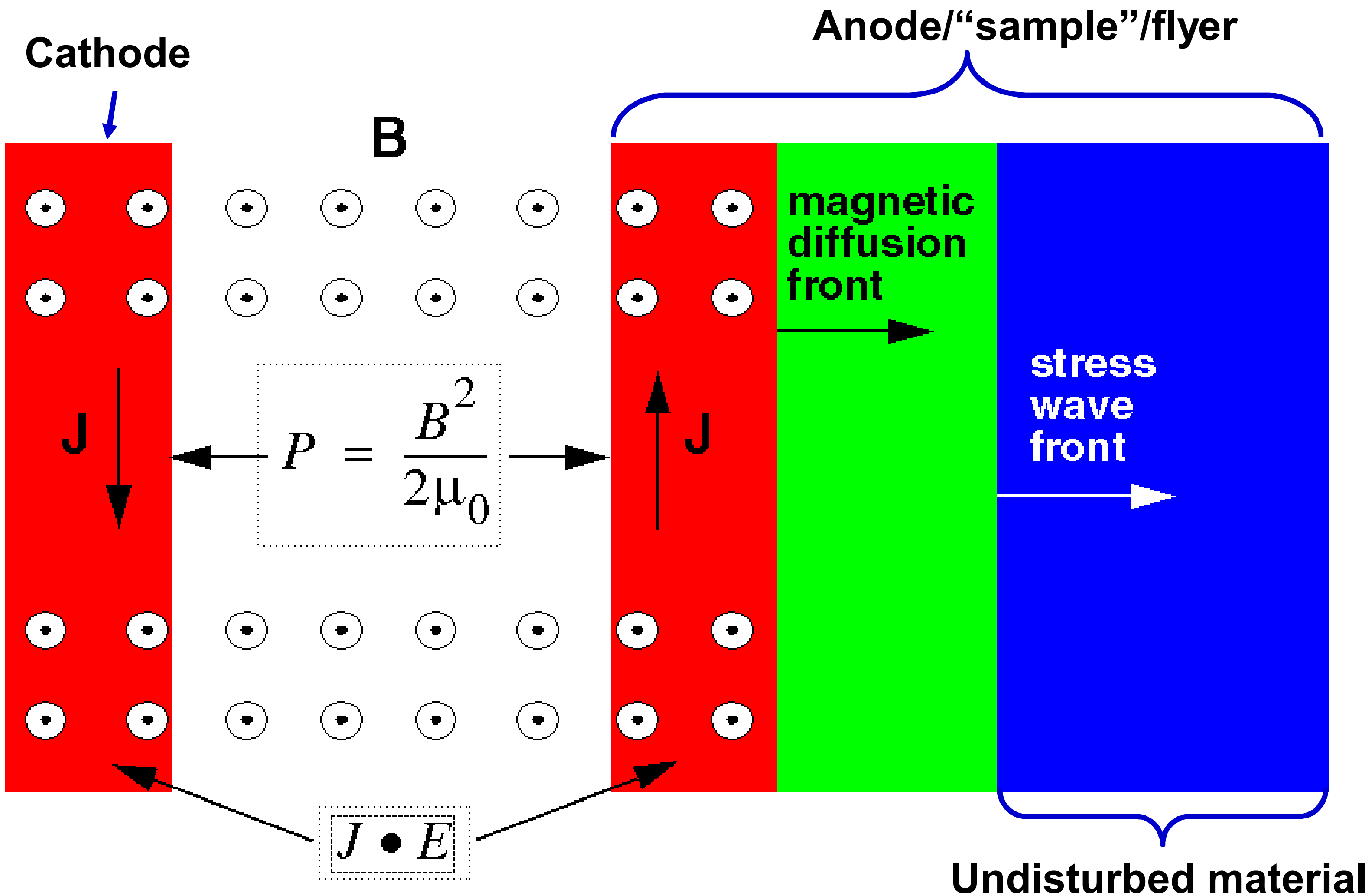




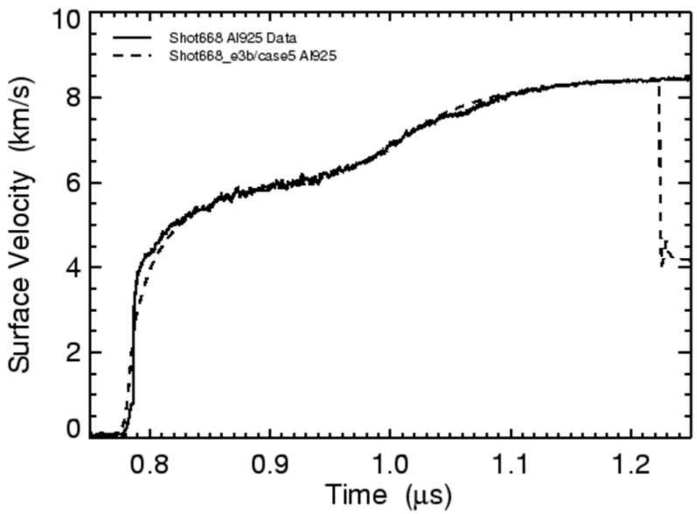


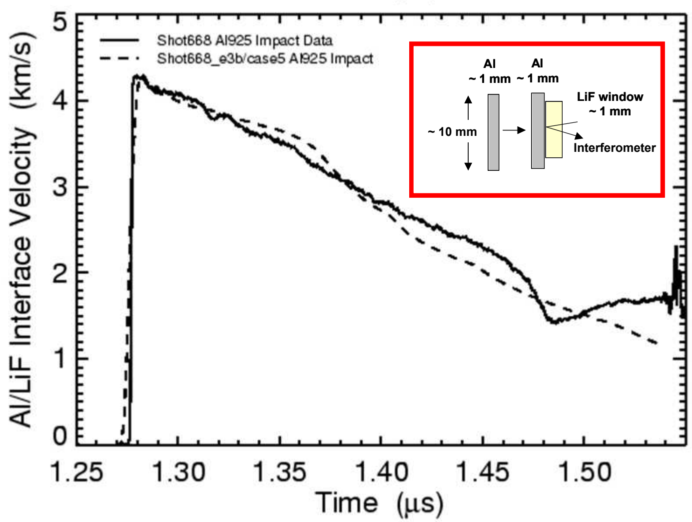


The ICE / flyer plate experiment requires accurate knowledge of MHD effects



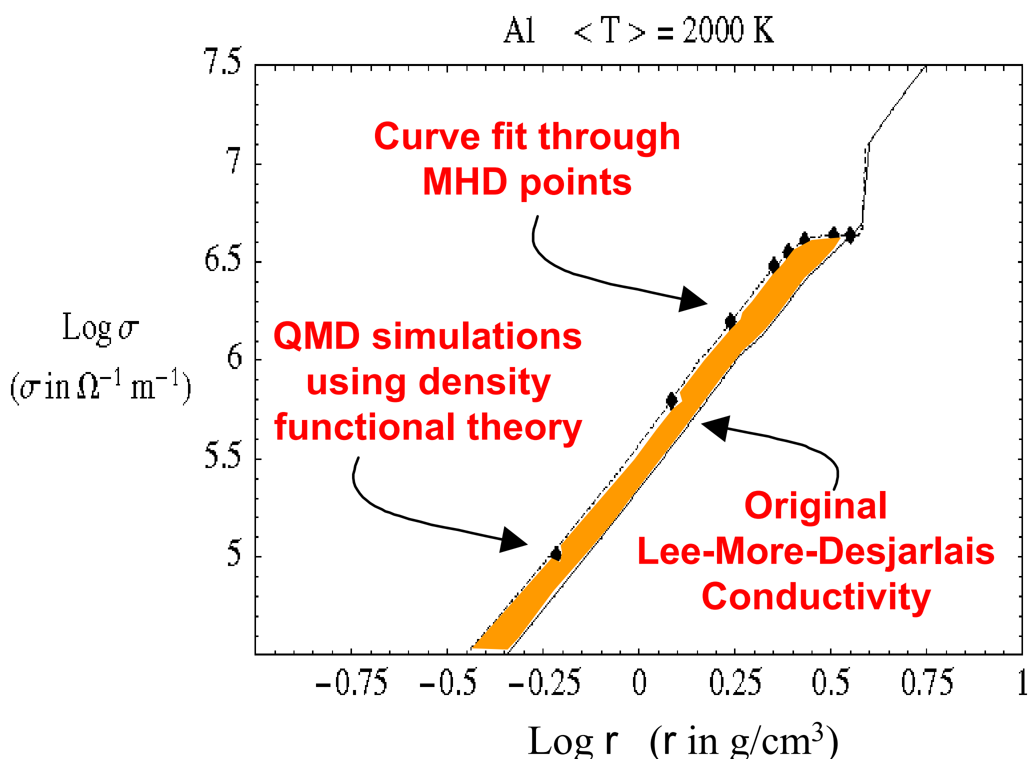
New conductivity models are validated through comparison with flyer plate experiments





R.W. Lemke, et al., Phys. Plasmas **10**, 1092 (2003)

State-of-the-art conductivity model developed for Al – treatment of conductivity in liquid-vapor phase



M.P. Desjarlais, Contrib. Plasma Phys. **41**, 267 (2001)

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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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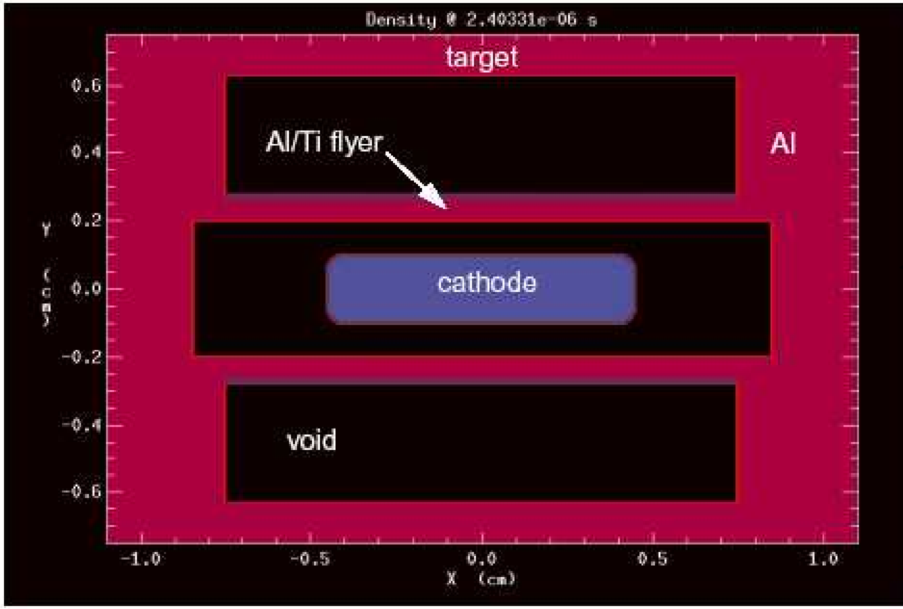
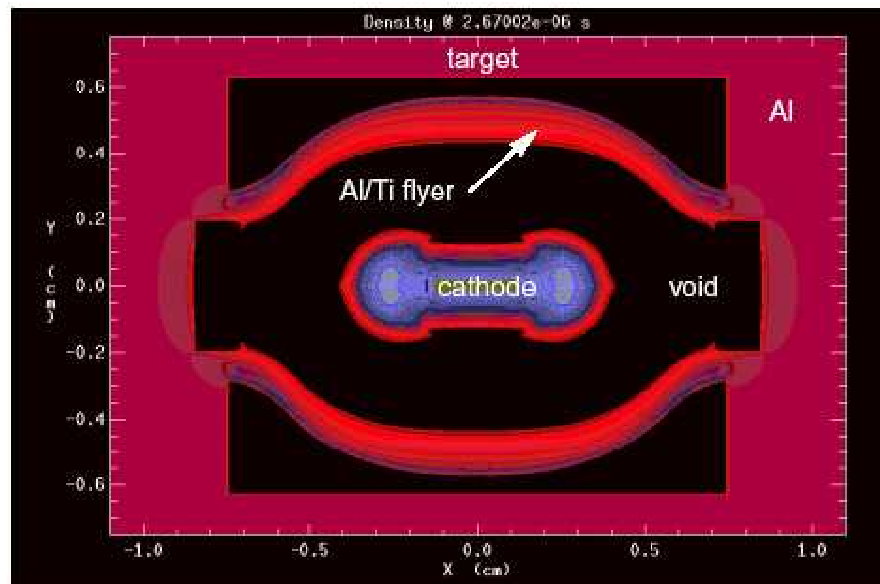
Power is coupled to the load via inductance which is determined by geometry



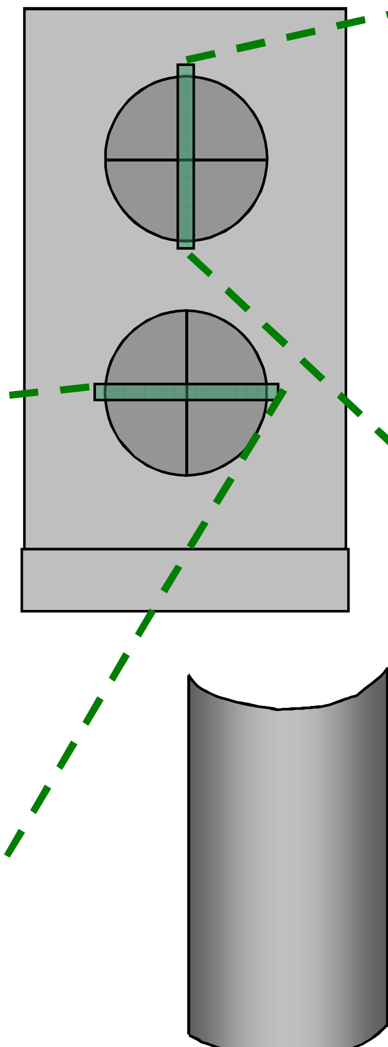
Initial 2D geometry of flyer plate load; perpendicular slice through coaxial region (~2 nH)

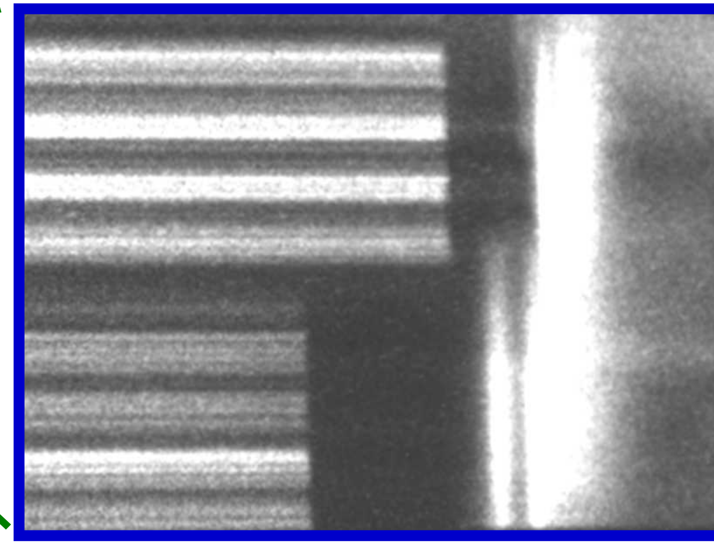


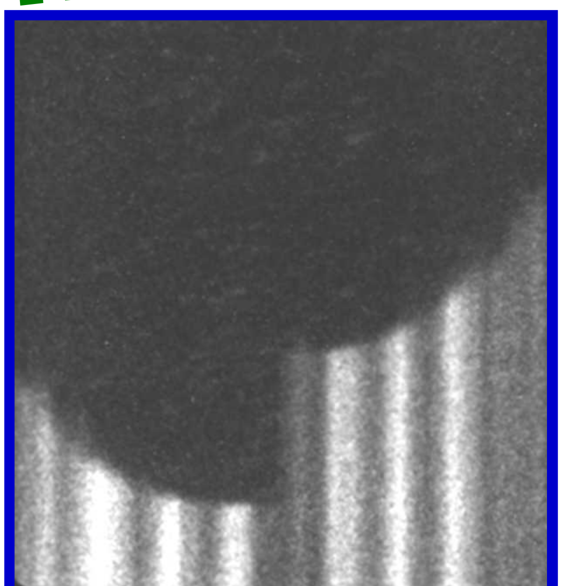
Geometry prior to impact; electrode deformation significantly increases load inductance (~7-8 nH)

Shock breakout of stepped targets suggests bowing due to magnetic pressure gradients

Line Imaging VISAR diagnostic over ~8 mm line

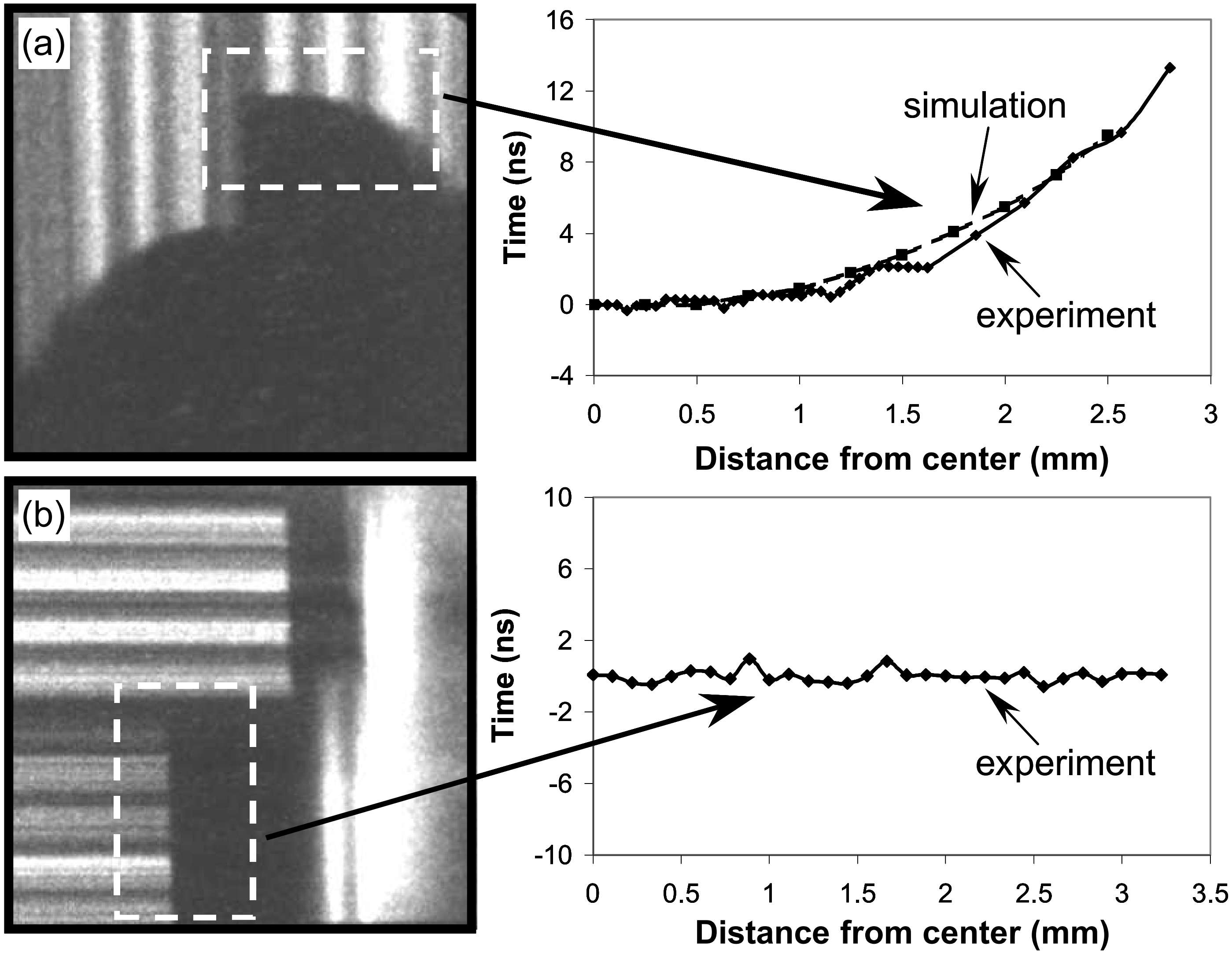






Measurements indicate the flyer is only bowed in the horizontal direction

Careful analysis suggests a planar shock of over 2.5 mm width at impact



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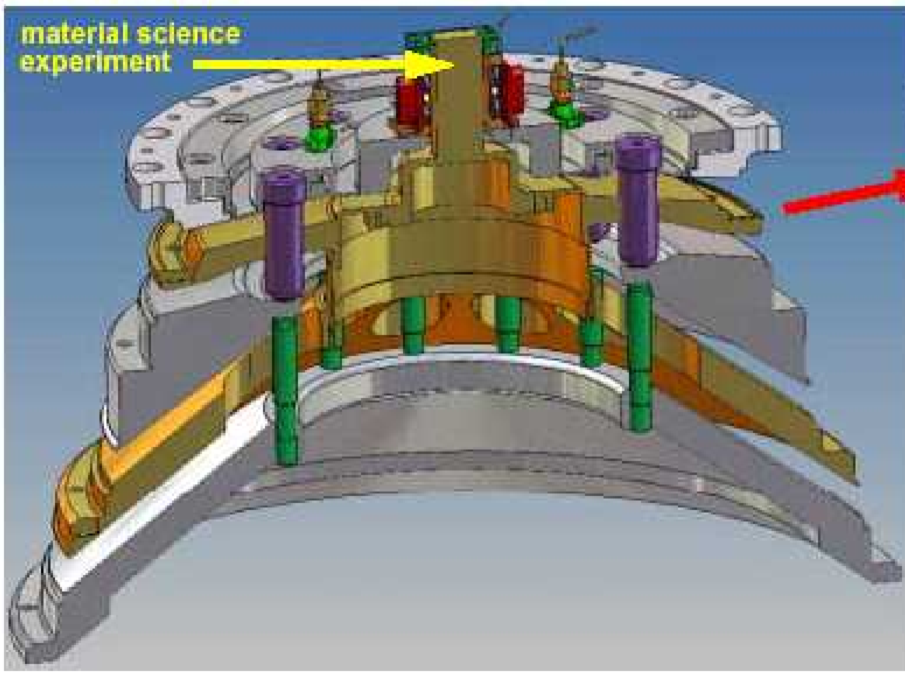
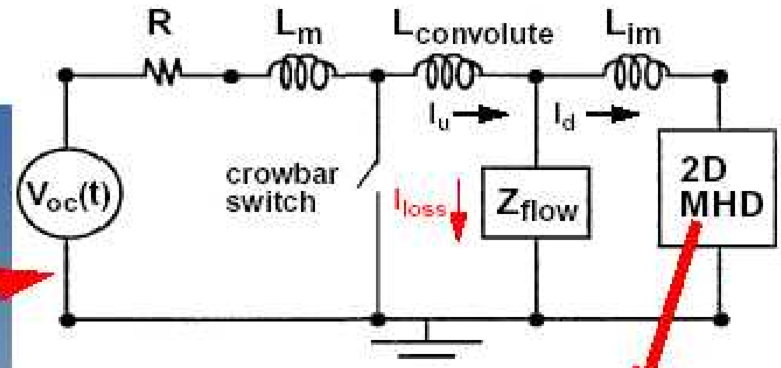
Predictive MHD requires accurate circuit description of Z with crowbar and loss models

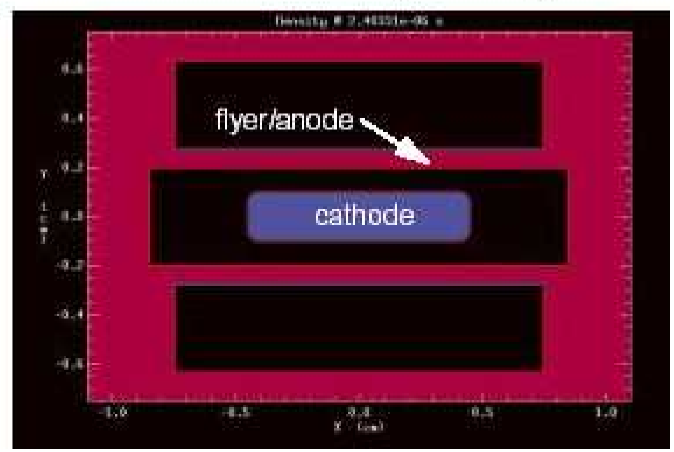
Circuit Driven MHD Simulation

Z MITLs, Convolute, and Load





MHD: Slab Electrode/Flyer Configuration



R.W. Lemke, et al., Phys. Plasmas **10**, 1867 (2003)

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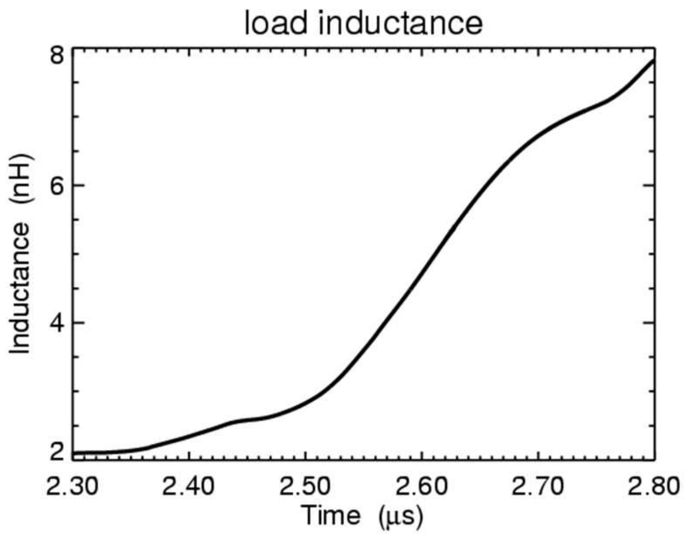
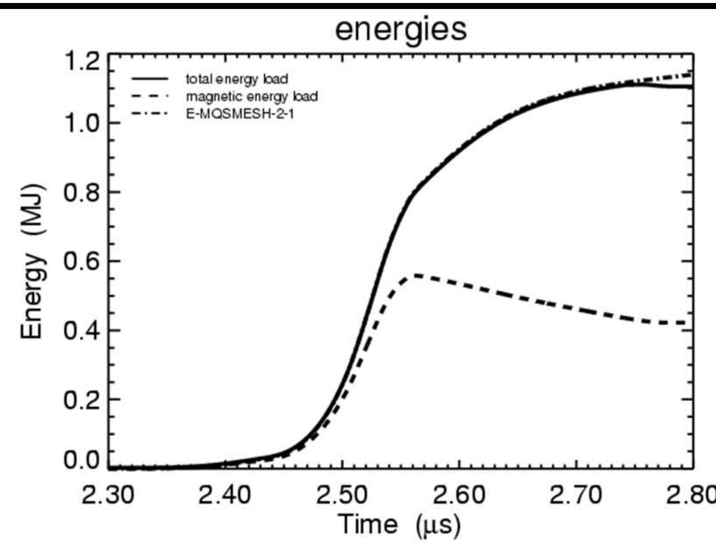
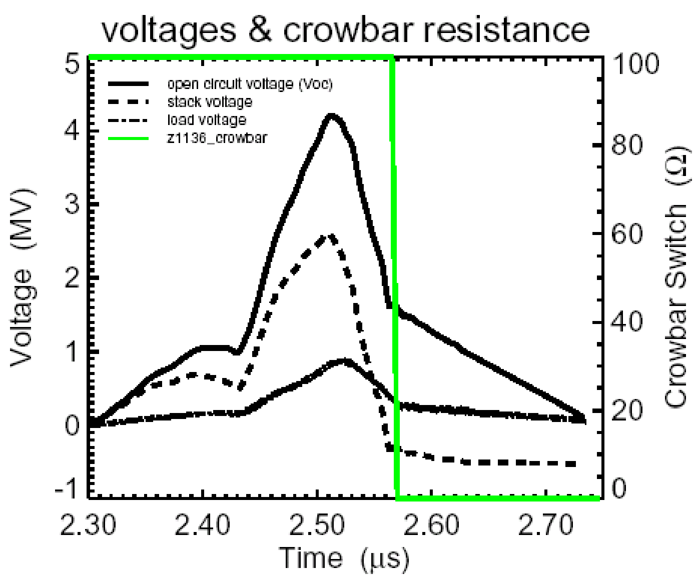
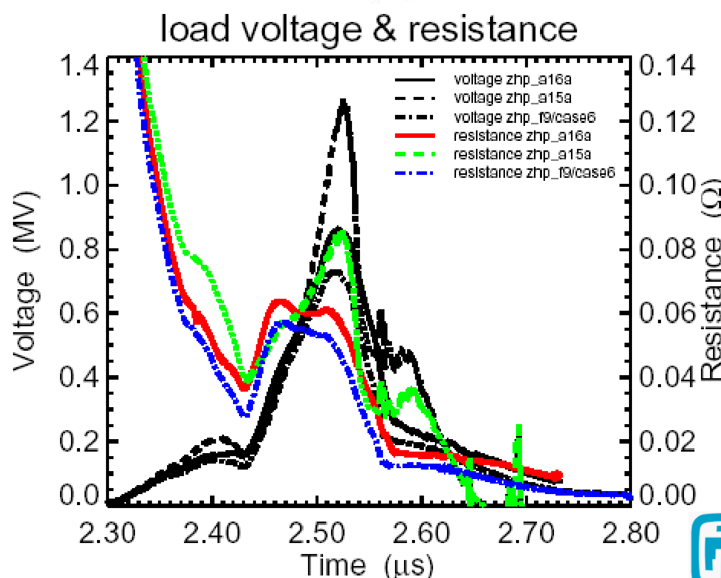
Simulations provide significant amount of information regarding the electrodynamics









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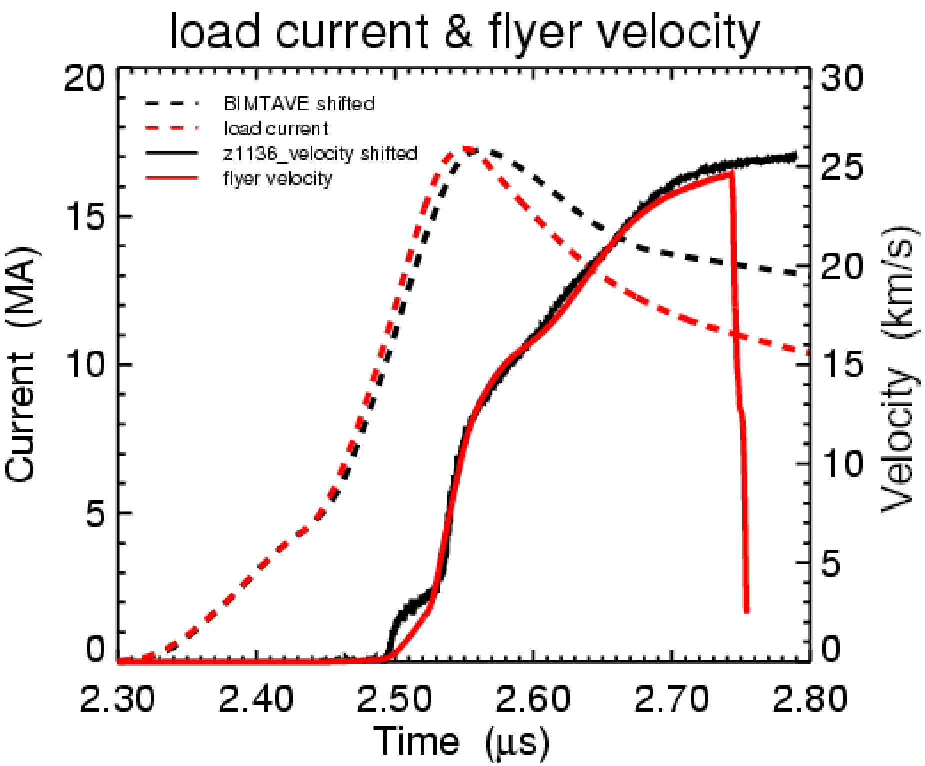
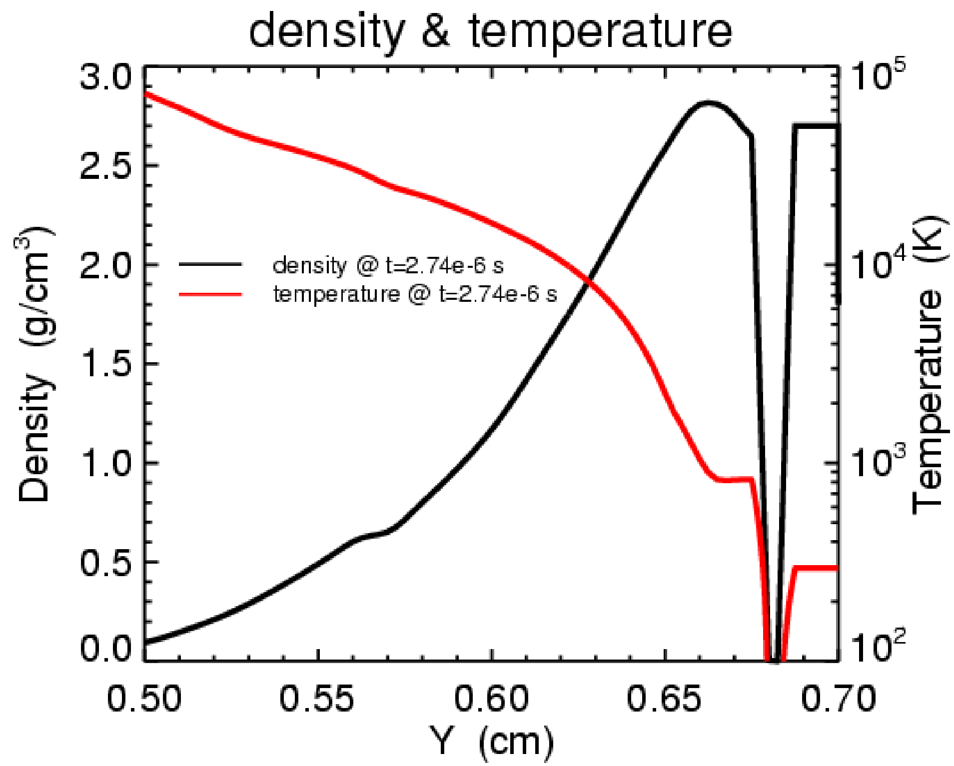
2D circuit driven MHD reproduces measured flyer velocity and load and MITL currents

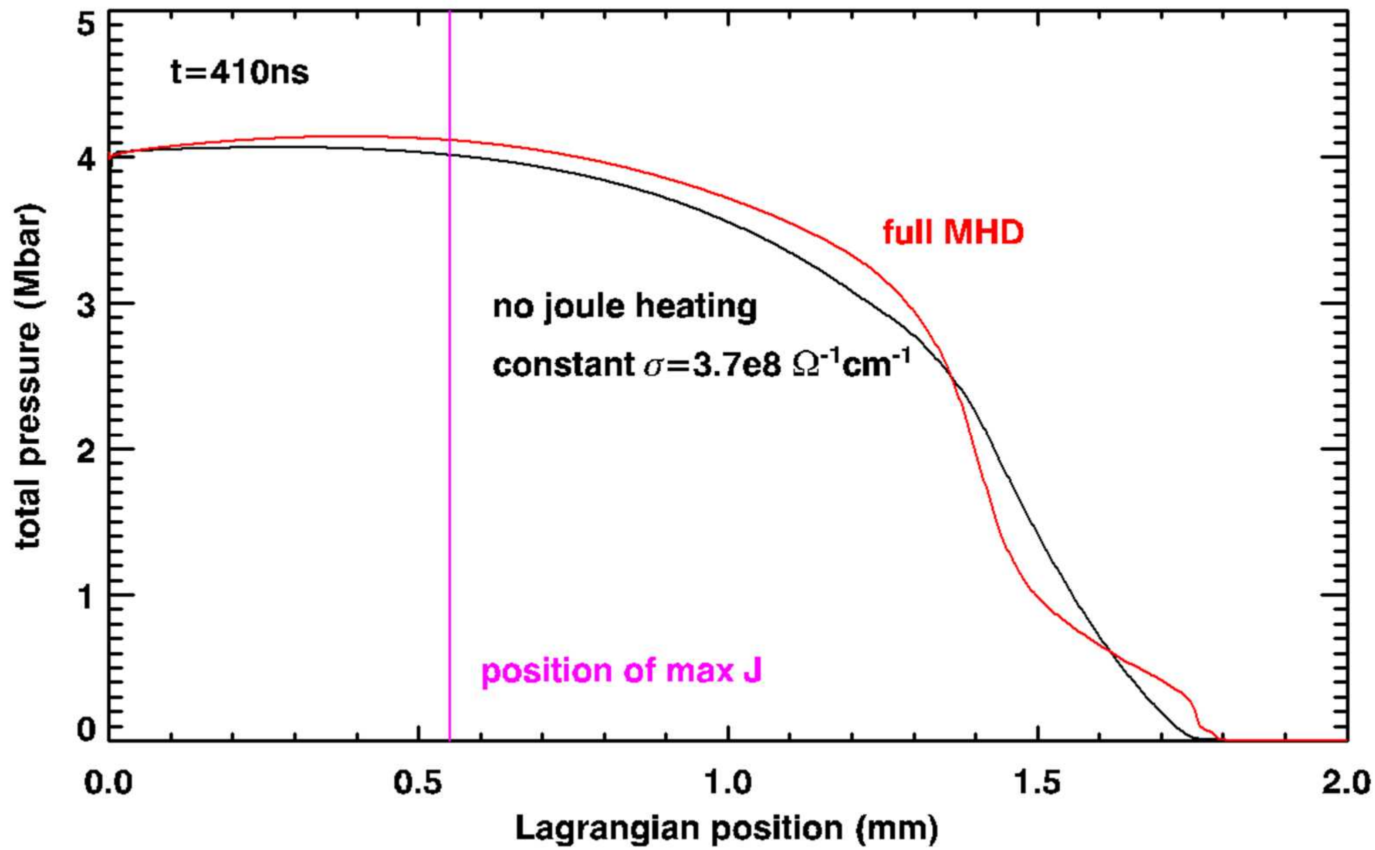




Excellent agreement between simulated and measured flyer velocity throughout entire trajectory

Simulation provides insight into the state of the flyer plate upon impact with the target

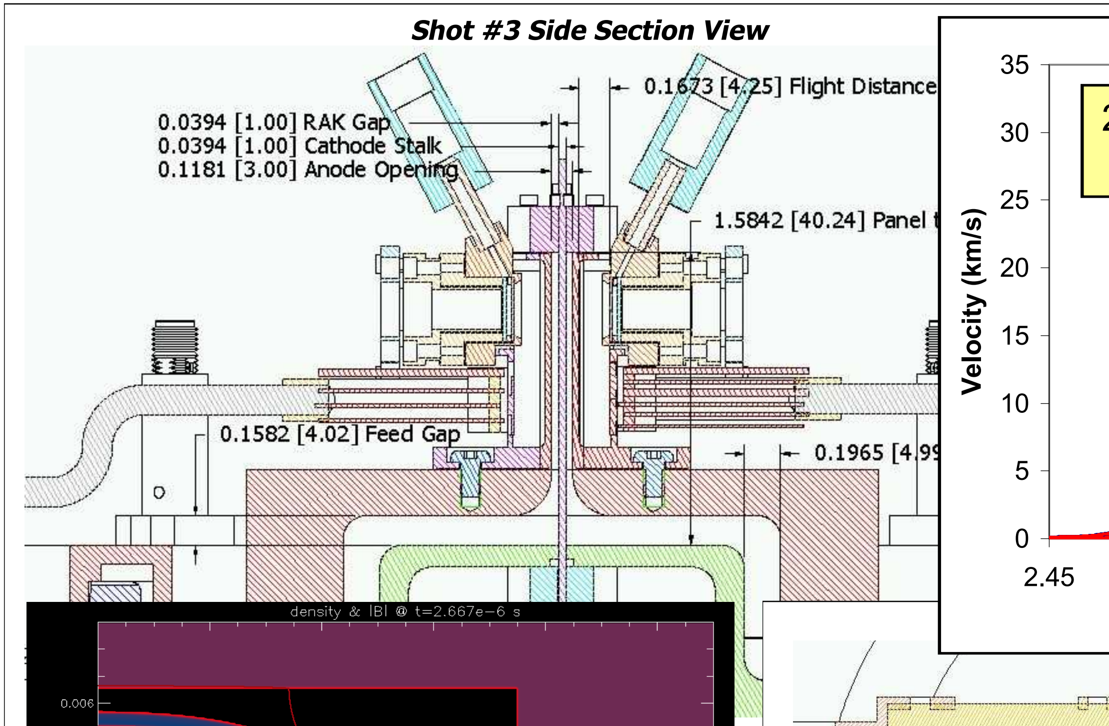
We are also gaining insight into MHD effects on the "ideal" pulse shape

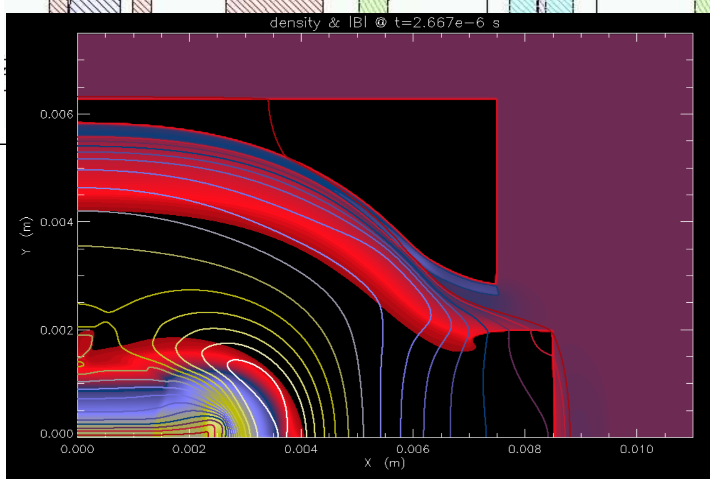


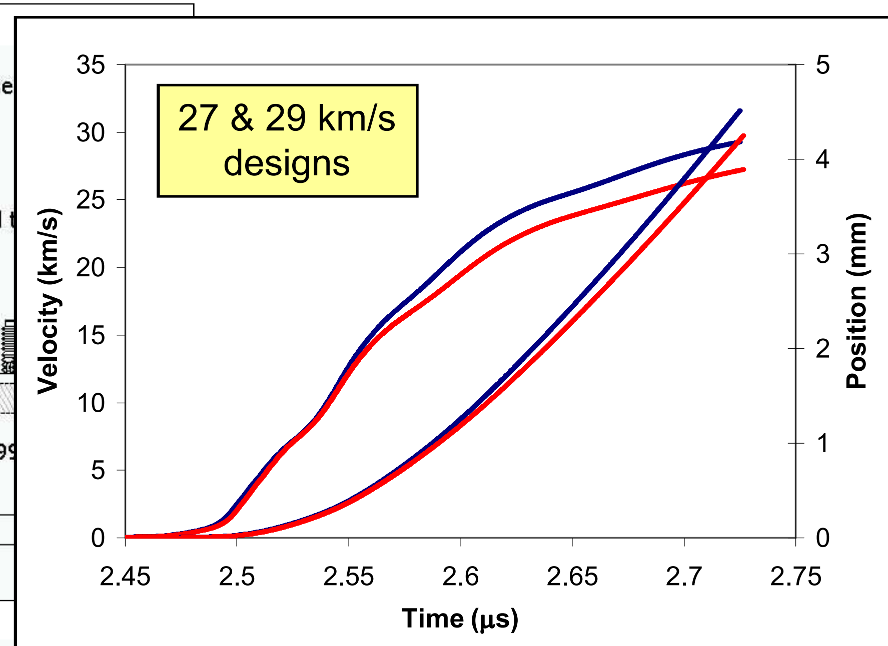
Rapid expansion early in time results in extra "push"

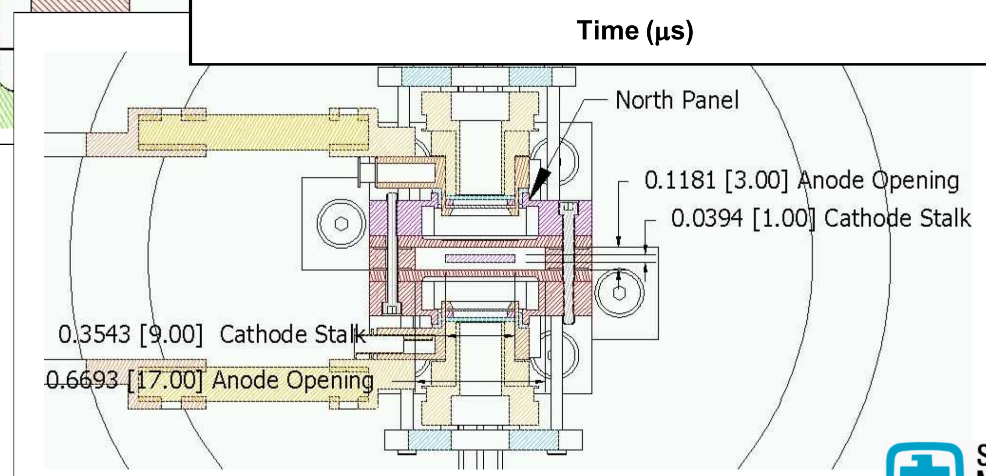
Magnetic force applied to compressible gas/plasma layer results in delayed, steepened upper part of profile for high-pressure loads

Load designs to increase pressure and flyer velocity are being guided by MHD simulations









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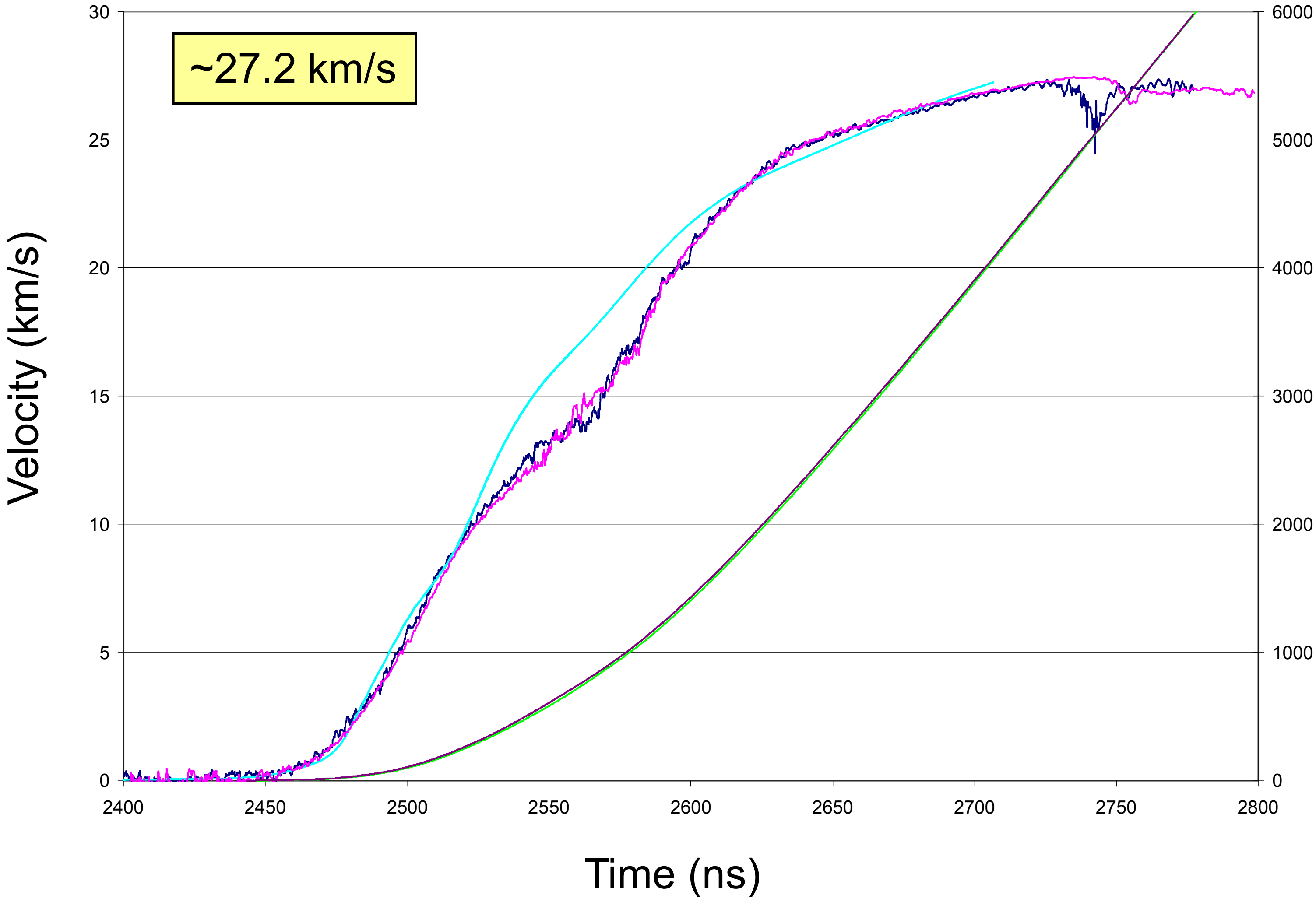
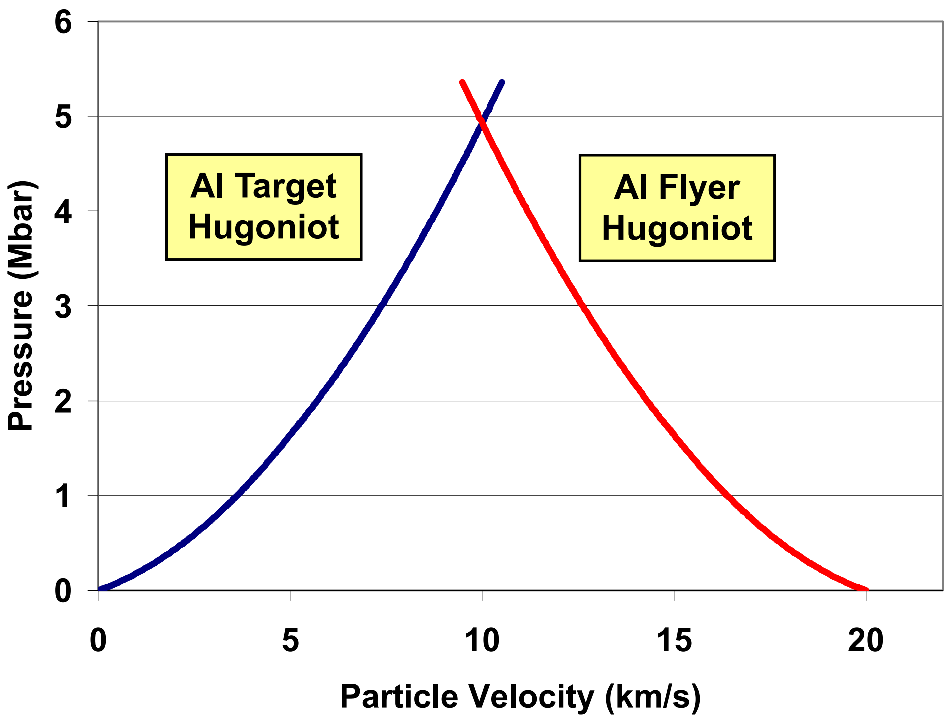
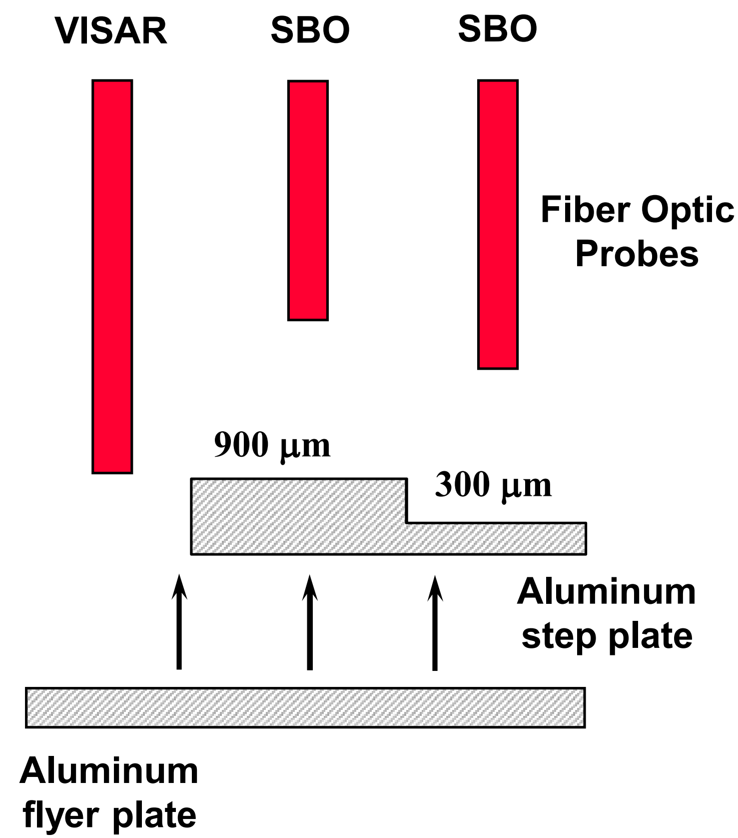
We have demonstrated shock-less acceleration of flyers to greater than 27 km/s



Aluminum experimental configuration utilizes symmetric impact



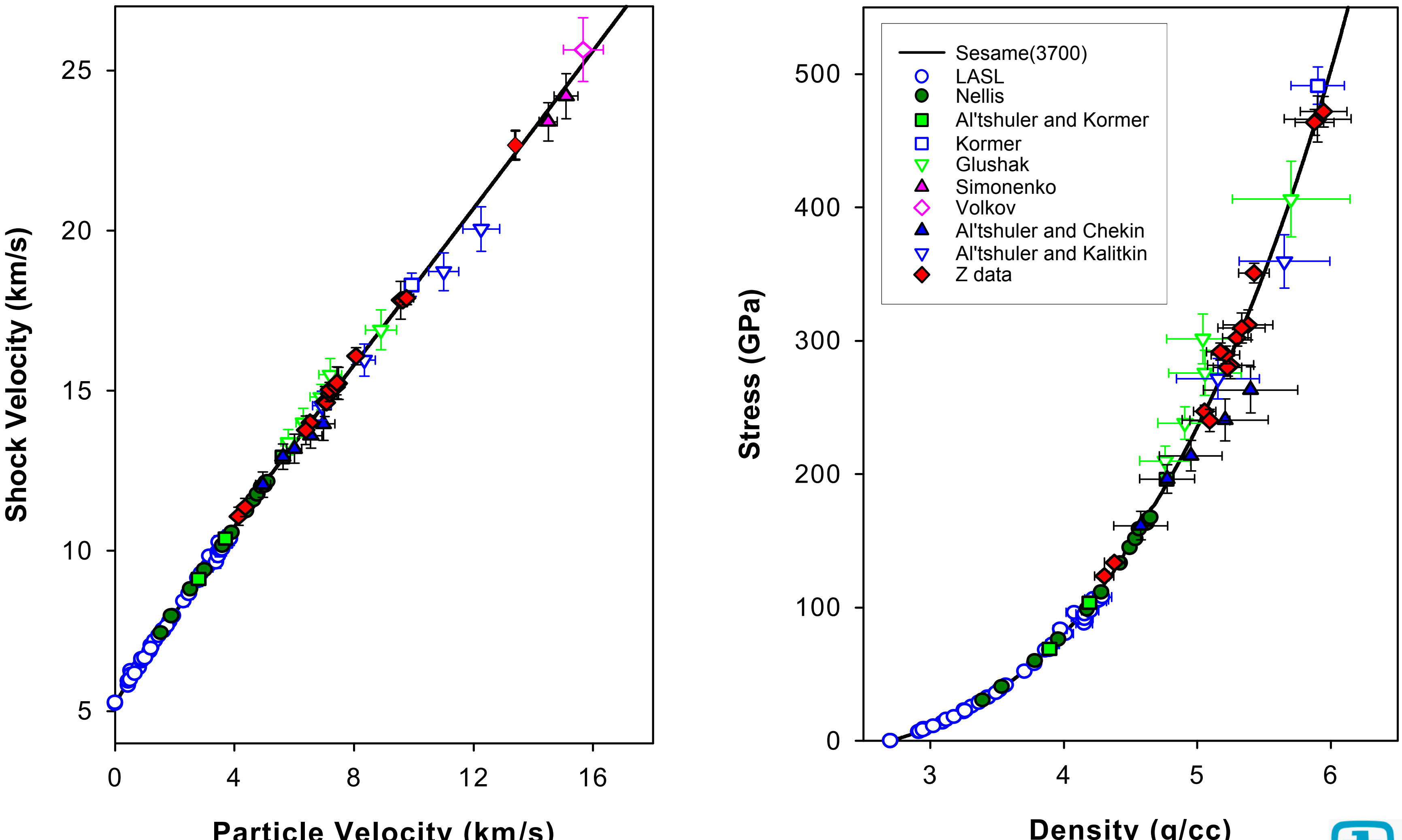


Measure:

Flyer velocity

Shock velocity in Al

Flyer plate technique has been validated against high-pressure Hugoniot of Aluminum

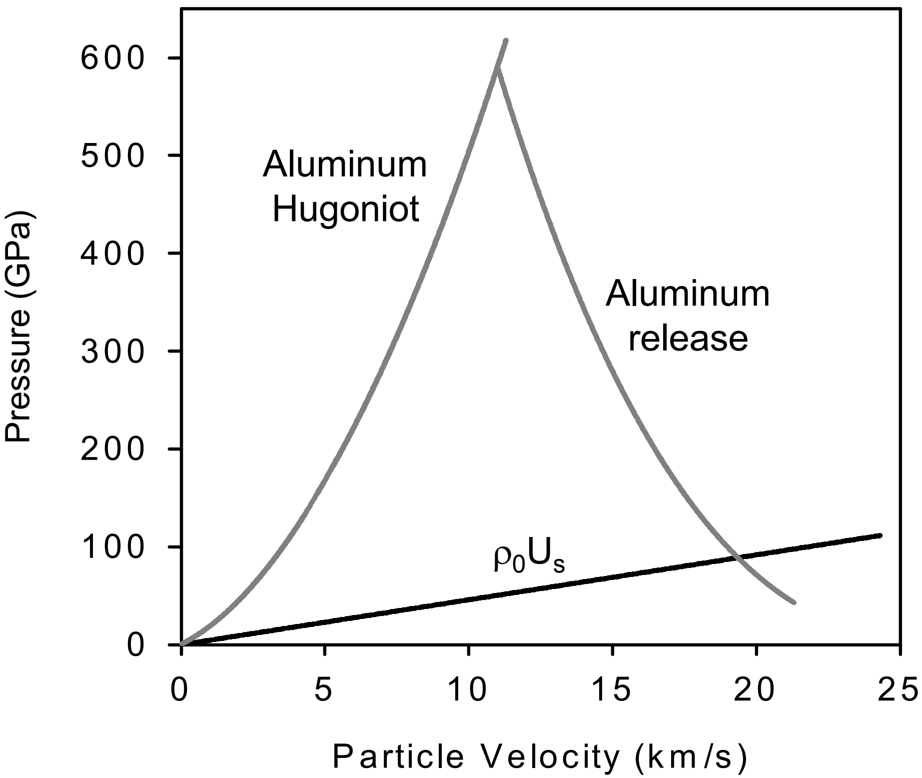


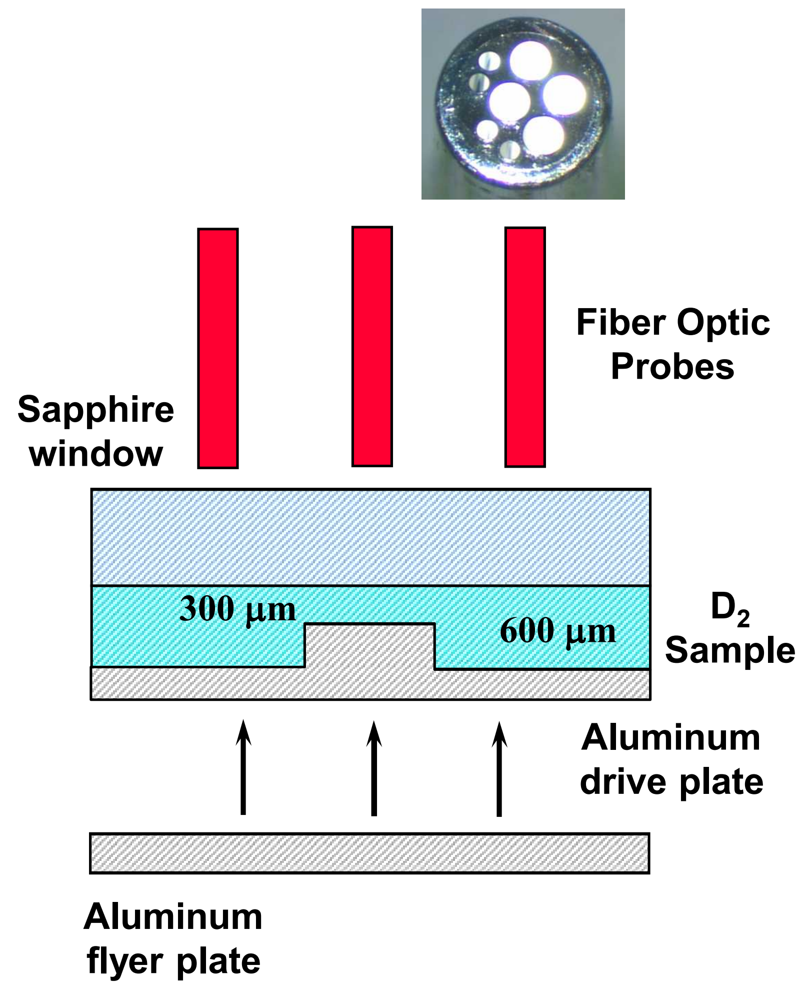
M.D. Knudson, et al., J. Appl. Phys. **94**, 4420 (2003)

Outline

- Summary of magnetic flyer technique on Z
- Independent, self-consistent measurements show agreement with ab-initio models to 1 Mbar
  - Primary Hugoniot
  - Reverberation
  - Re-shock Pressure
  - Hugoniot Temperature
  - Re-shock Temperature
- Release response of aluminum calibrated for impedance matching technique
  - Main source of potential systematic uncertainty
- Conclusions & Future directions

Sandia experimental configuration utilizes an impedance matching method





<u>Measure:</u>

Shock velocity in Al	Shock velocity in D_2
Shock trajectory in D_2	Self-emission

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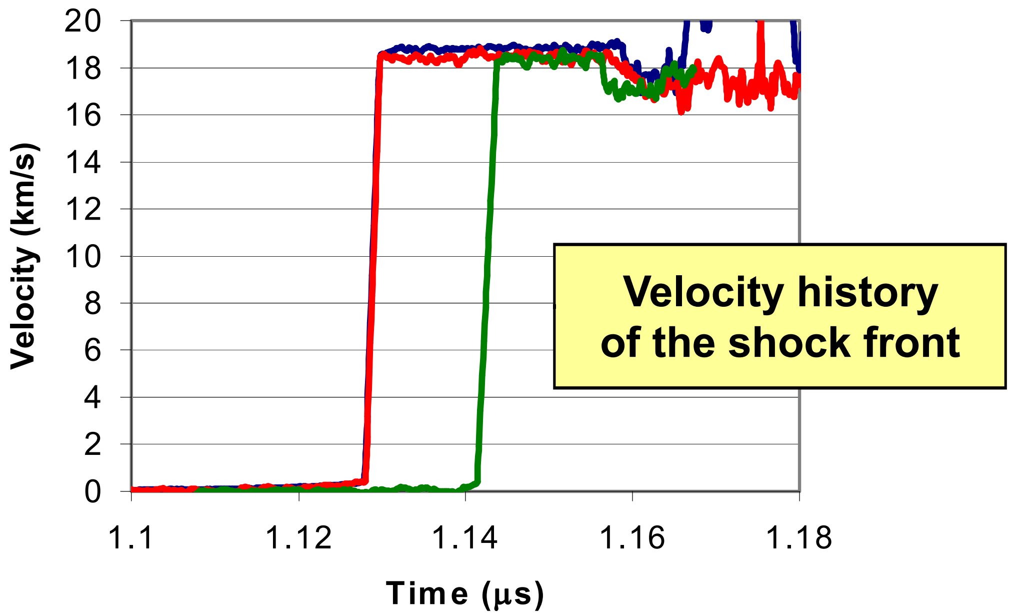
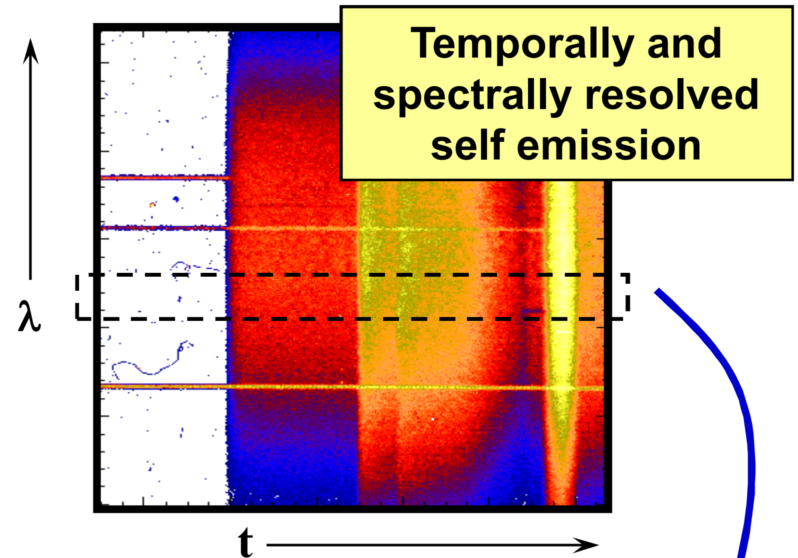
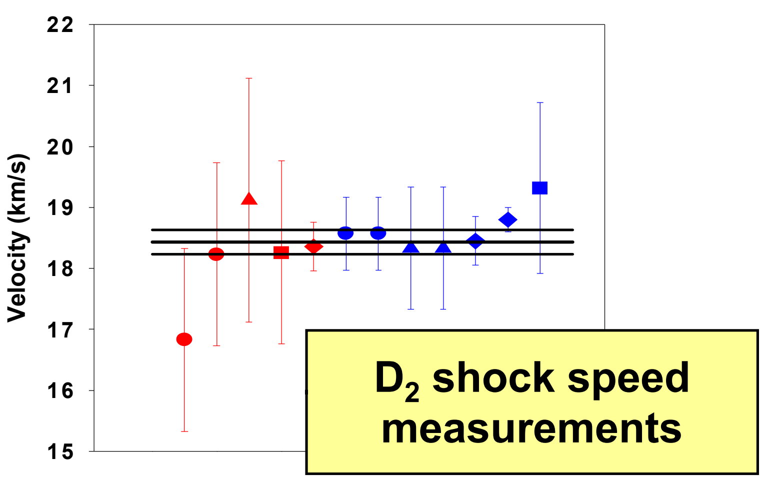
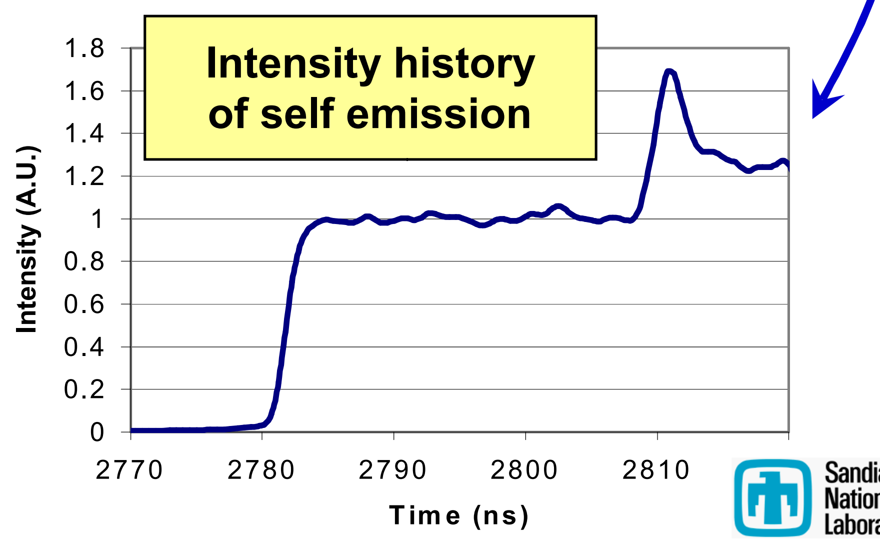
Experimental data indicate this method provides very good quality pressure drive









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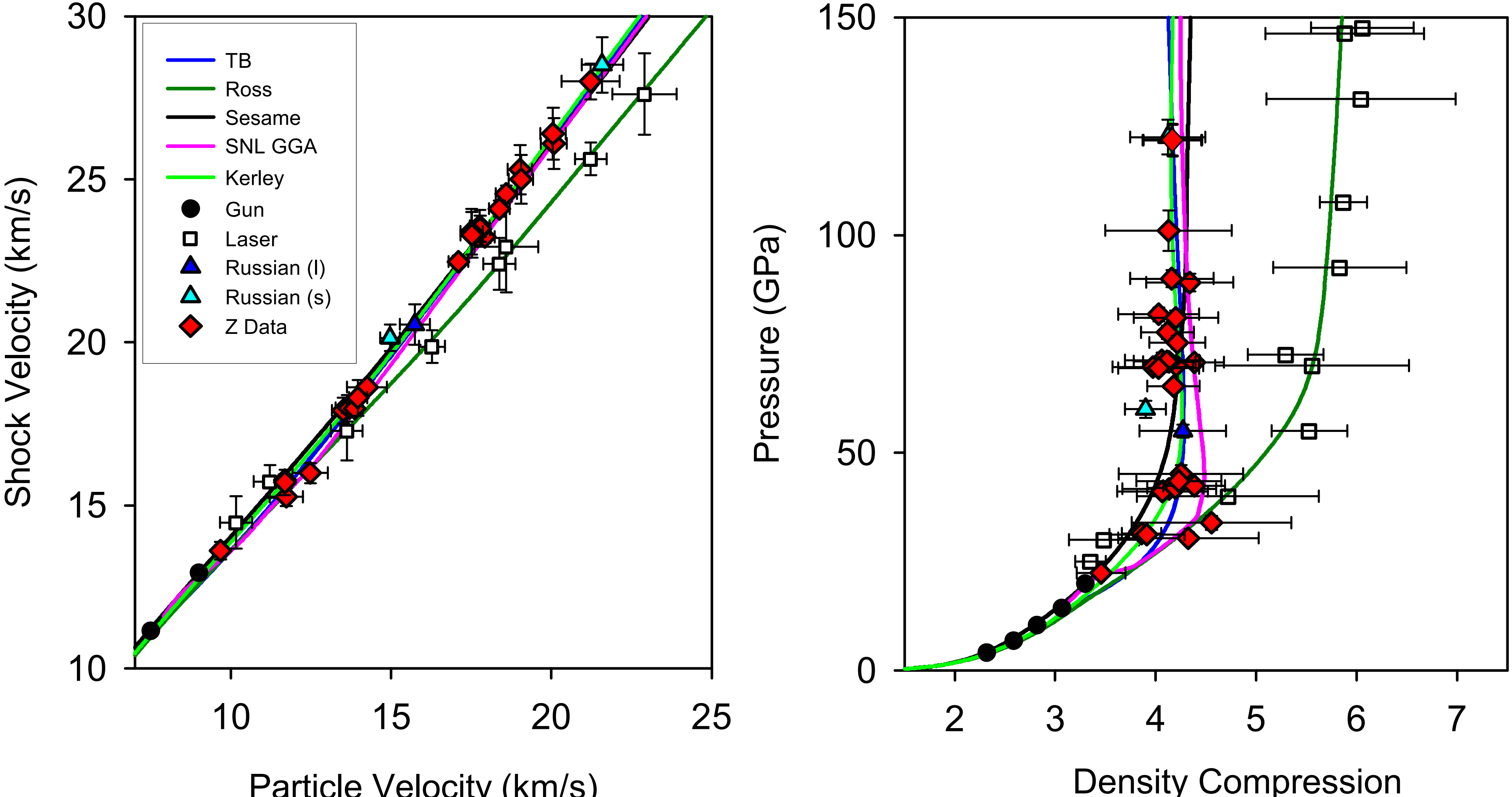
Data to 1 Mbar obtained on liquid D_2 to help resolve discrepancy in high-pressure response



M.D. Knudson, et al., Phys. Rev. Lett. **87**, 225501 (2001)

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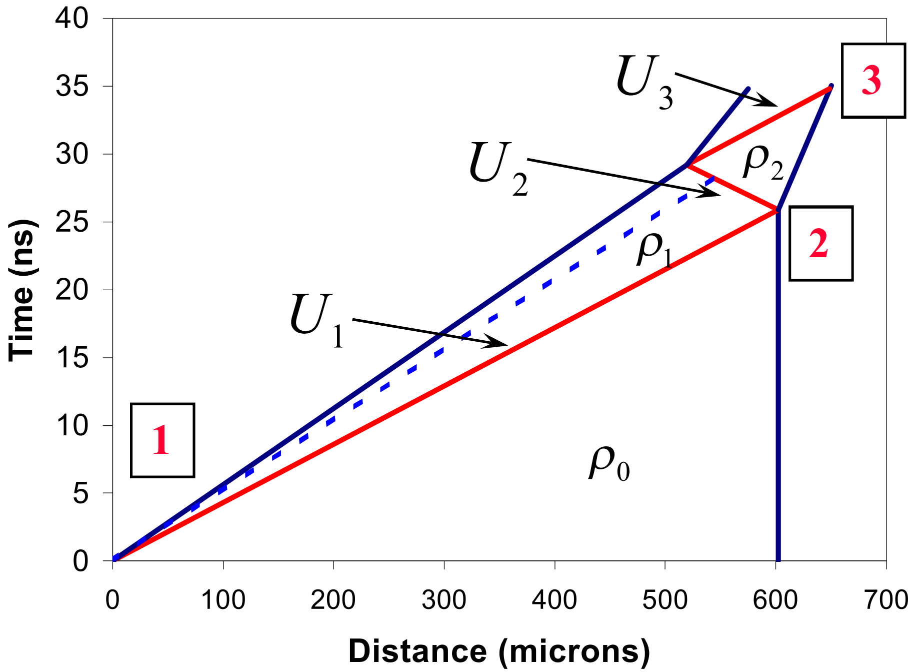
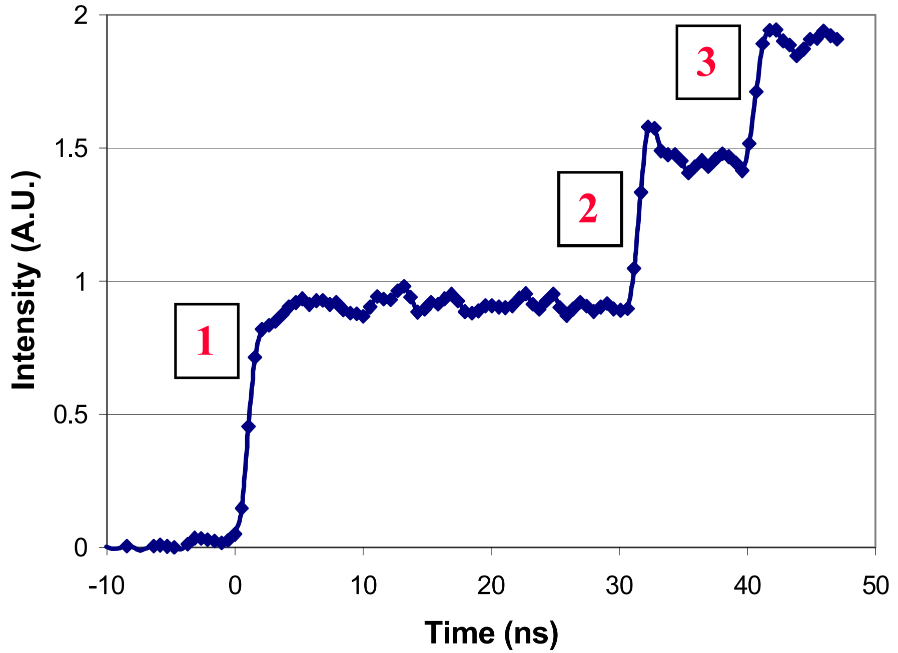
Shock reverberation timing is sensitive to the density compression achieved by first shock

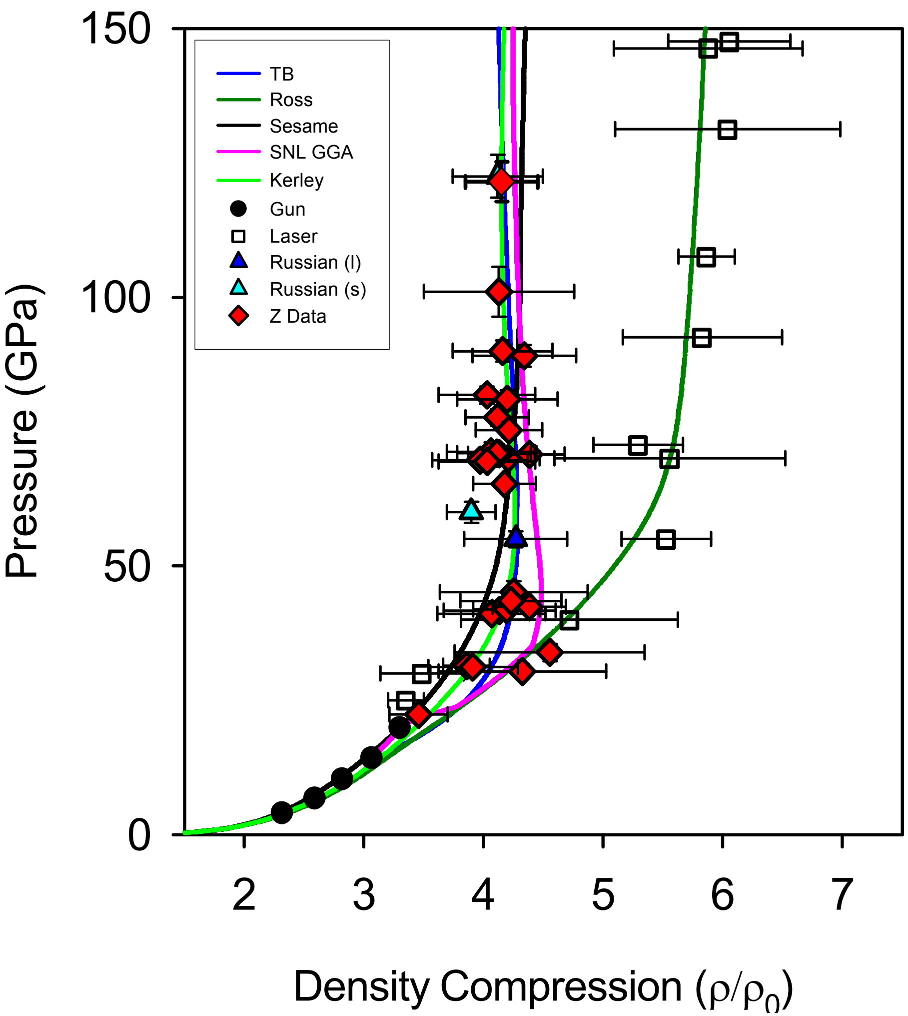


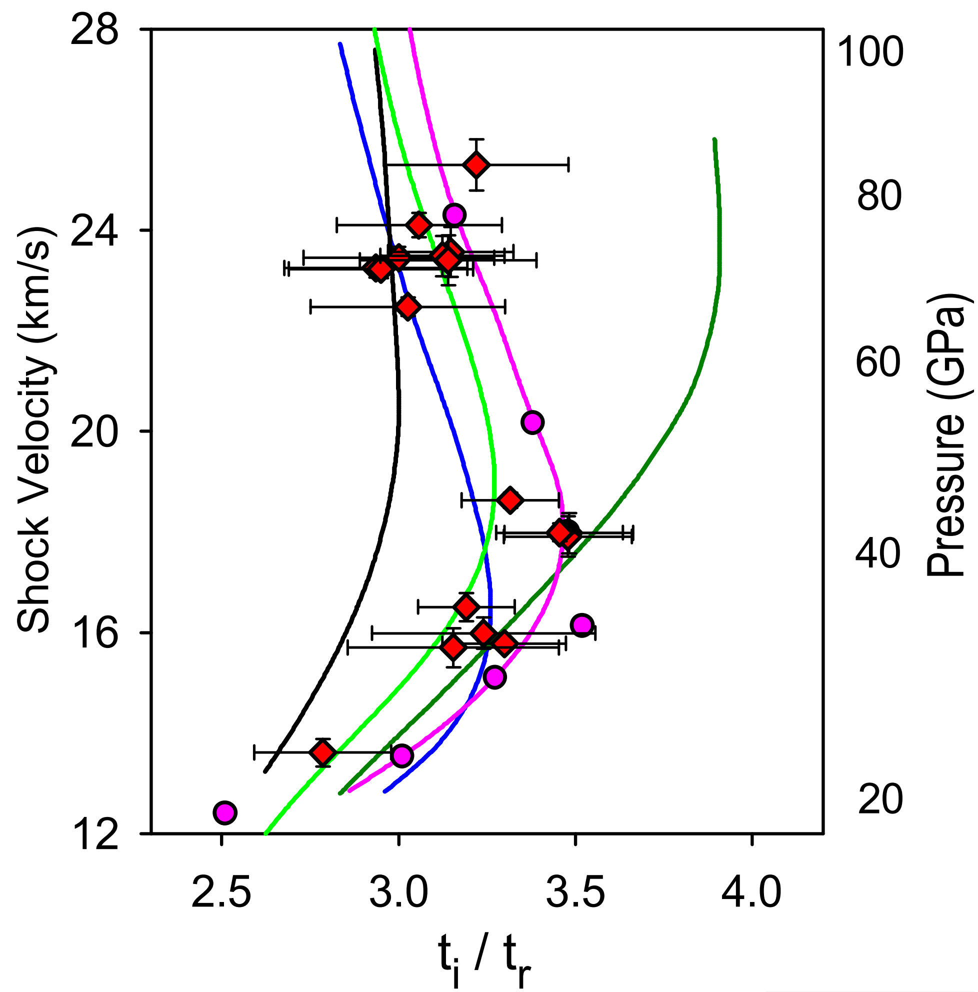


$$\frac{t_{reverb}}{t_{transit}} = \rho_0 U_1 \left(\frac{1}{\rho_1 U_2} + \frac{1}{\rho_2 U_3} \right)$$

Sensitive to ρ_1,
the density compression
upon first shock

Reverb timing corroborates the stiff response inferred from the Hugoniot measurements





M.D. Knudson, et al., Phys. Rev. Lett. **90**, 035505 (2003)

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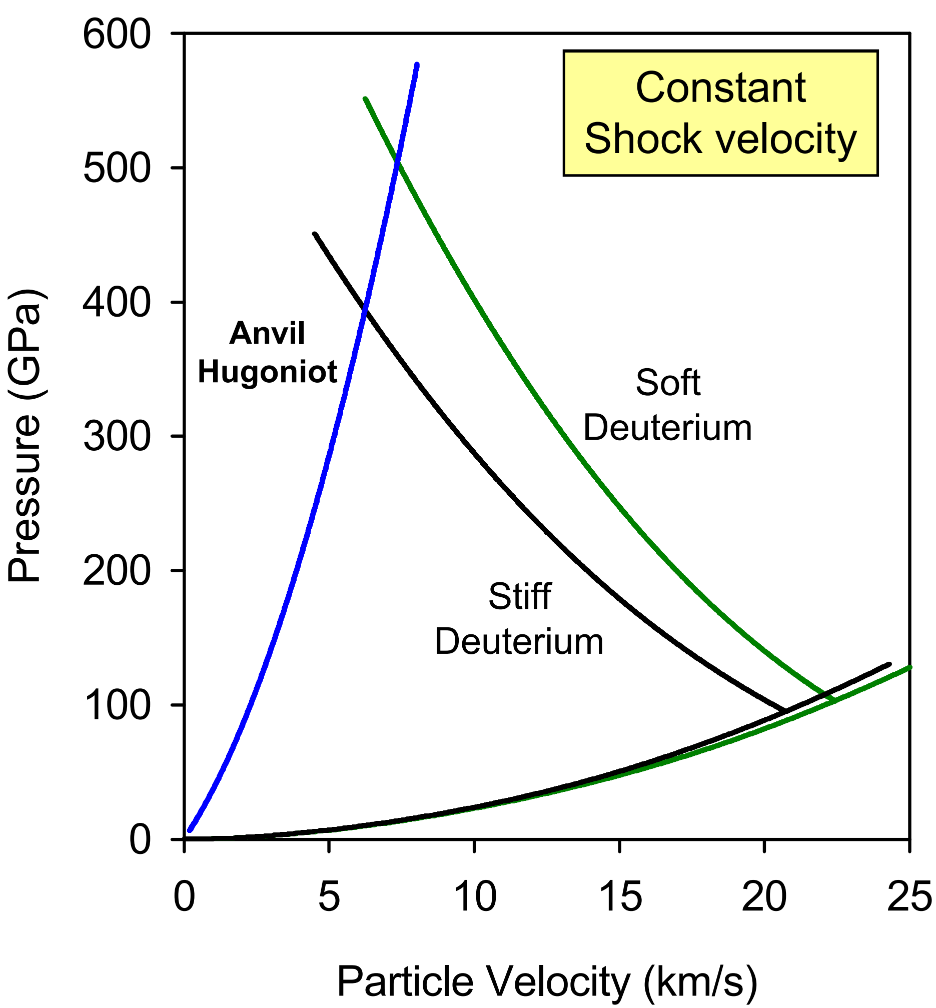
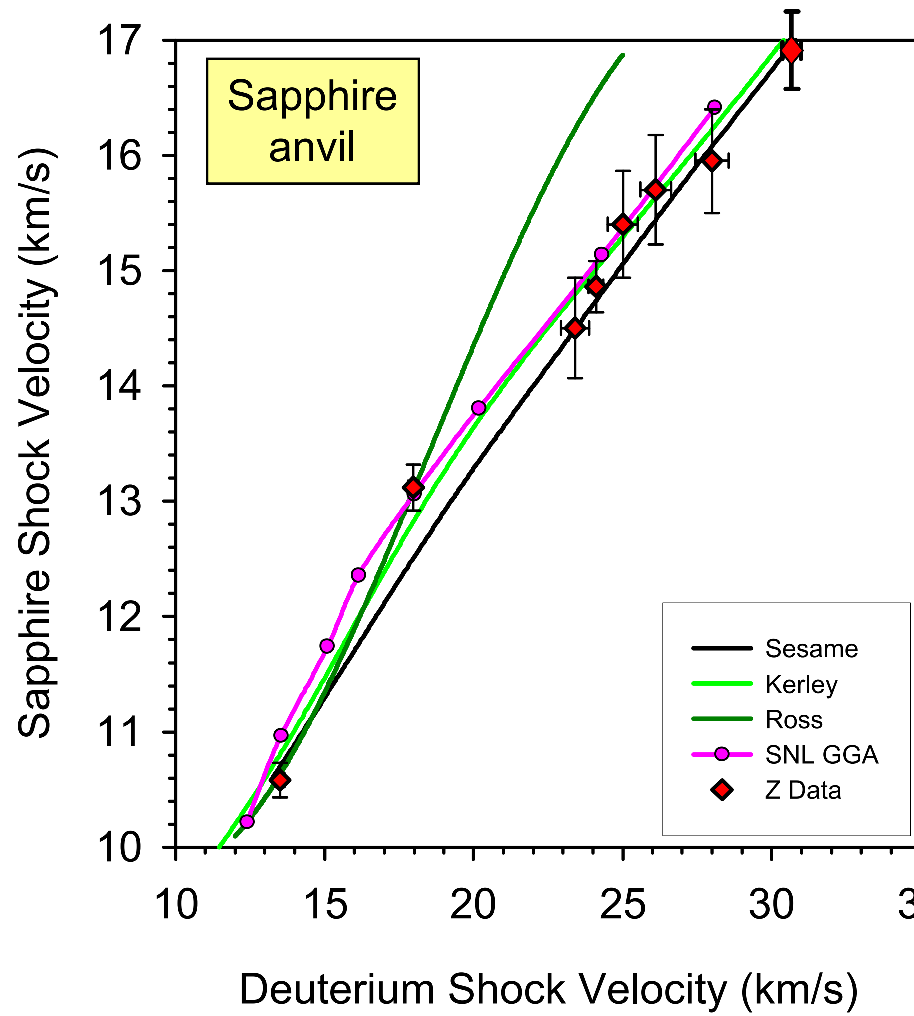
Re-shock also provides insight into density compression along the Principal Hugoniot





A.N. Mostovych, et al., Phys. Rev. Lett. **85**, 3870 (2000)

M.D. Knudson, et al., Phys. Rev. B, accepted

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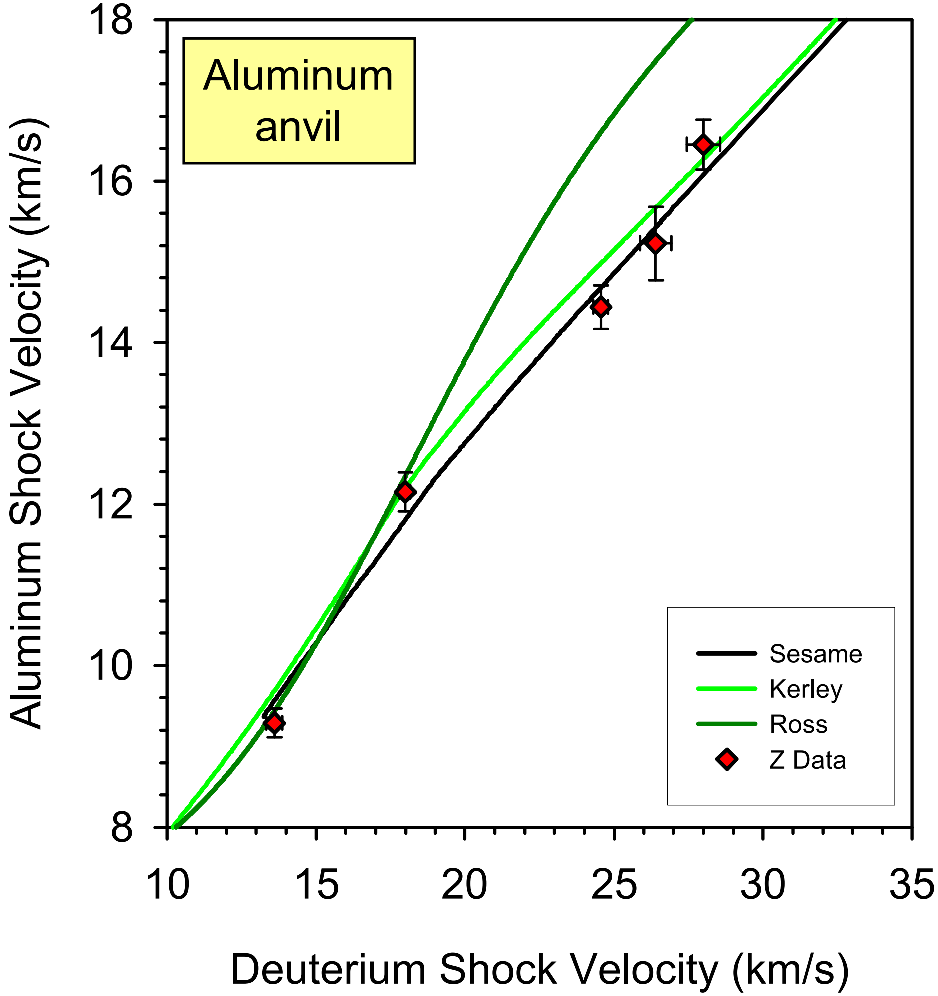
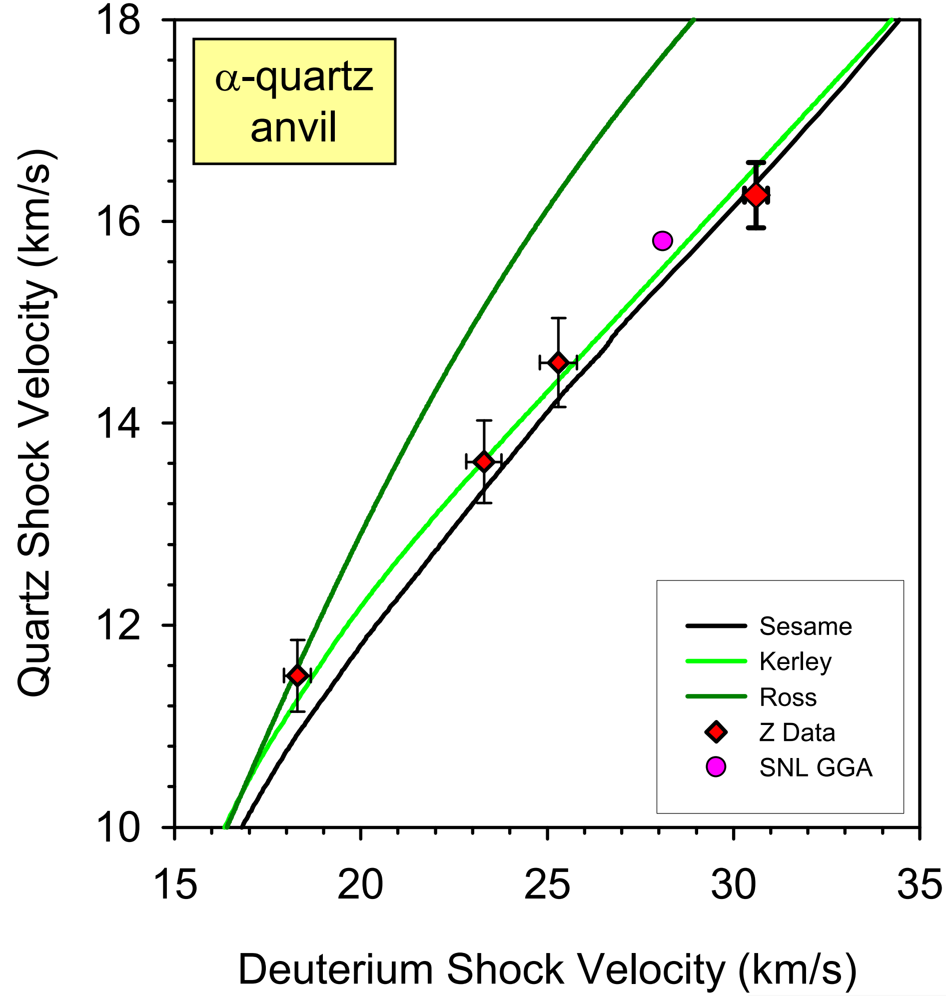
Re-shock using aluminum and α-quartz anvils also indicate stiff response on the Hugoniot





M.D. Knudson, et al., Phys. Rev. B, accepted for publication (2004)

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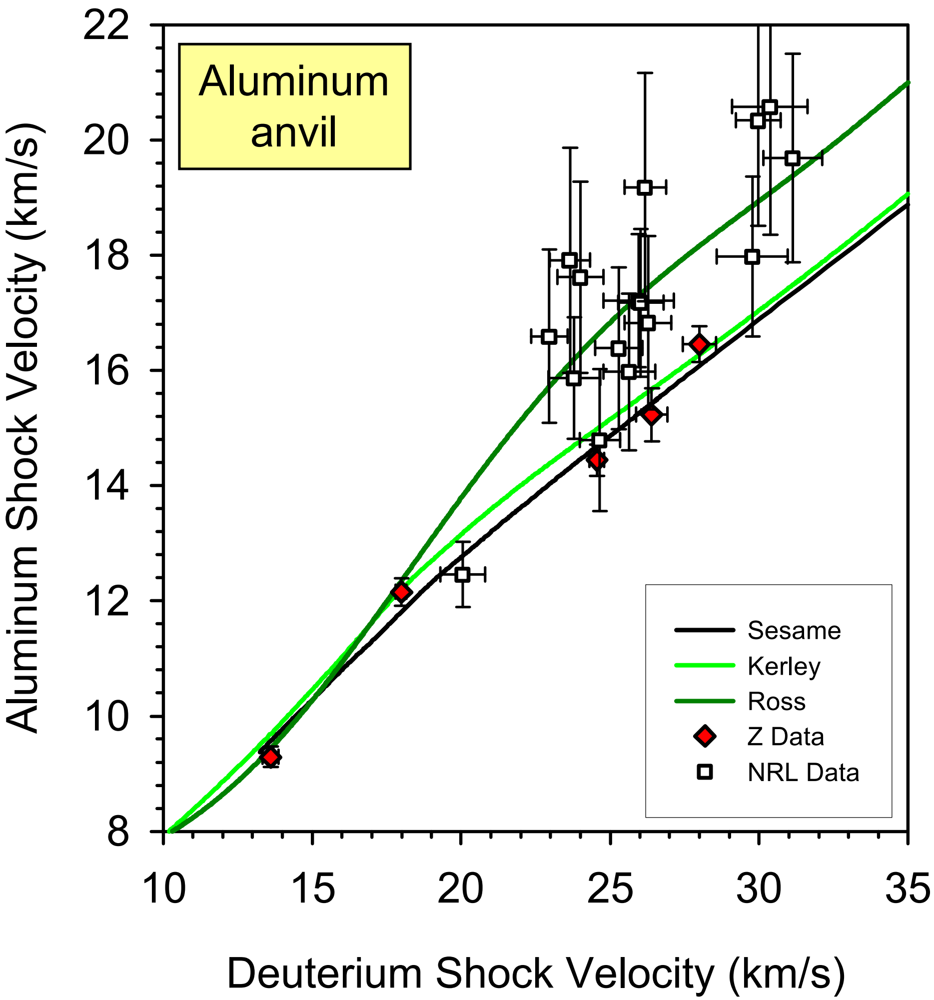
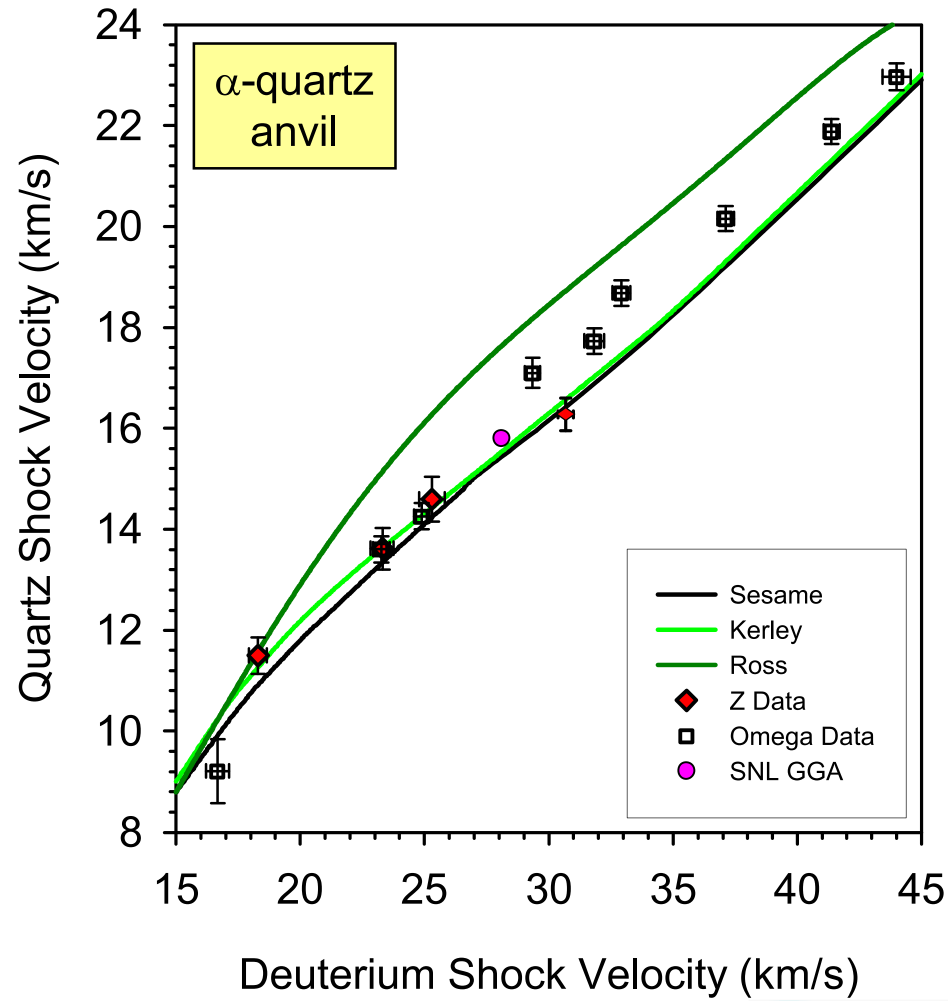
Comparison of Z re-shock data with laser driven experiments (Nike and Omega)



A.N. Mostovych, et al., Phys. Rev. Lett. **85**, 3870 (2000)



T. Boehly, et al., private communication

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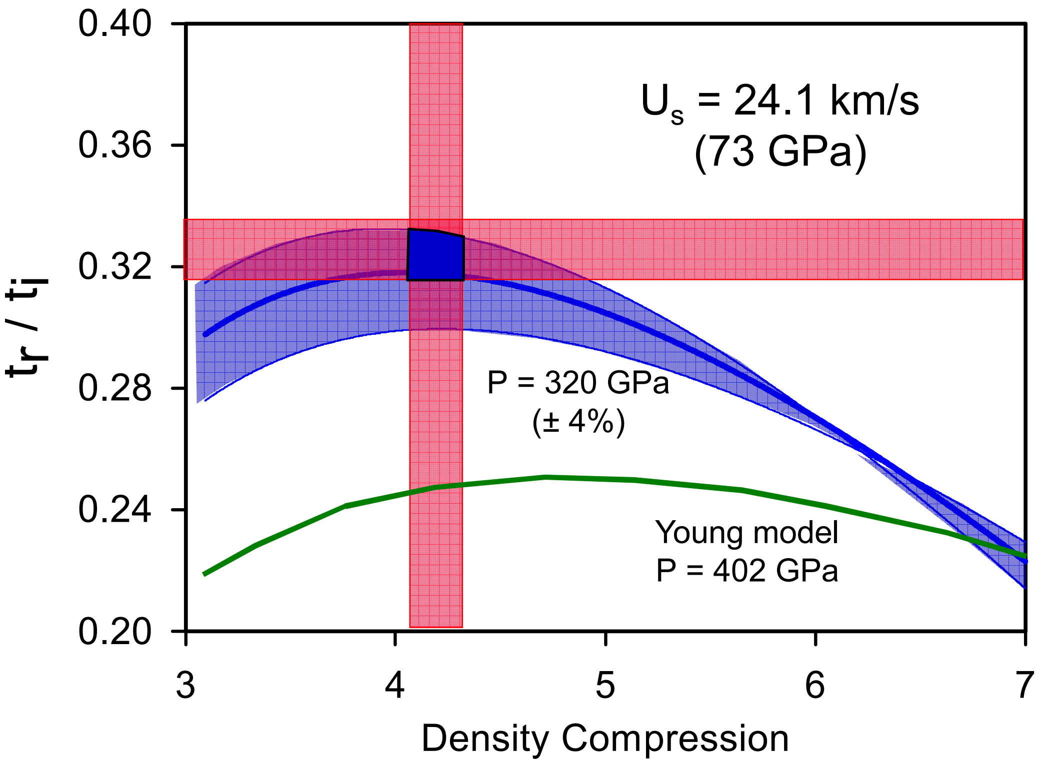
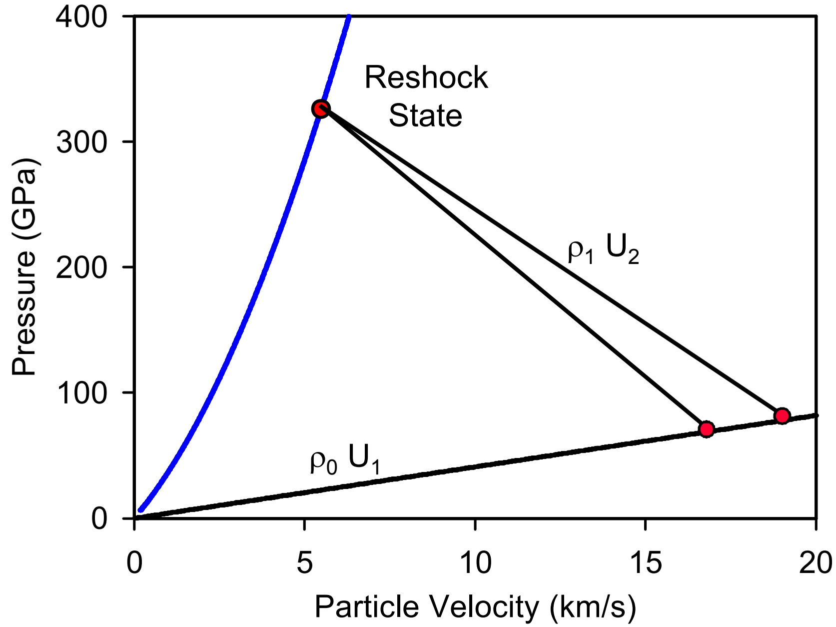
Complete consistency observed between Hugoniot, reverb, and re-shock measurements





$$\frac{t_{reverb}}{t_{transit}} = \rho_0 U_1 \left(\frac{1}{\rho_1 U_2} + \frac{1}{\rho_2 U_3} \right)$$

Similar consistency observed for all initial shock pressures studied

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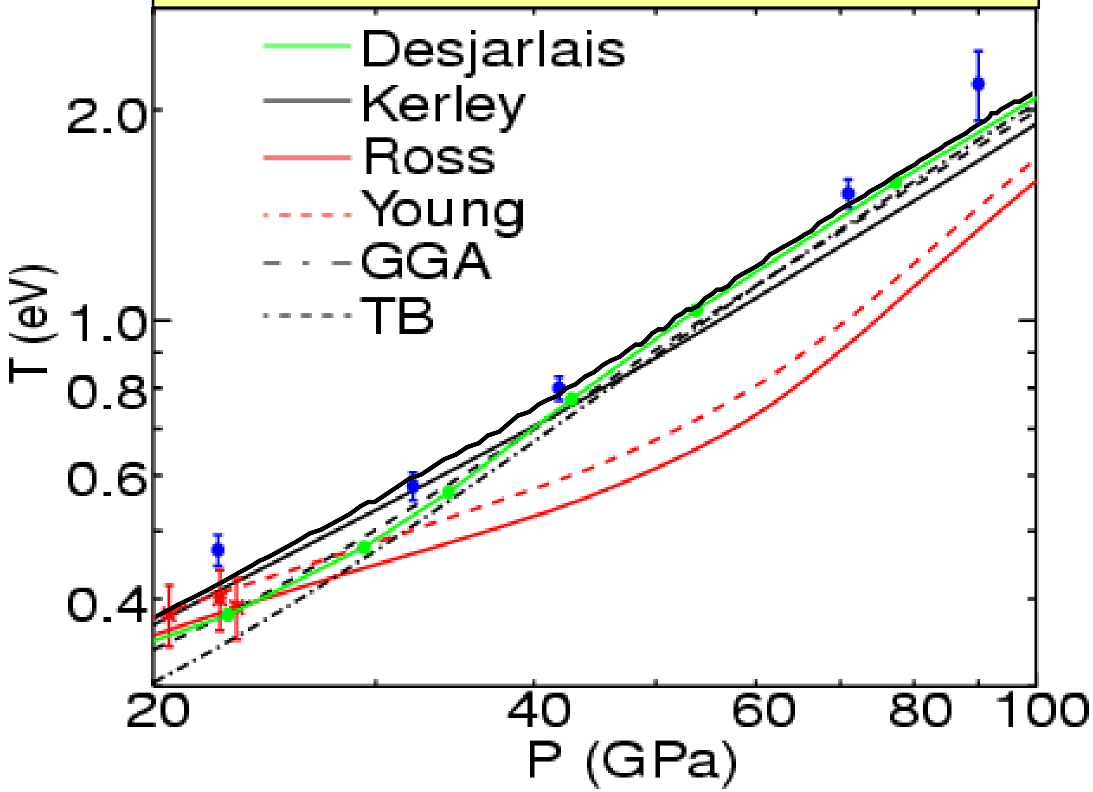
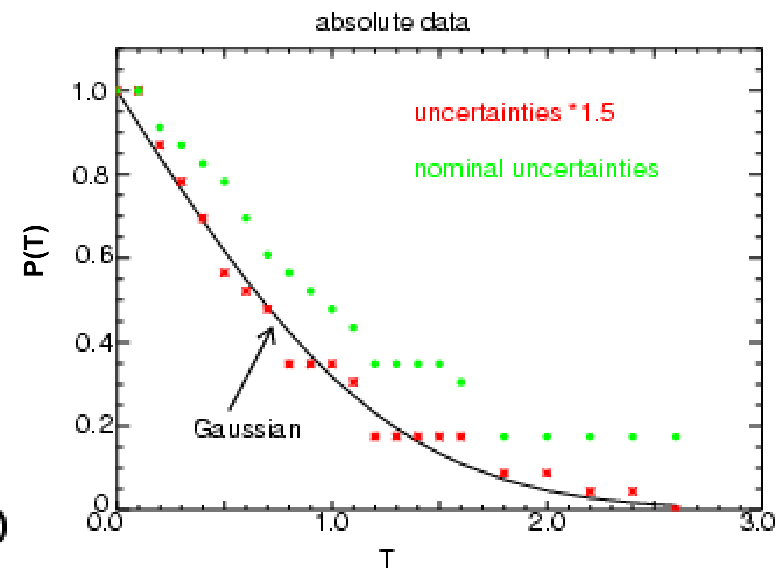
Analysis of temperature nearing completion – results consistent with mechanical measurements

Hugoniot Temperature



Statistical analysis performed to test validity of individual uncertainties prior to use in determining weighted averages



Hugoniot temperatures in very good agreement with stiffer models – consistent with mechanical measurements

G. Dunham, et al., Rev. Sci. Instrum., accepted (2004)

J.E. Bailey, et al., in preparation

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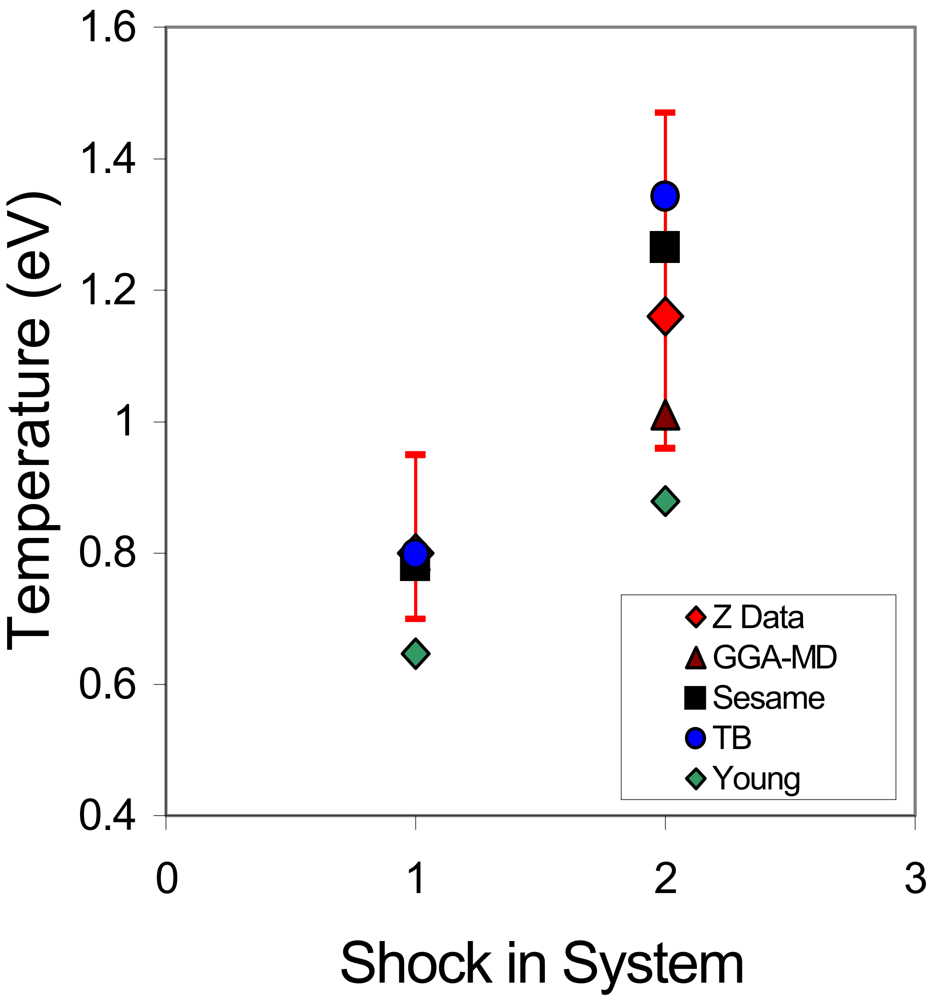
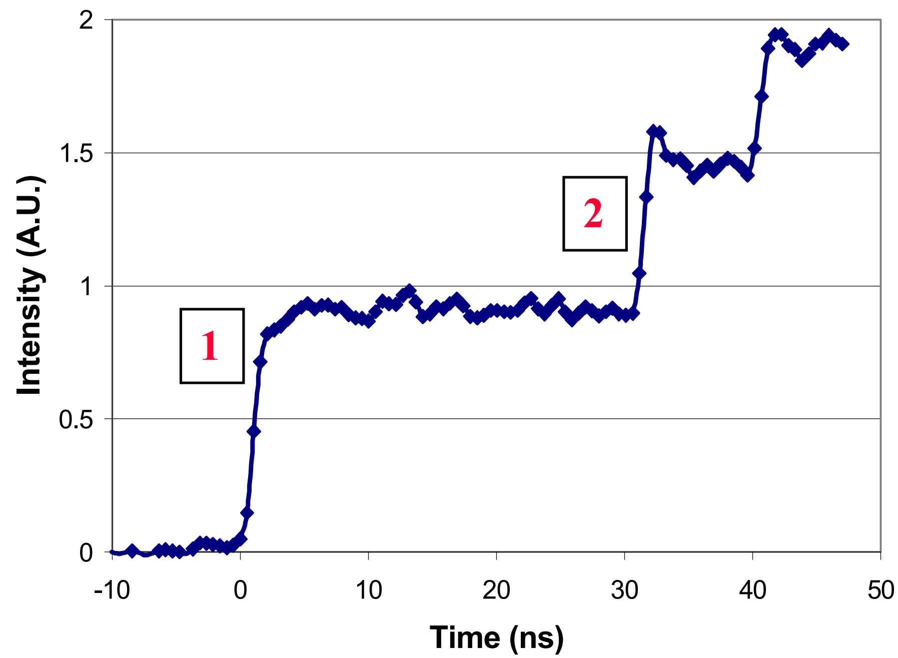
Reshock temperatures also show better agreement with the stiffer EOS models





Temperature increase upon reshock is observed to be greater than increase predicted by the softer EOS models

Outline

- Summary of magnetic flyer technique on Z
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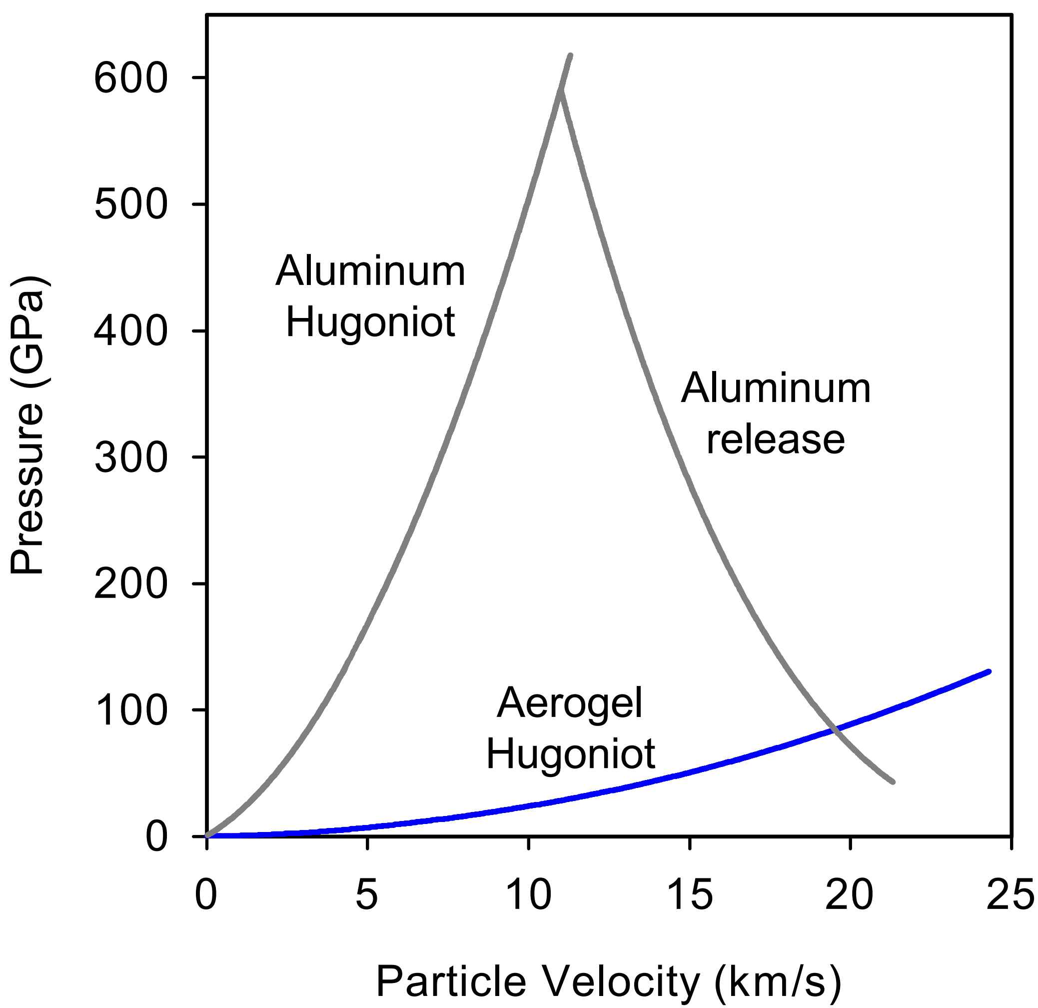
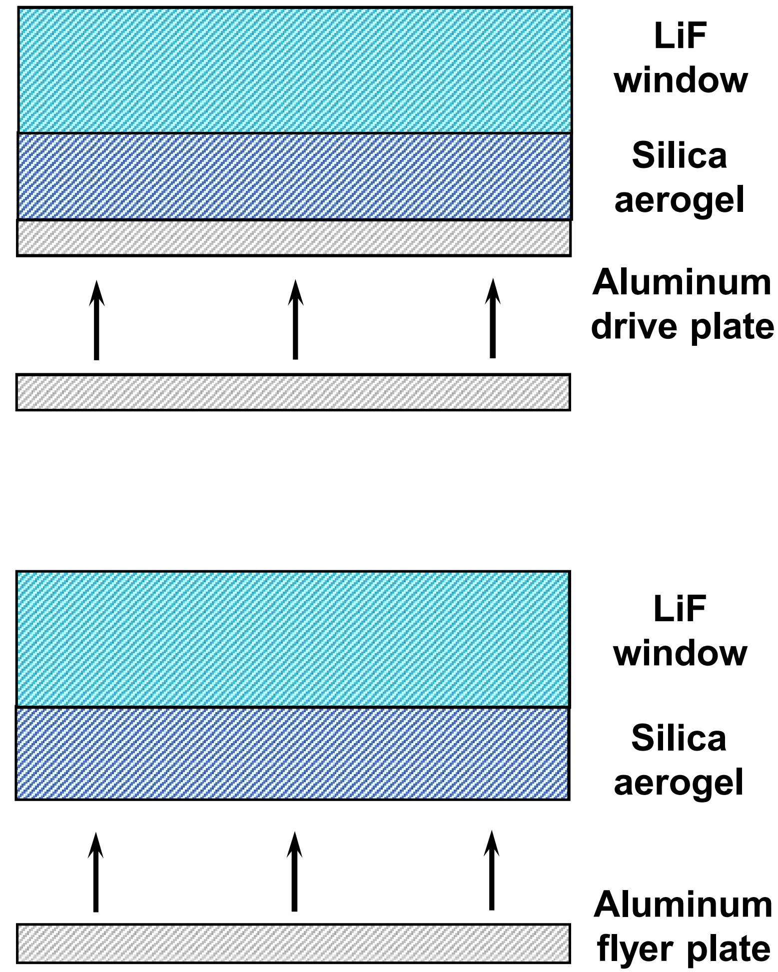
- Release response of aluminum calibrated for impedance matching technique
  - Main source of potential systematic uncertainty
- Conclusions & Future directions

Low density silica aerogel has been used to perform aluminum release experiments





N.C. Holmes, et al., in *High-Pressure Science and Technology – 1993*, p. 153

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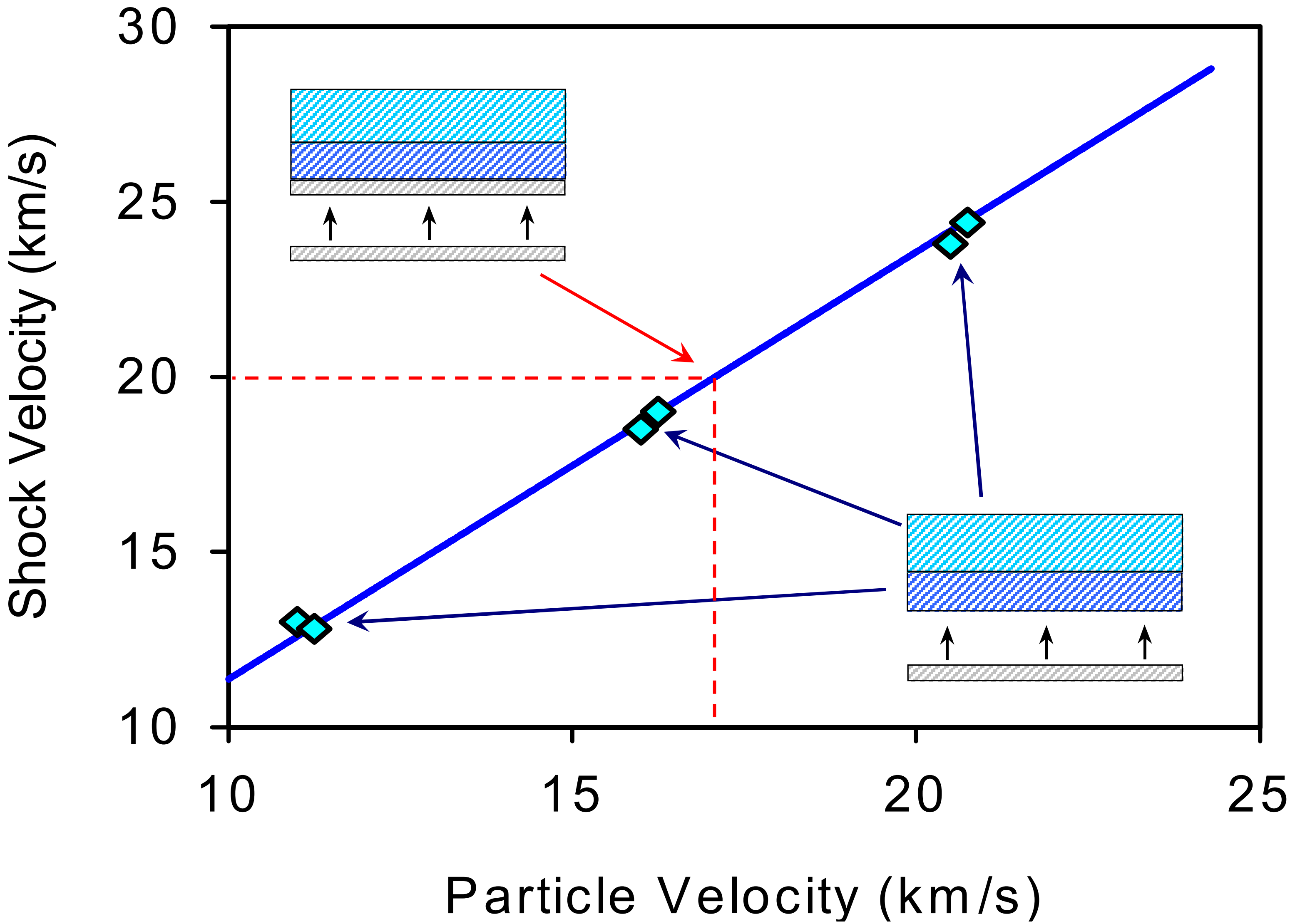
Aerogel experiments allow us to directly measure the effect of release from high pressure



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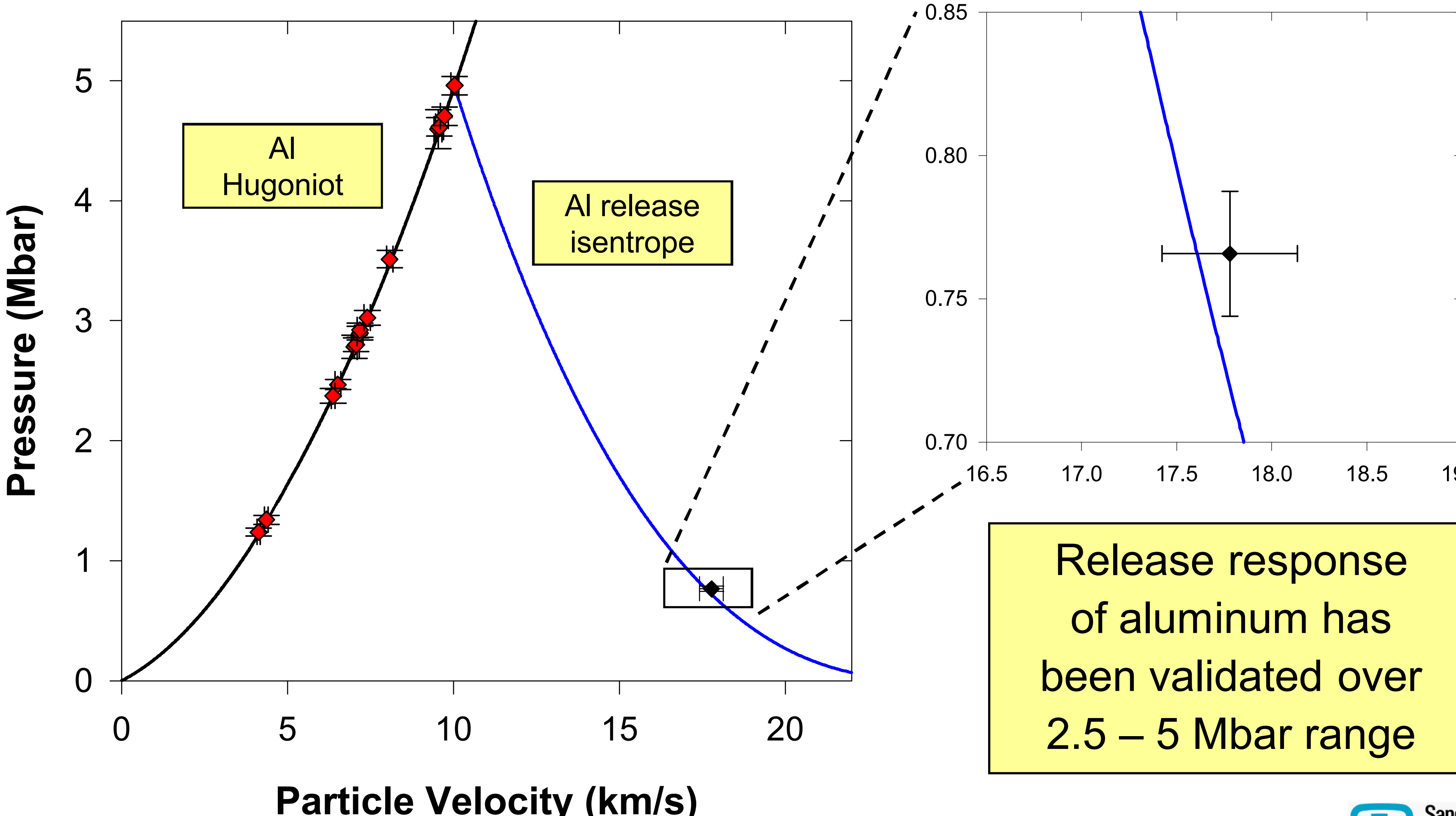
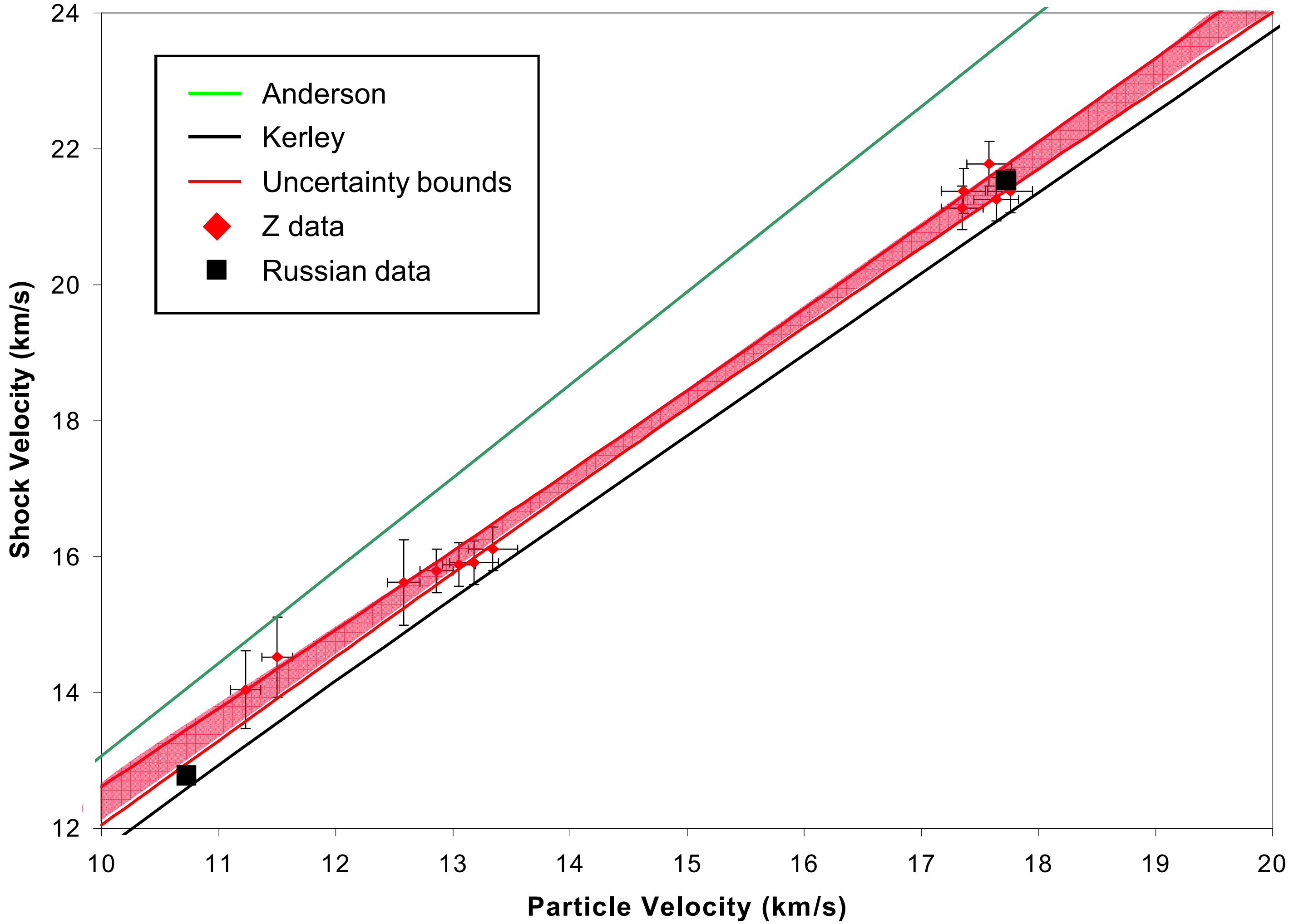
Release measurement yields P-u_p point through which the release isentrope must pass



Release response of aluminum has been validated over 2.5 – 5 Mbar range

The Hugoniot for aerogel has been measured in the region of interest



M.D. Knudson, et al., in preparation

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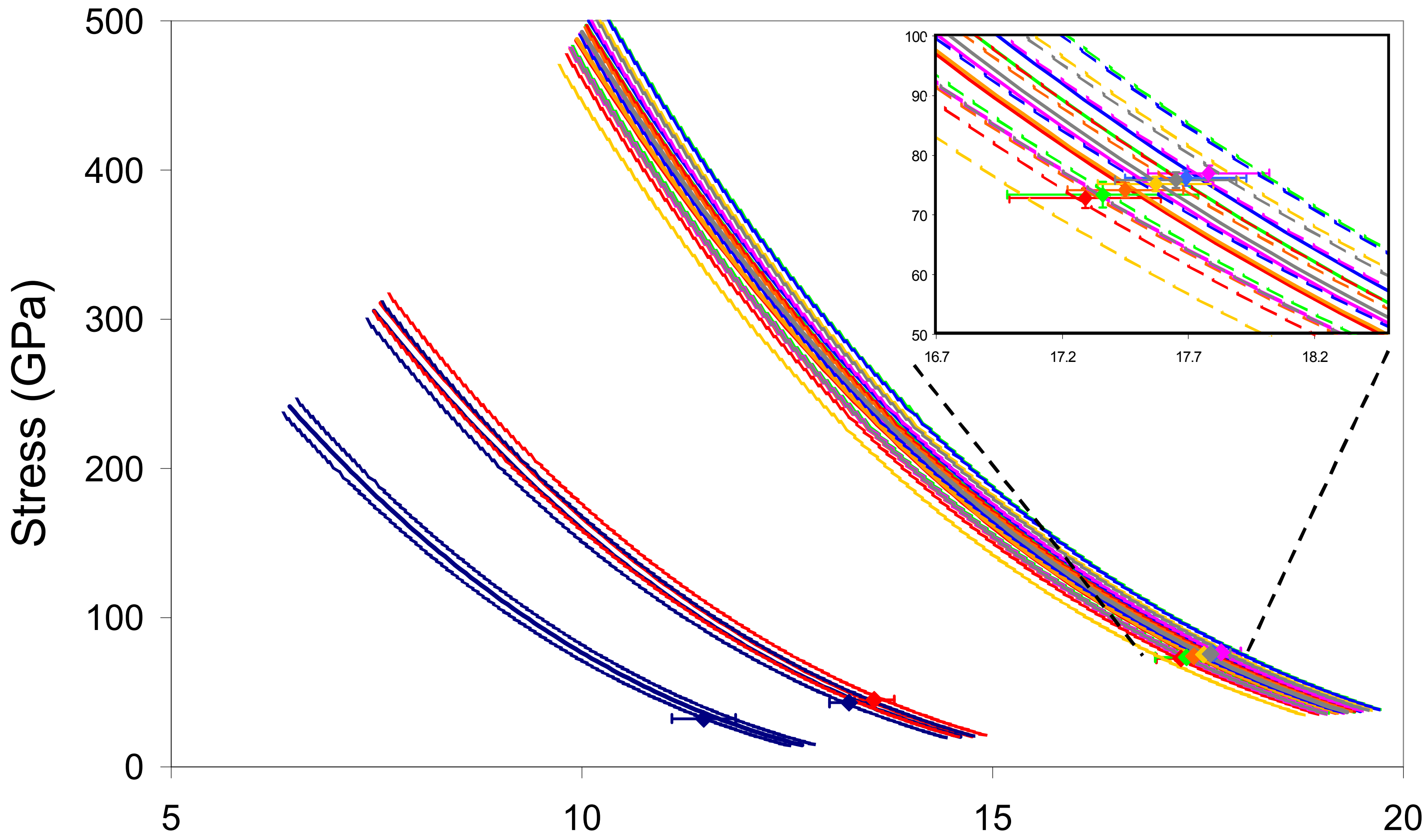
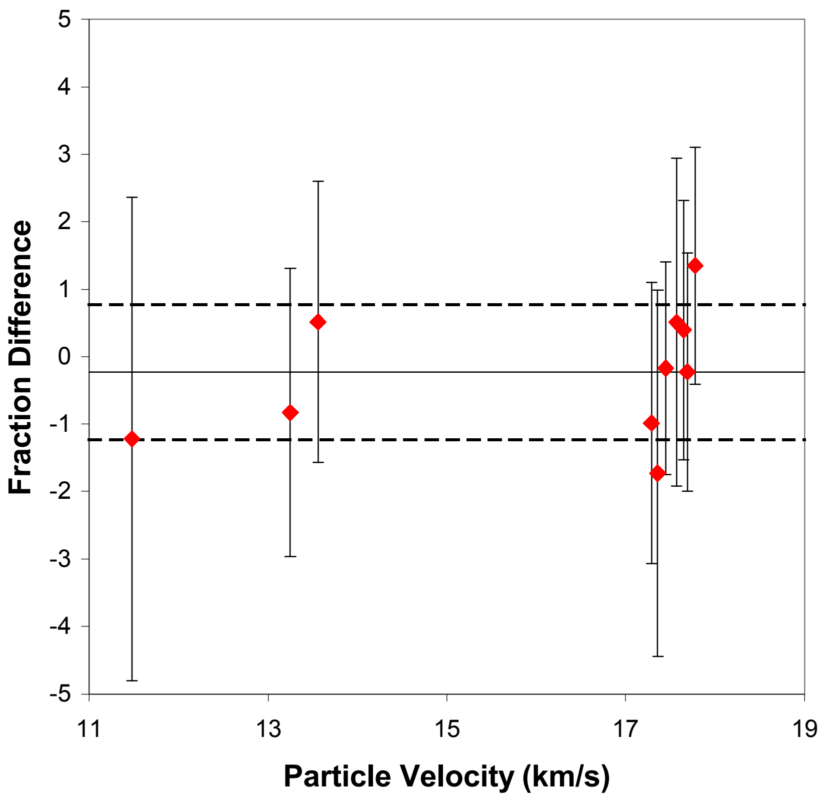
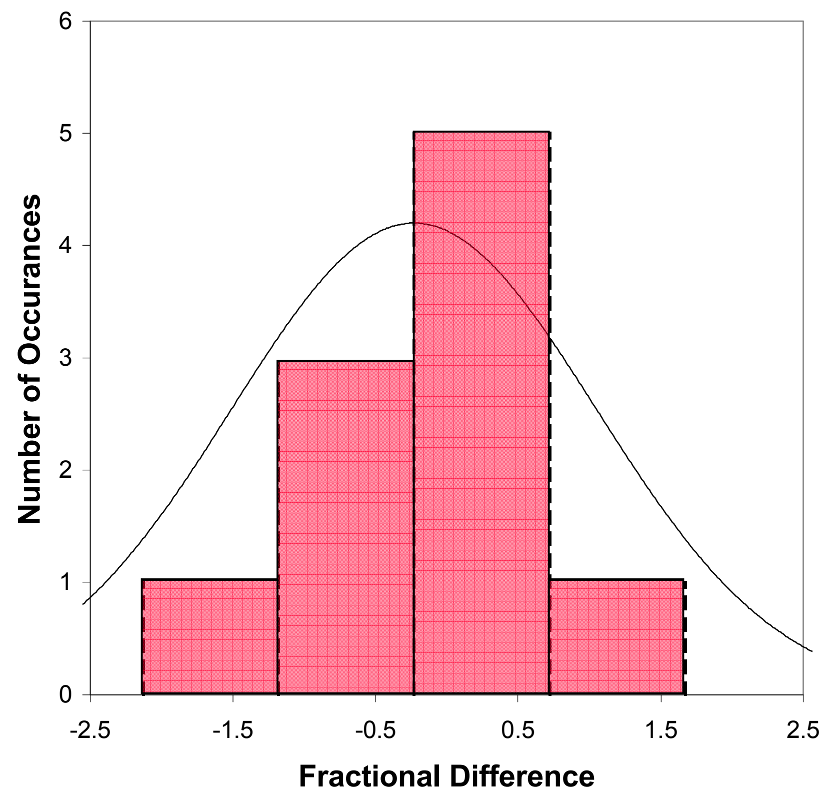
Release isentrope predictions have been verified over the stress range of ~250-500 GPa



M.D. Knudson, et al., in preparation

Statistical analysis does not indicate systematically stiff or soft release in 3700





Data is consistent with a Gaussian distribution with average of –0.23% and standard deviation of 0.95%

M.D. Knudson, et al., in preparation

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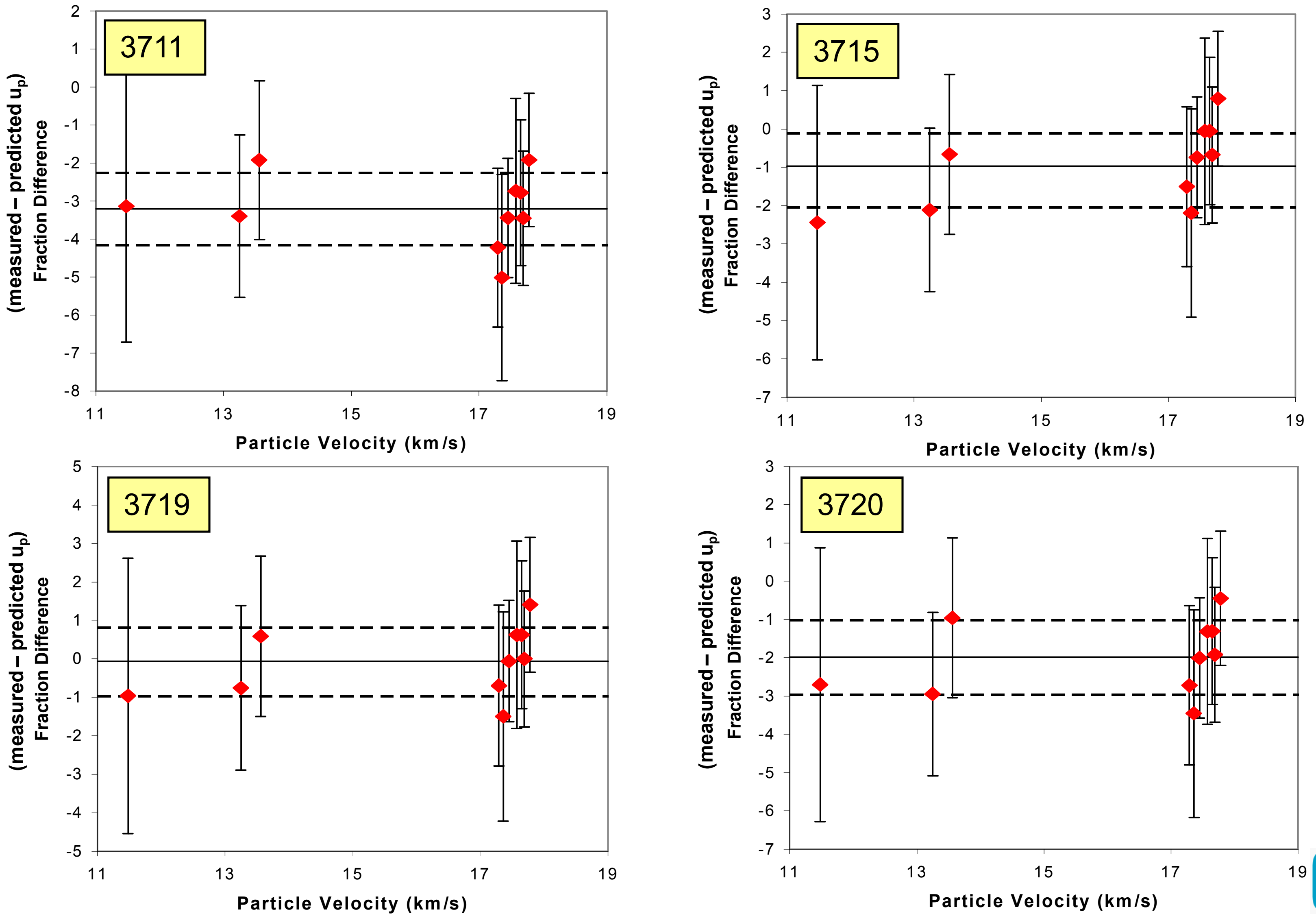
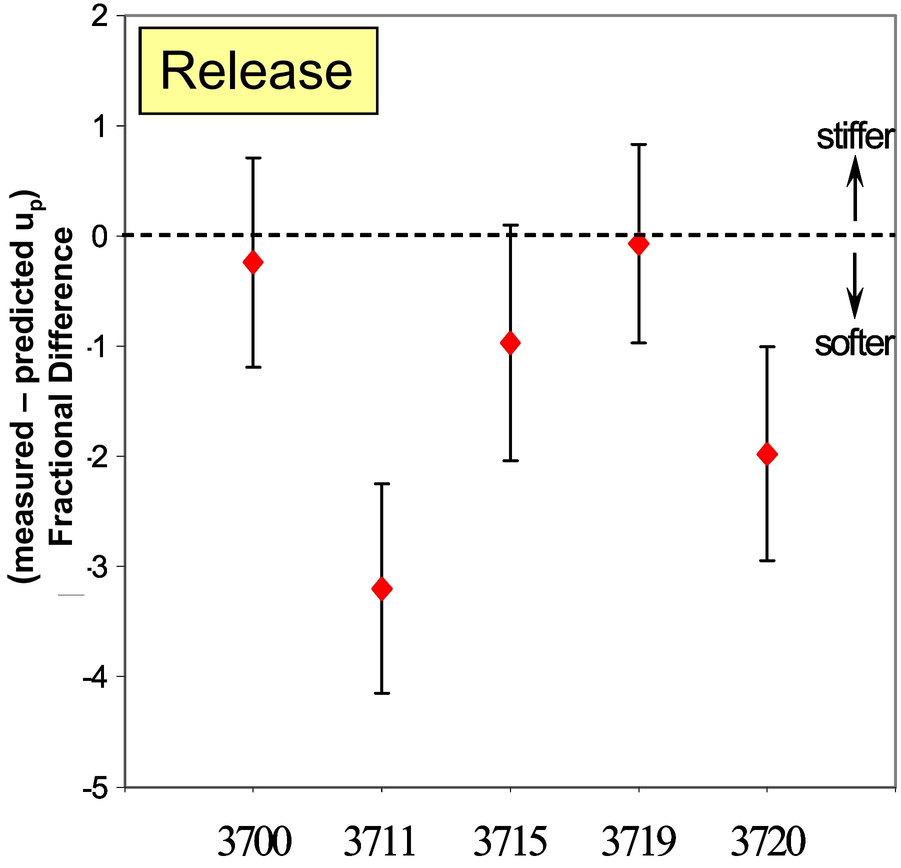
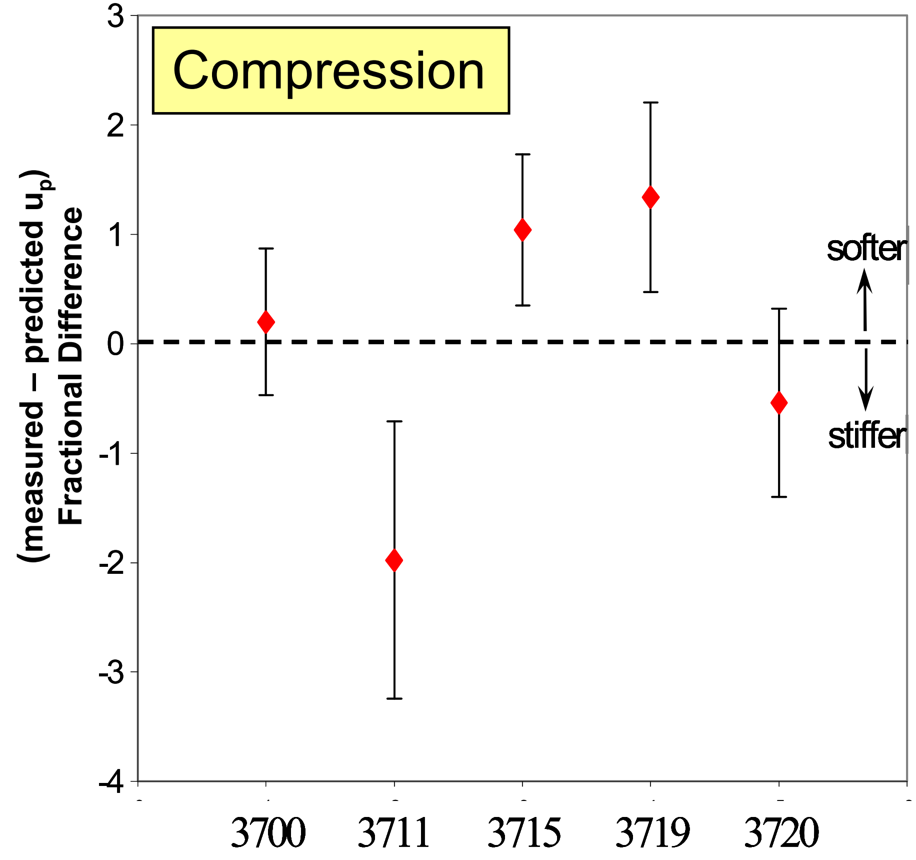
We have analyzed four other models commonly used for aluminum

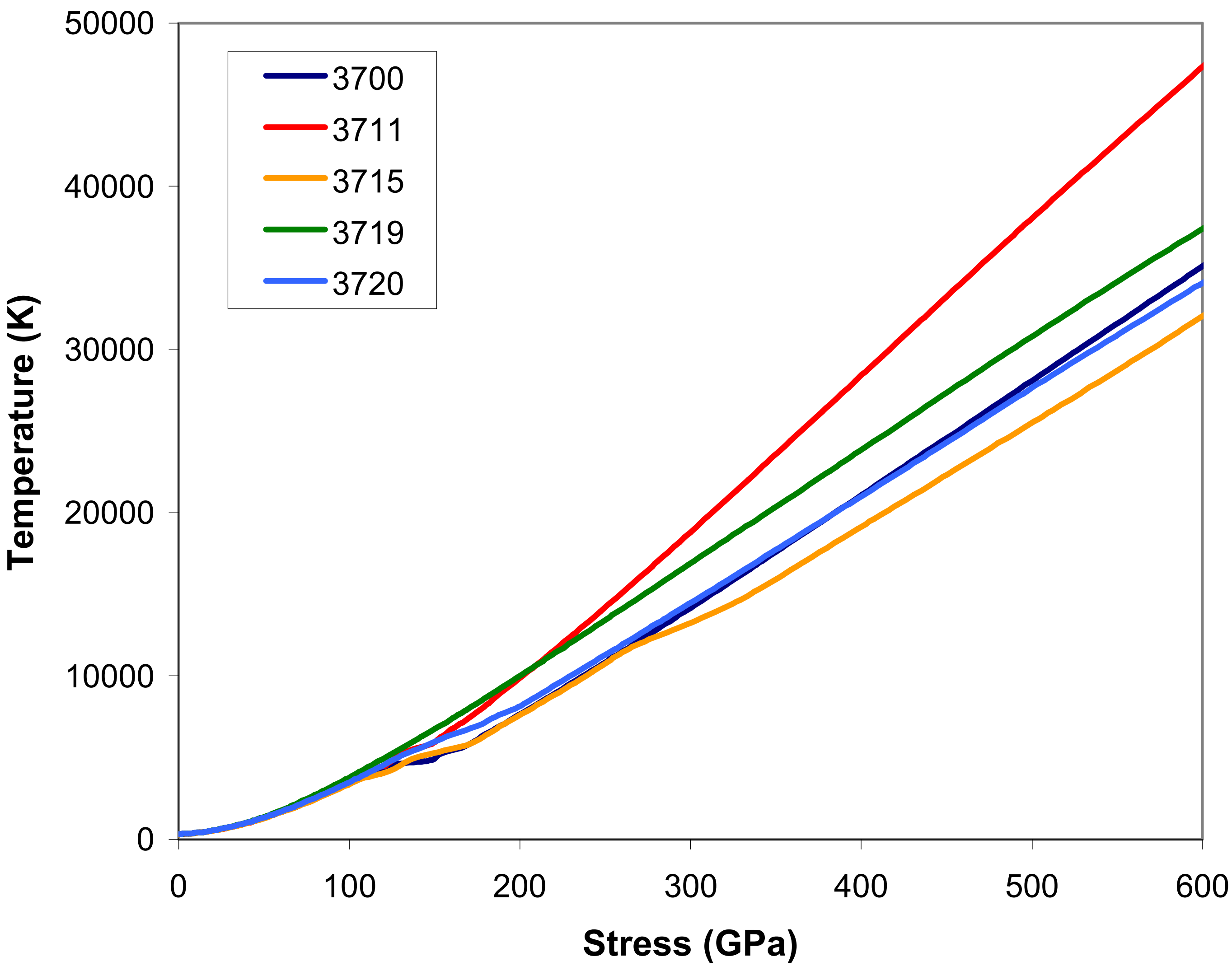


Statistical analysis does indicate systematics in some aluminum models





Aluminum results can be understood by considering model behaviors

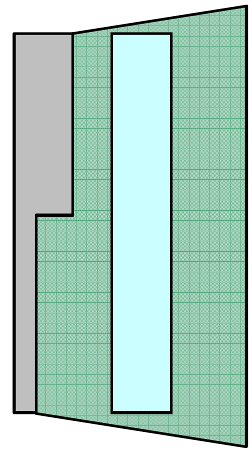


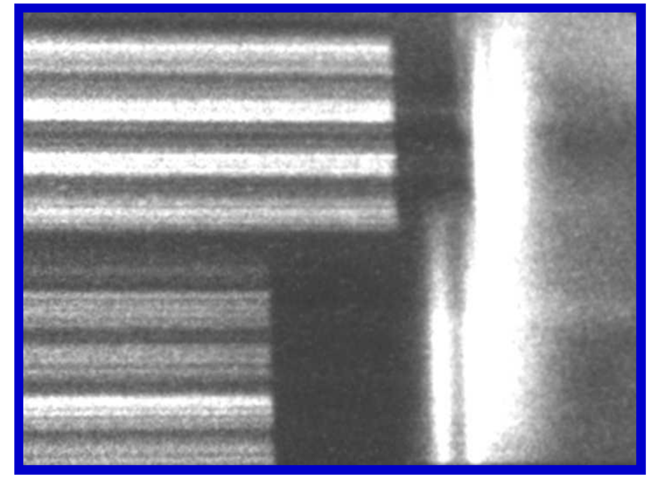
3711 significantly overestimates the Hugoniot temperature resulting in soft release response

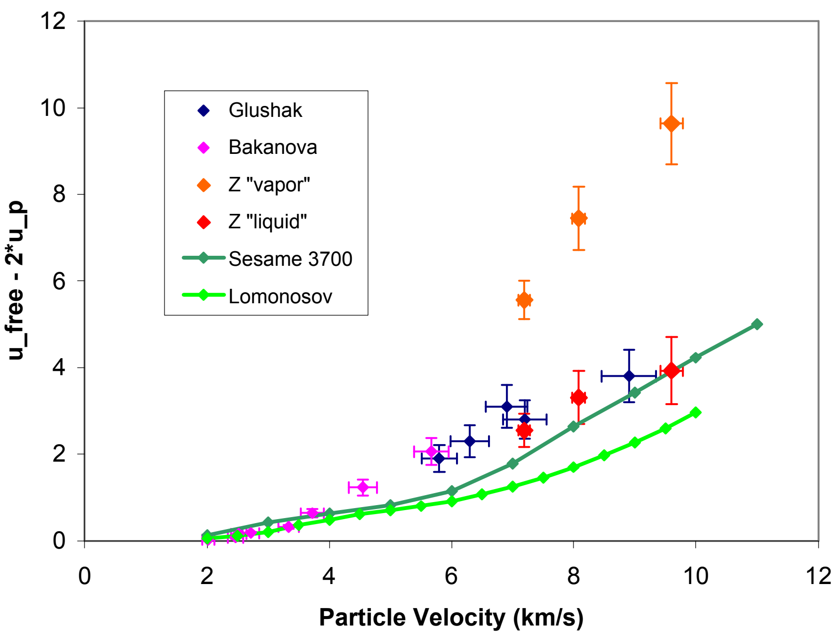
3719 exhibits a zero latent heat of fusion an has errors near melt regions – i.e. ~1-2 Mbar on Hugoniot

We have also obtained full release data for aluminum from ~5 Mbar

Clearly observe two distinct features at the LiF witness plate







Tentatively explain these features to a fast vapor and a slower bulk component

M.D. Knudson, et al., in preparation

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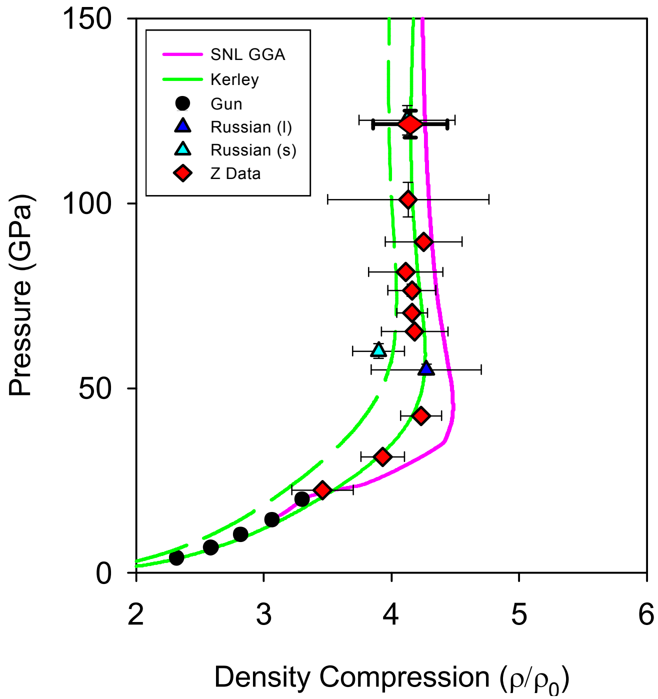
We are distinguishing between EOS models for liquid deuterium

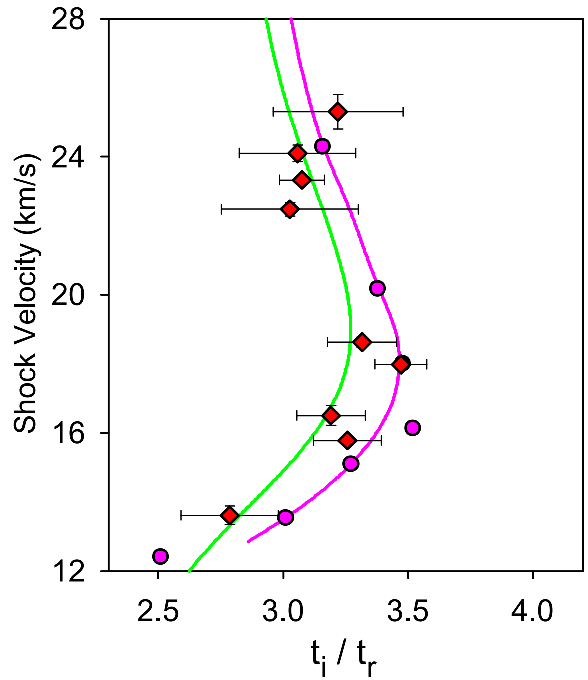
Measurement		Sesame 72	Ross/ Young 96	TB 97	Sesame 98	GGA 00	Kerley 03	SNL GGA 03
Principal Hugoniot				✓	✔	✓	✔	✔
Reverberation				✓	✓		✔	✔
Re-shock pressure				✓	✓	✓	✔	✔
Hugoniot temperature		✔		✔	✔	✔	✔	✔
Re-shock temperature		✔		✔	✔	✔	✔	✔

Excellent agreement with both a chemical picture model and an ab-initio model

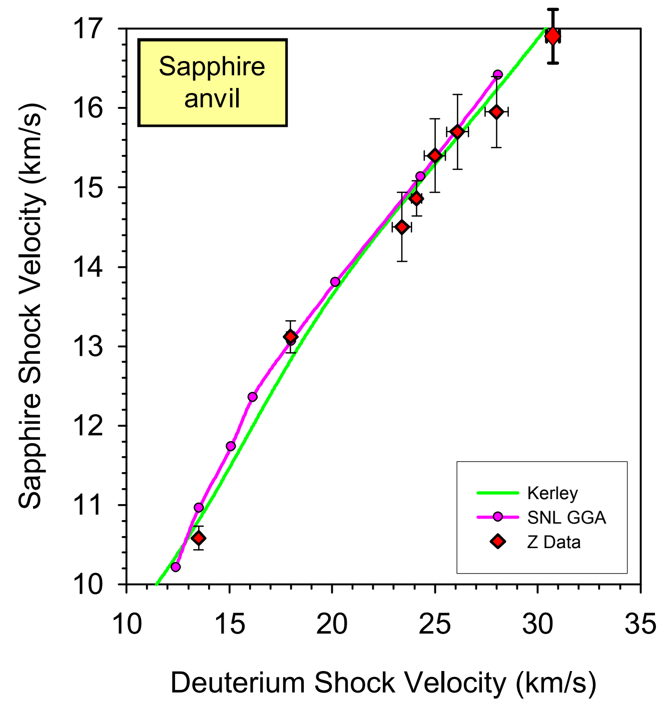
Hugoniot



Reverberation



Re-shock



Both a chemical picture (Kerley 03) and an ab-inito (SNL GGA 03) model accurately reproduce the EOS data obtained in all of the flyer plate experiments

M.D. Knudson, et al., Phys. Rev. B, accepted for publication (2004)

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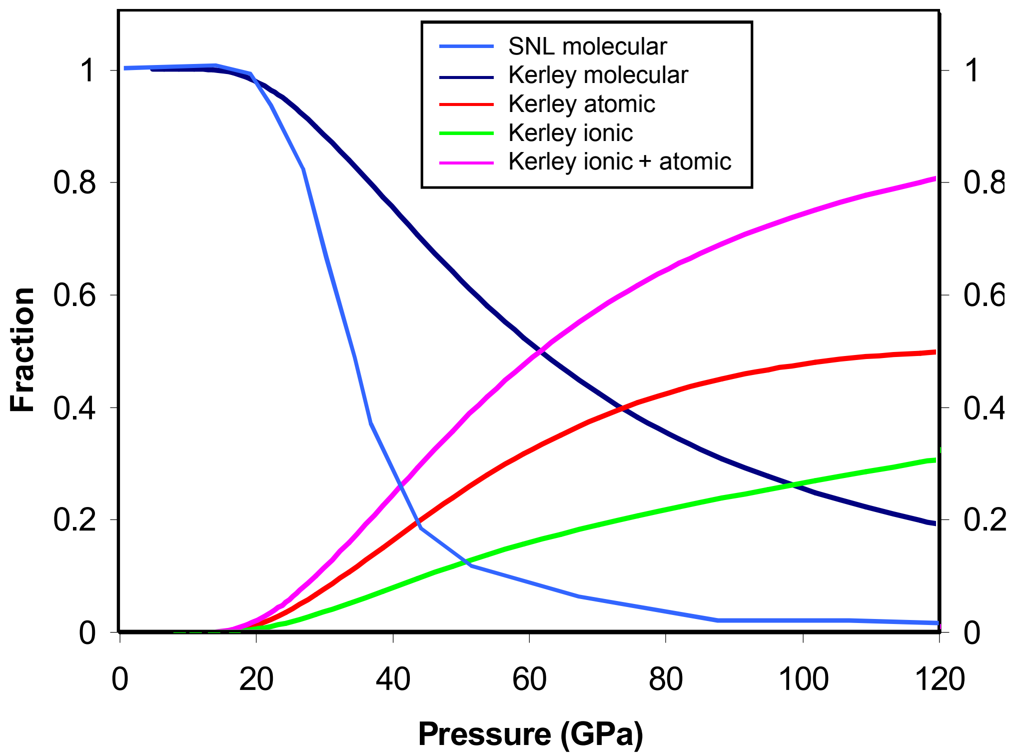
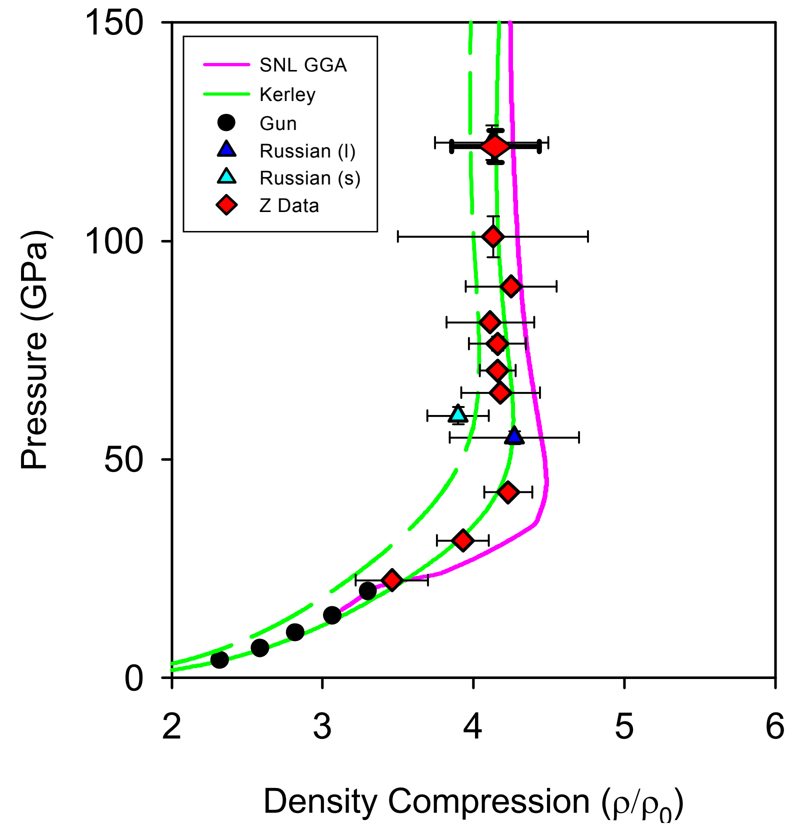
What do these results tell us about deuterium in the Mbar regime?





At ~100-150 GPa deuterium is likely fully dissociated and roughly 50% ionized – Hugoniot likely approaches 4-fold compression from the higher density side

G.I. Kerley, SAND Report 2003-3613

M.P. Desjarlais, Phys. Rev. B **68**, 064204 (2003)

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Conclusions

- Ultra-high velocity flyer plate experiments becoming routine on Z
  - Shock-less acceleration to ~27 km/s
  - Fully predictive, self-consistent, 2-D MHD capability
- Technique has been validated for Equation of State
  - Absolute Hugoniot measurements on aluminum to ~8 Mbar
  - Aluminum release behavior has been calibrated
  - Deuterium Hugoniot response is stiff, at least to ~1.2 Mbar
  - Multiple, self-consistent measurements confirm stiff response
  - *ab-initio* models provide very good description of hydrogen and its isotopes

Future direction

- Extend D_2 results to higher pressures
  - Plans to extend flyer velocity to > 30 km/s on Z
    - » ~10 Mbar states in aluminum and ~1.5 Mbar state in D_2
  - Predicted flyer velocity to > 40 km/s on ZR (2007)
    - » ~15 Mbar states in aluminum and ~ 2.5 Mbar states in D_2
- Perform similar study on H_2/D_2 mixtures and HD
  - Identify any potential isotopic differences
- Continue to address aluminum release
  - Qualify aluminum release from pressure greater than 5 Mbar

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