SAND2015-2630C

Exceptional service in the national interest

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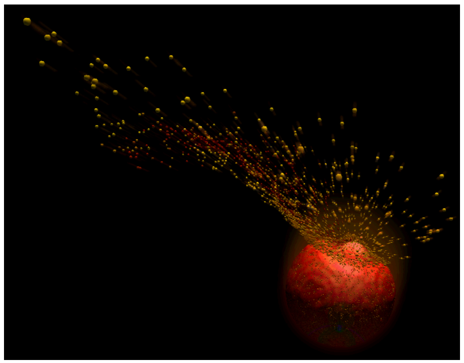
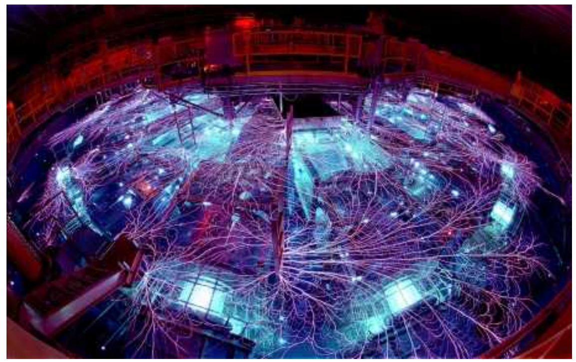
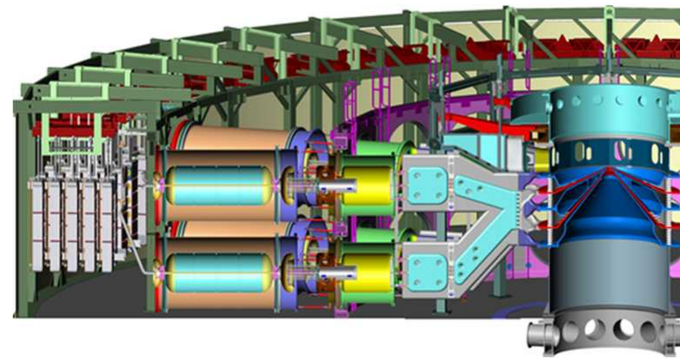


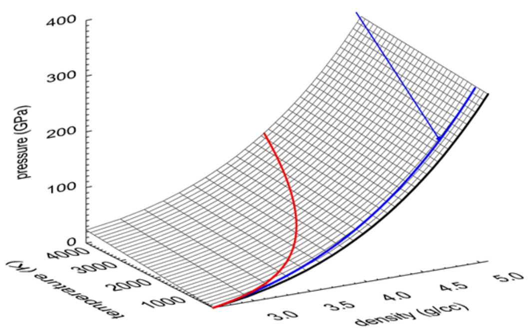




Dynamic Materials Experiments on Sandia's Z Facility

2015 International Workshop on Electromagnetic Driven High Energy Density Physics

Chengdu, China April 12-15, 2015



Dawn Flicker

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Albuquerque, New Mexico

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Sandia's Z Machine is a unique platform for multi-mission research on high energy density (HED) environments

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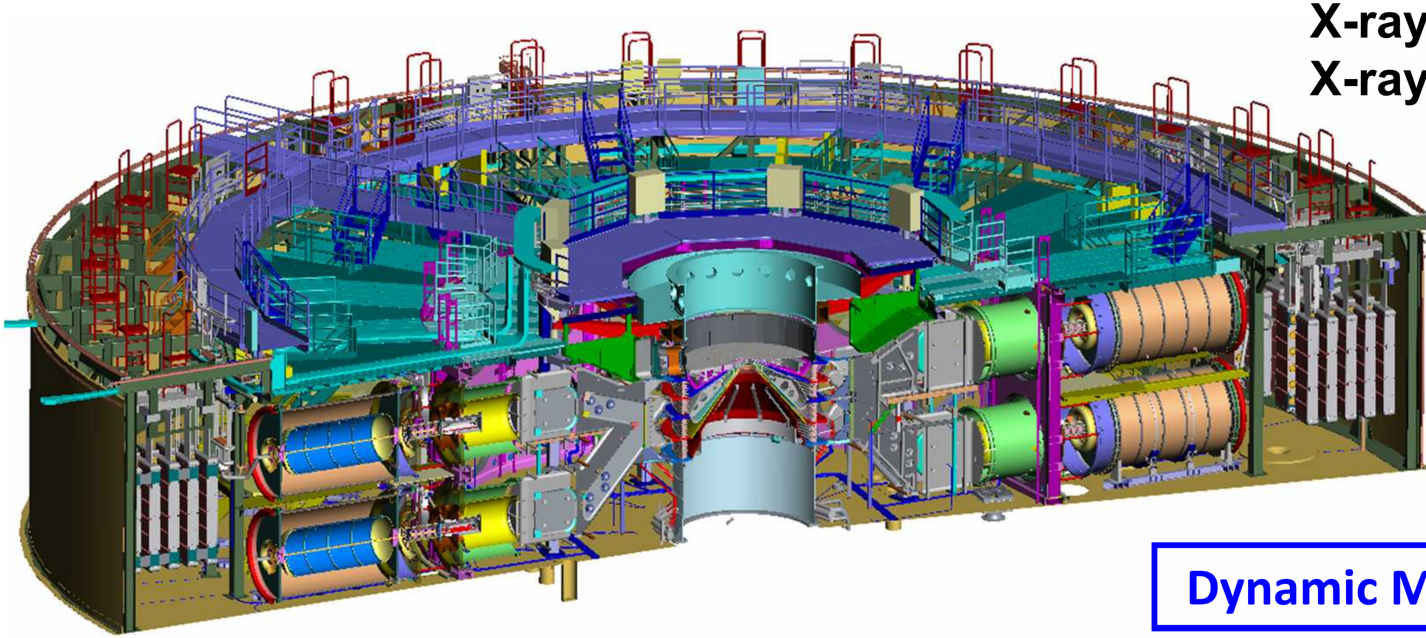
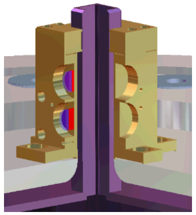
I ~ 26 MA, τ ~100 ns
X-ray power > 250 TW
X-ray energy > 2 MJ



Dynamic Materials



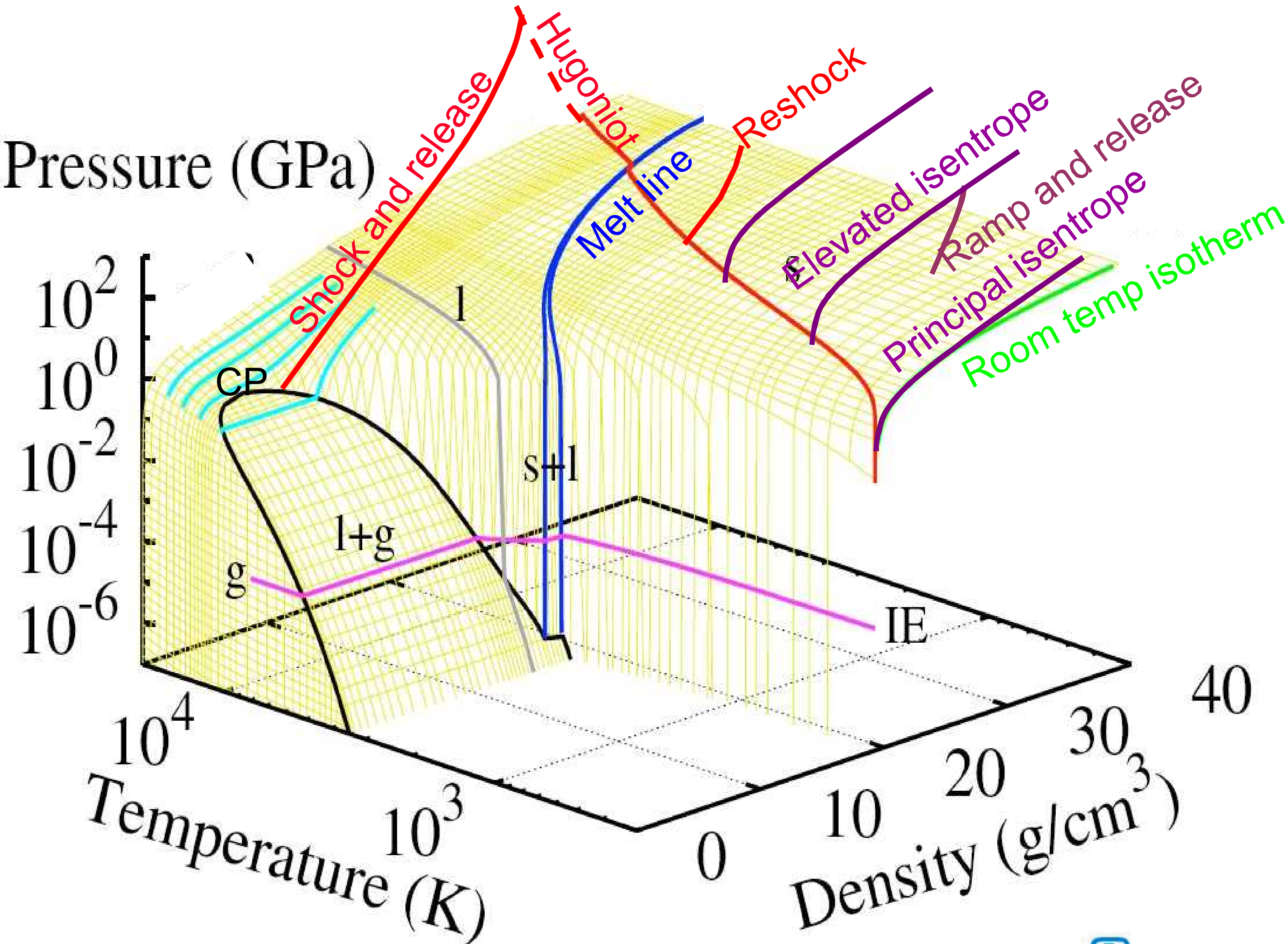
Equation of State

Pulsed Power Technology

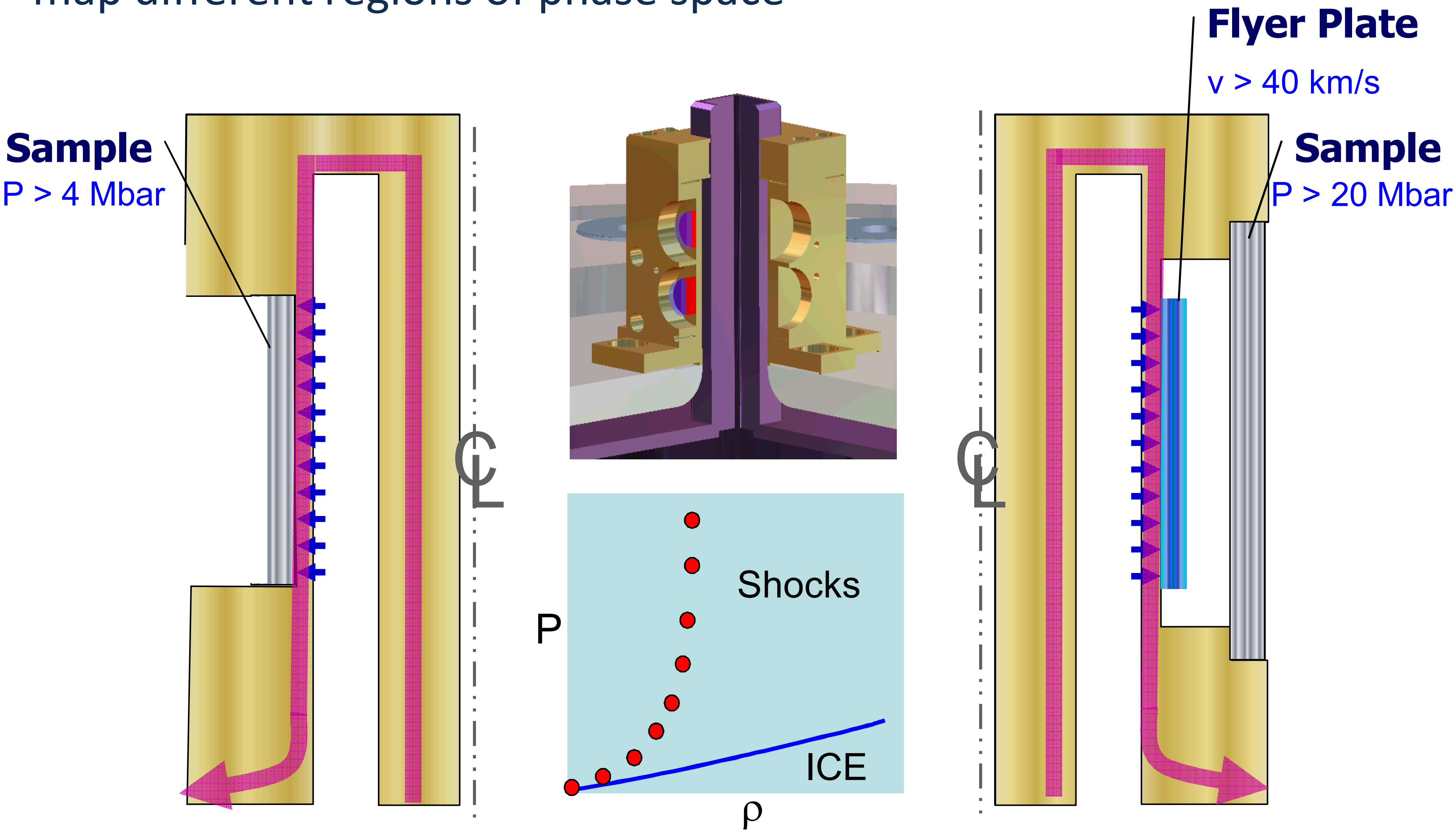
Magnetically Driven Implosions

Inertial Confinement Fusion

Dynamic compression experiments on Z can probe large regions of a material's equation-of-state surface



Isentropic compression and shock wave experiments map different regions of phase space



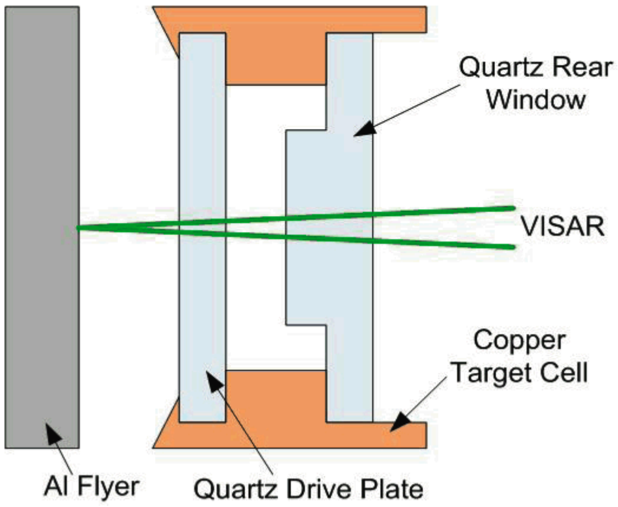
Isentropic Compression Experiments:
gradual pressure rise in sample

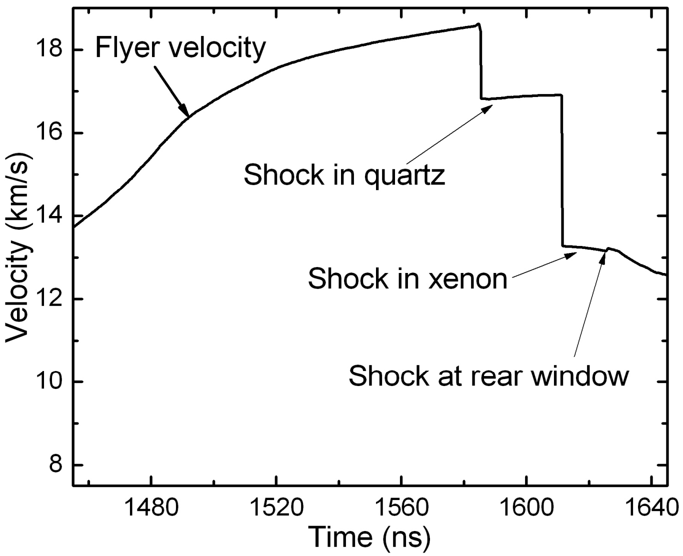
Shock Hugoniot Experiments:
shock wave in sample on impact

Outline: A variety of Z experiments provide broad coverage of material phase space

- Hugoniot experiments
  - Examples of Hugoniot experiment results
- Quasi-Isentropic Compression Experiments (ICE) experiments
  - Examples of ICE experiment results
- Shock-Ramp experiments
  - Example of shock-ramp experiment results
- Strength Experiments
  - Examples of strength experiment results

It is possible to measure shock velocities in xenon, deuterium, and other transparent materials with sub-percent accuracy



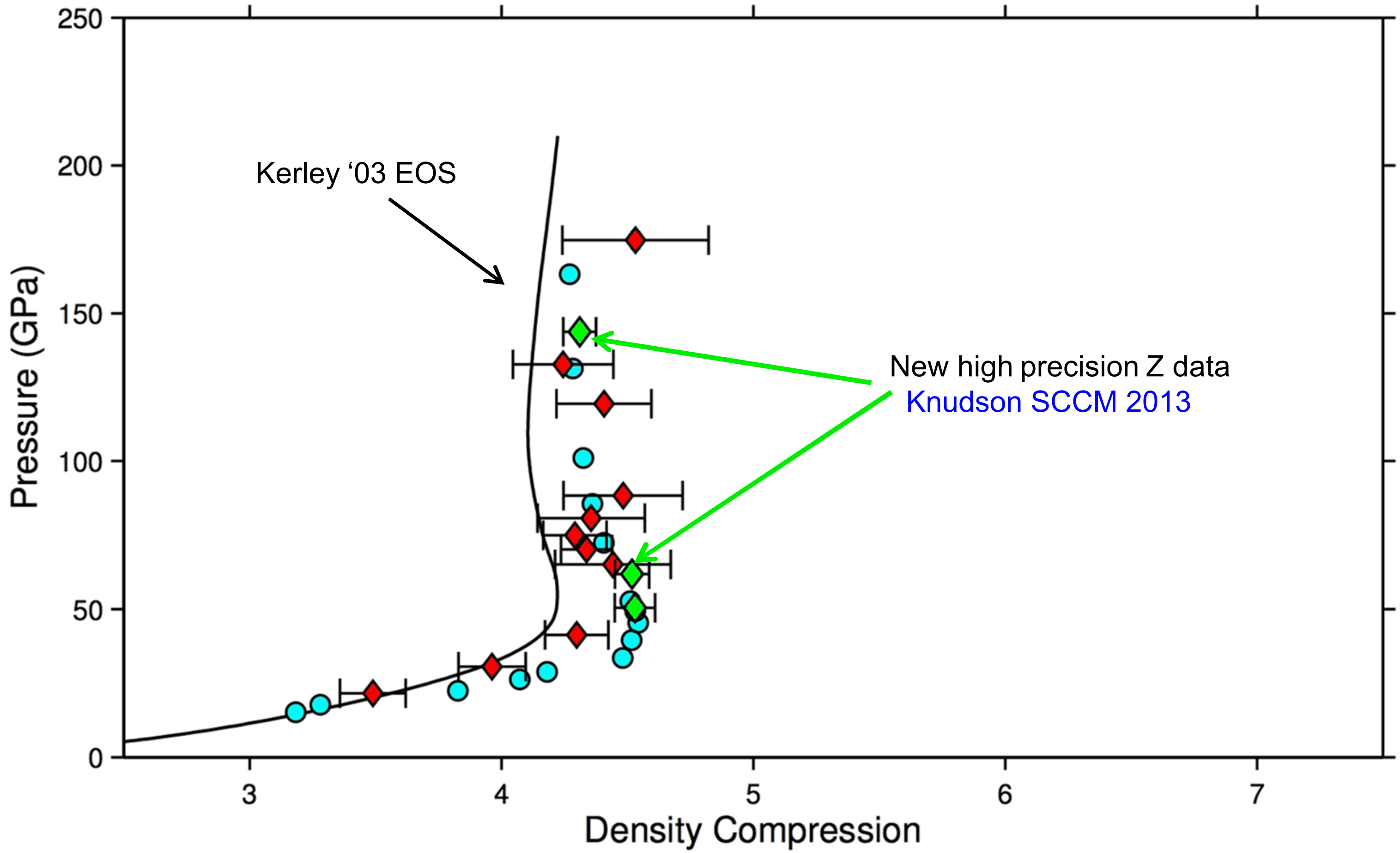


VISAR measurements as main tool

- Flyer velocity, time of impact
- Arrival at interfaces and breakout
- Shock velocity in sample

VISAR trace from a xenon experiment with 18.5 km/s impact velocity

Deuterium equation of state is an active area of research



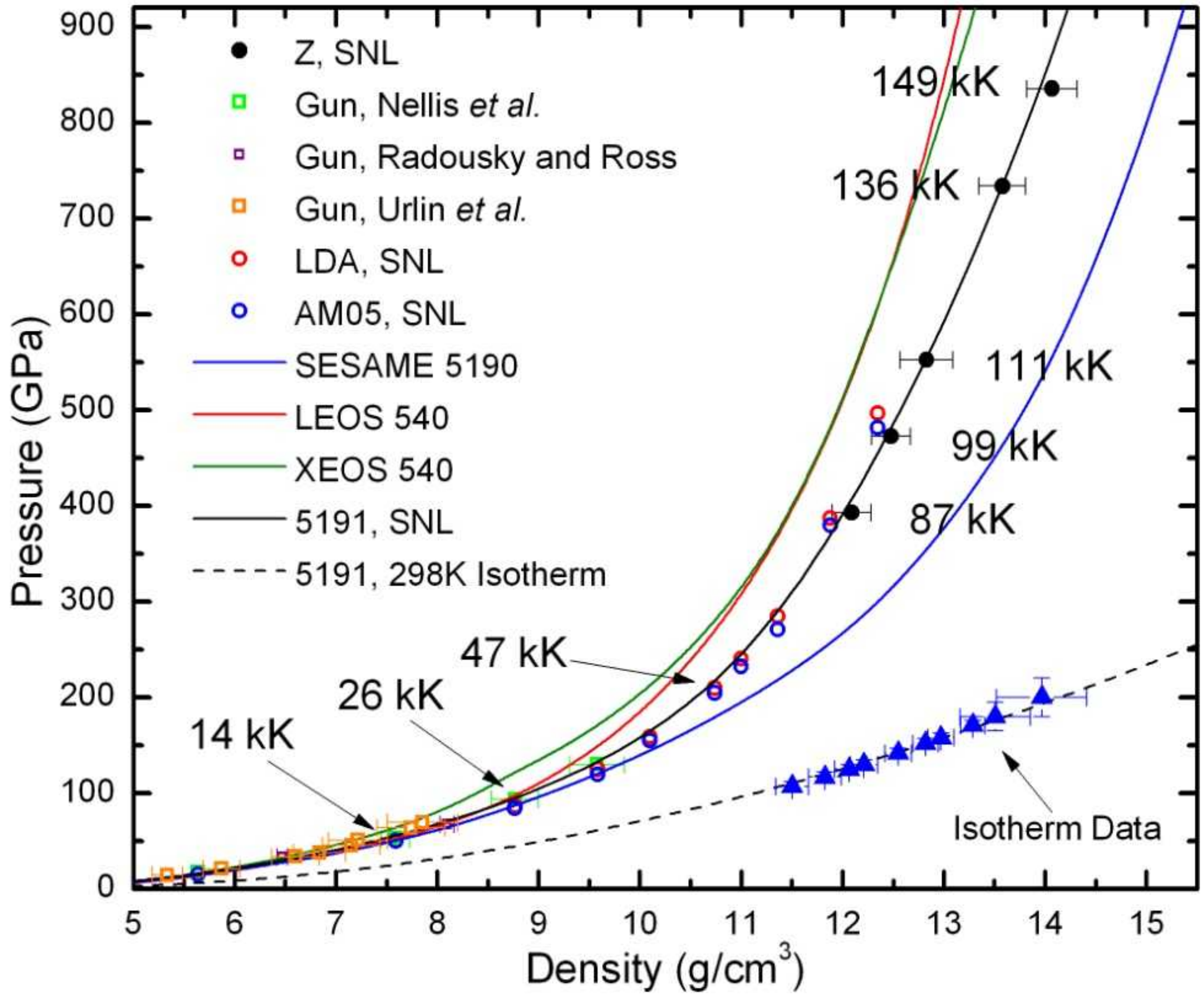
M. D. Knudson *et al.*, Phys. Rev. Lett. **87**, 225501 (2001)
M. P. Desjarlais, Phys. Rev. B **68**, 064204 (2003)

Newer AIMD based EOS, e.g. Holst *et al.*, PRB 2008; Caillabet *et al.*, PRB 2011; Morales *et al.*, HEDP 2012, are in good agreement with Z data

See McMahon *et al.*, Rev. Mod. Phys. **84**, 1607 (2012) for a recent review on H and He

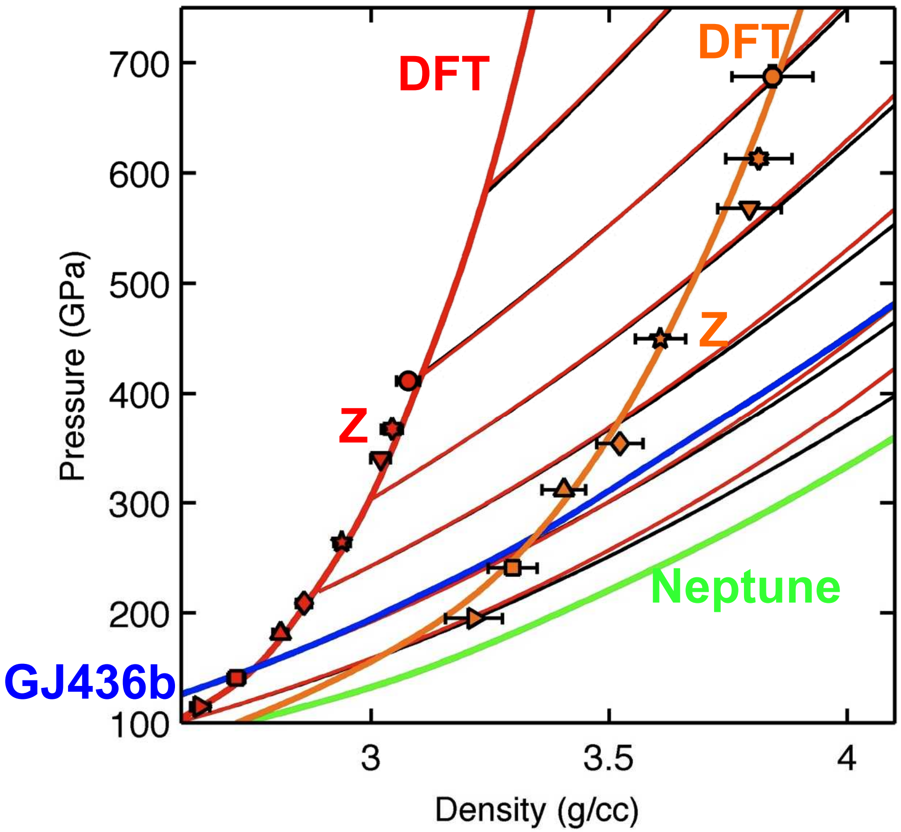
We have performed experiments and simulations for xenon at high pressures

- Measured the xenon Hugoniot to 840 GPa
- Data helped improve DFT potentials
- Developed a new wide-range, multi-phase equation of state for xenon (Carpenter *et al.*)



Root, Magyar, Carpenter, Hanson, Mattsson, Phys. Rev. Lett. **105**, 085501 (2010).
J. H. Carpenter *et al.*, EPJ Web of Conf. 10, 00018 (2010).

Re-shock states in H_2O approximate isentropic compression and are relevant to planetary interiors

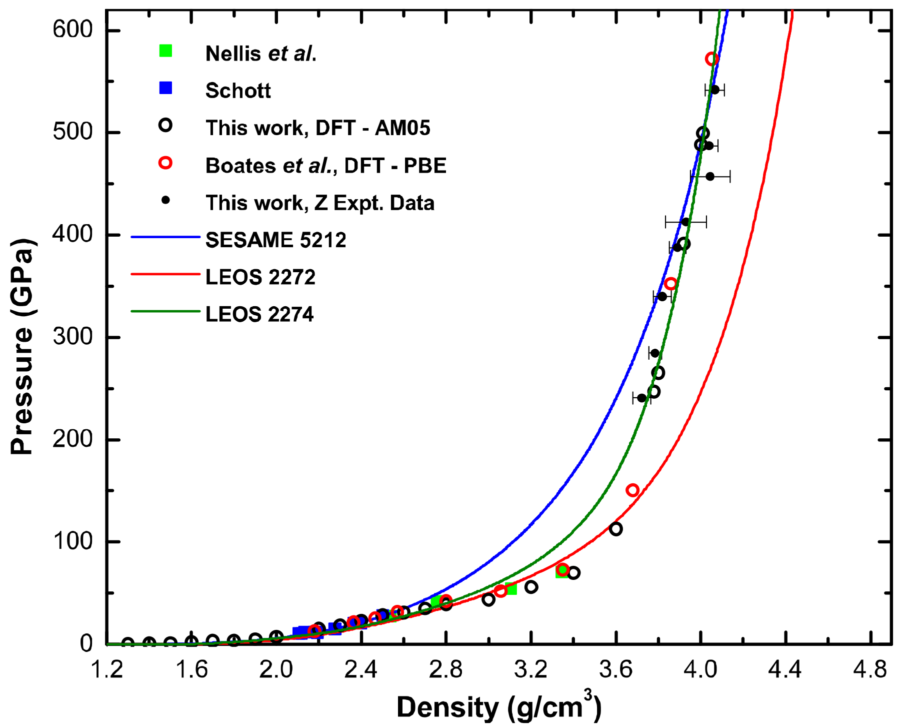


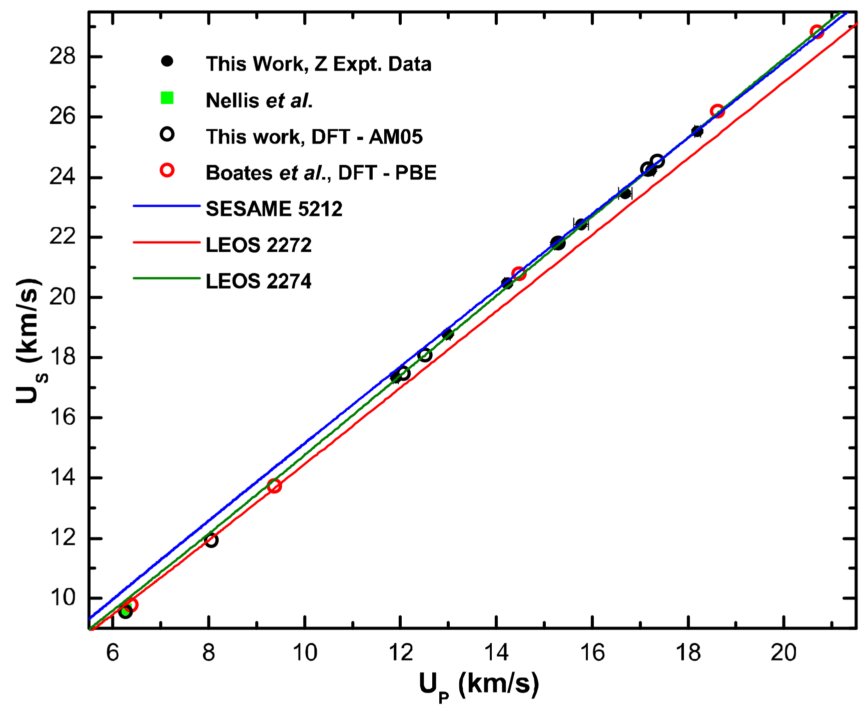
- Re-shock results validate isentropic compression results obtained from DFT
- Data along planetary isentropes for Neptune and hot exoplanets like GJ436b
- Data with unprecedented accuracy for second shock in water

Probing the interiors of the ice giants: Shock compression of water to 700 GPa and 3.8 g/cc, Knudson, Desjarlais, Lemke, Mattsson, French, Nettelmann, and Redmer, Phys. Rev. Lett. **108**, 091102 (2012).

Recent work has explored the Hugoniot of CO_2

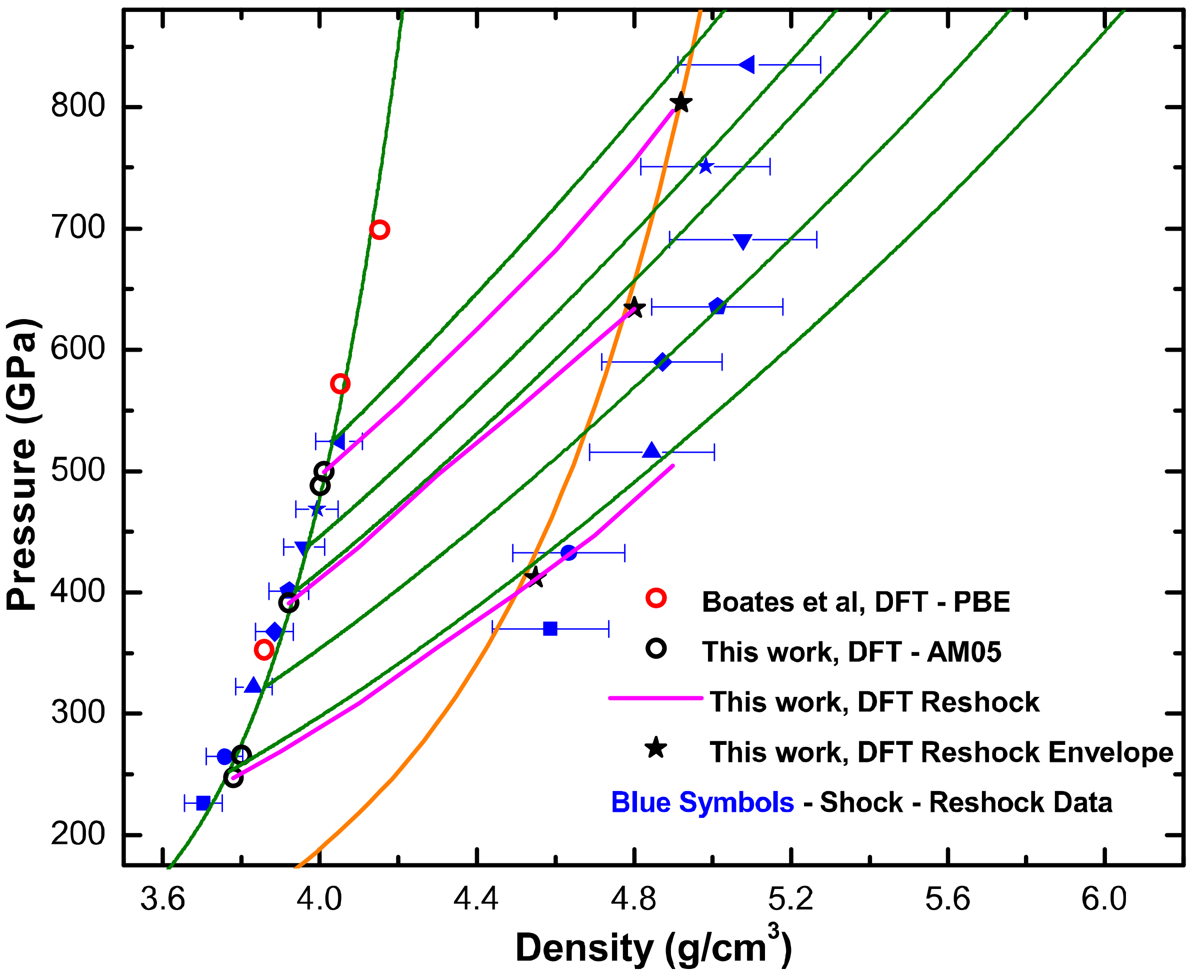
- Hugoniot measured to 5.5 Mbar – consistent with DFT results
- Data determined using quartz and sapphire impedance matching – consistent results between the two impedance standards
- Experiments show a less compressible Hugoniot after dissociation
- LEOS 2272 is too compressible and SESAME 5212 too stiff at intermediate pressures
- Christine Wu (LLNL) utilized the DFT and Z results to build EOS 2274





We have also obtained data on reshock states of CO_2

- Reshock state determined from quartz shock velocity
- CO_2 reshock state measured to 8.4 Mbar
- Experimental data suggests more compressibility on reshock than predicted by DFT



Root, Cochrane, Carpenter, and Mattsson, Phys. Rev. B **87**, 224102 (2013)

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

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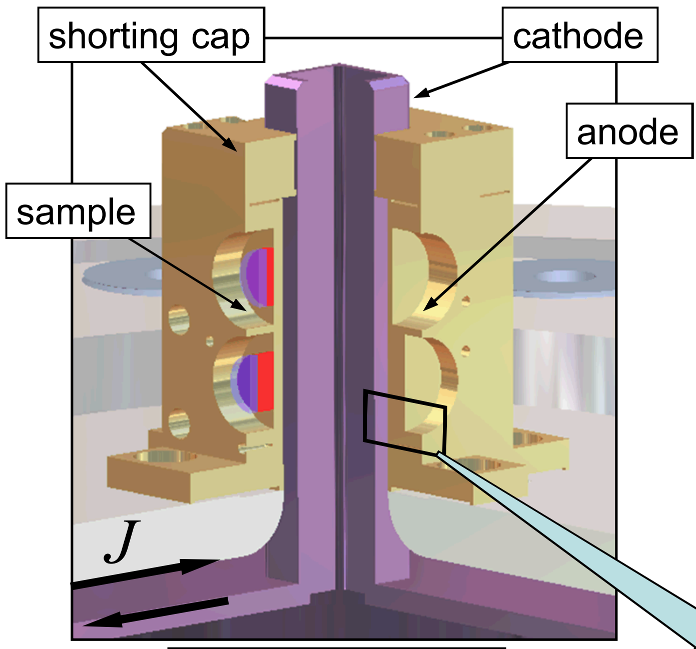
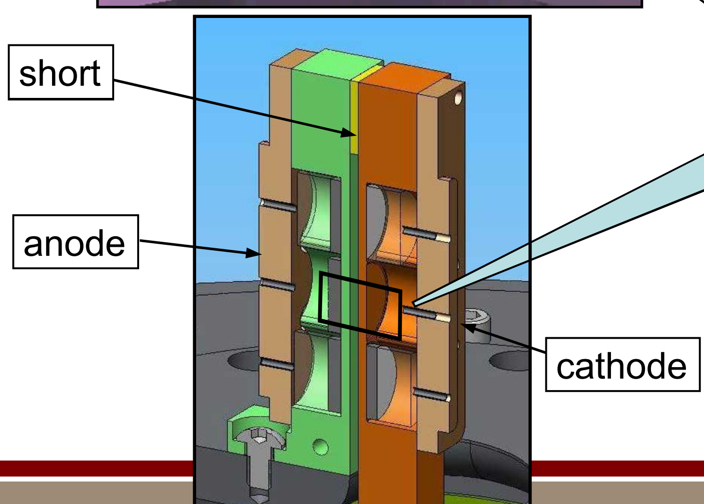
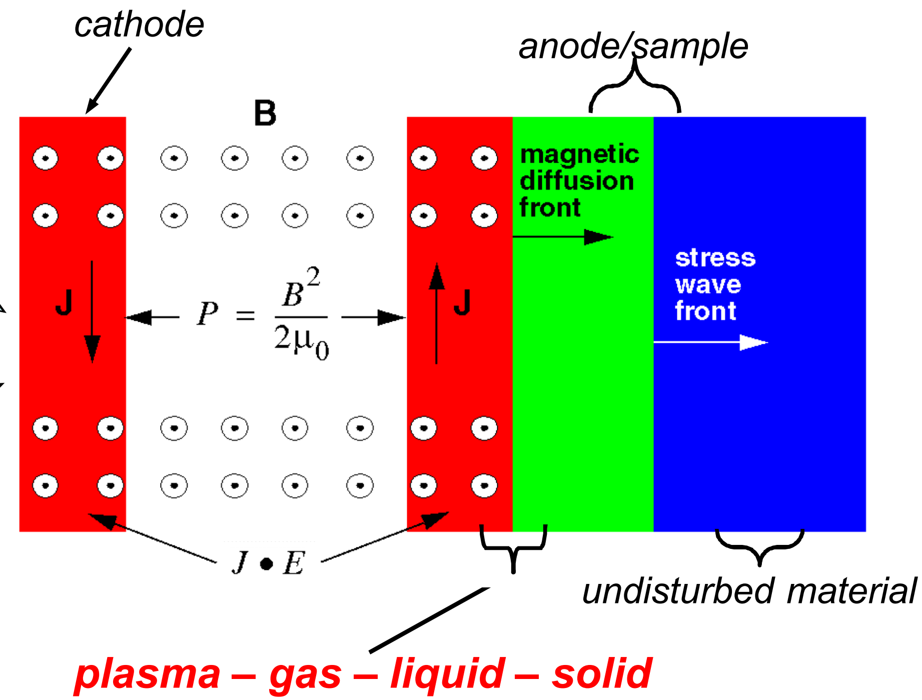
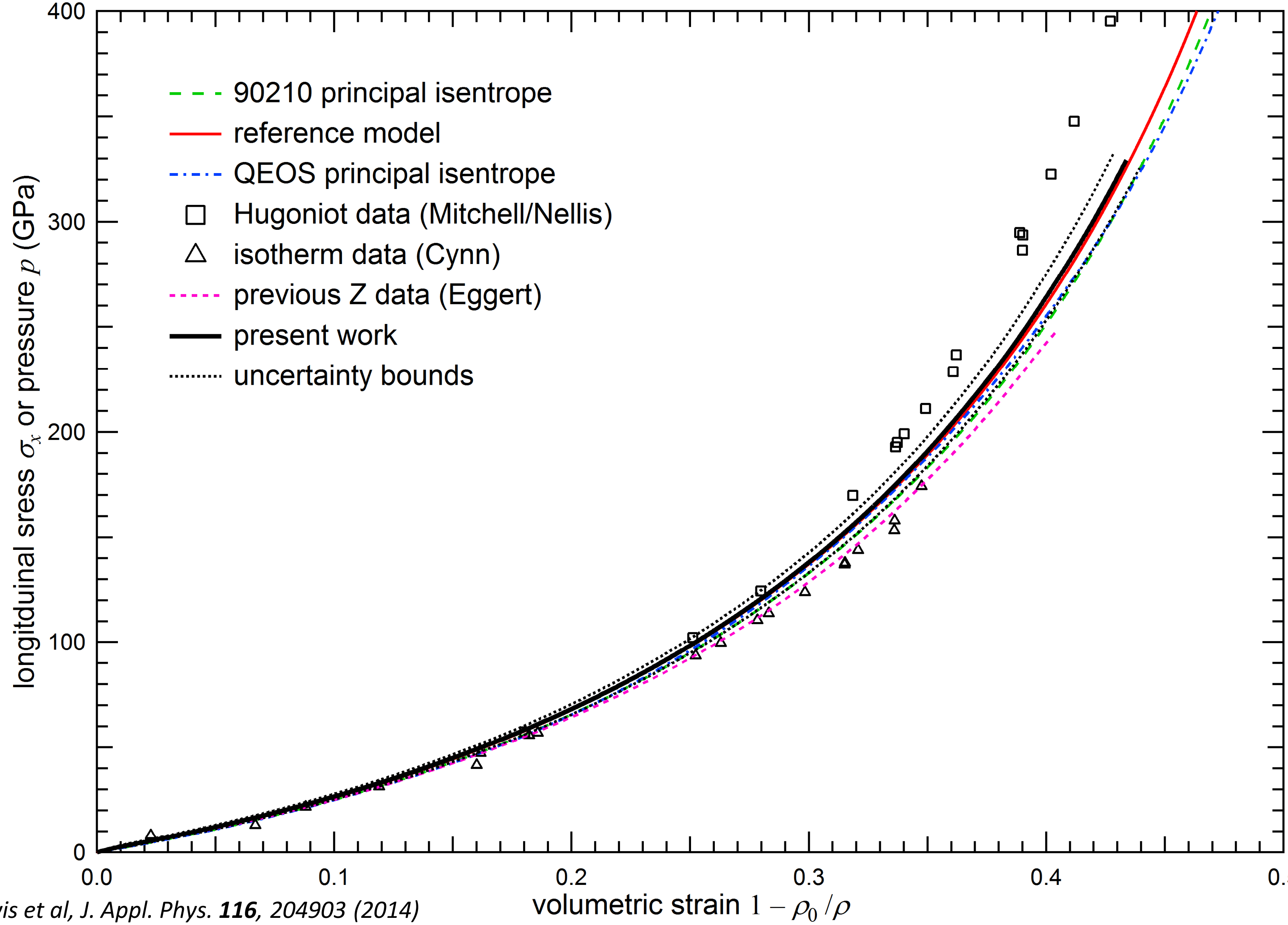




- pulse of electric current through experimental load (shorted at one end) induces magnetic field
- *J´B* magnetic force transferred to electrode material

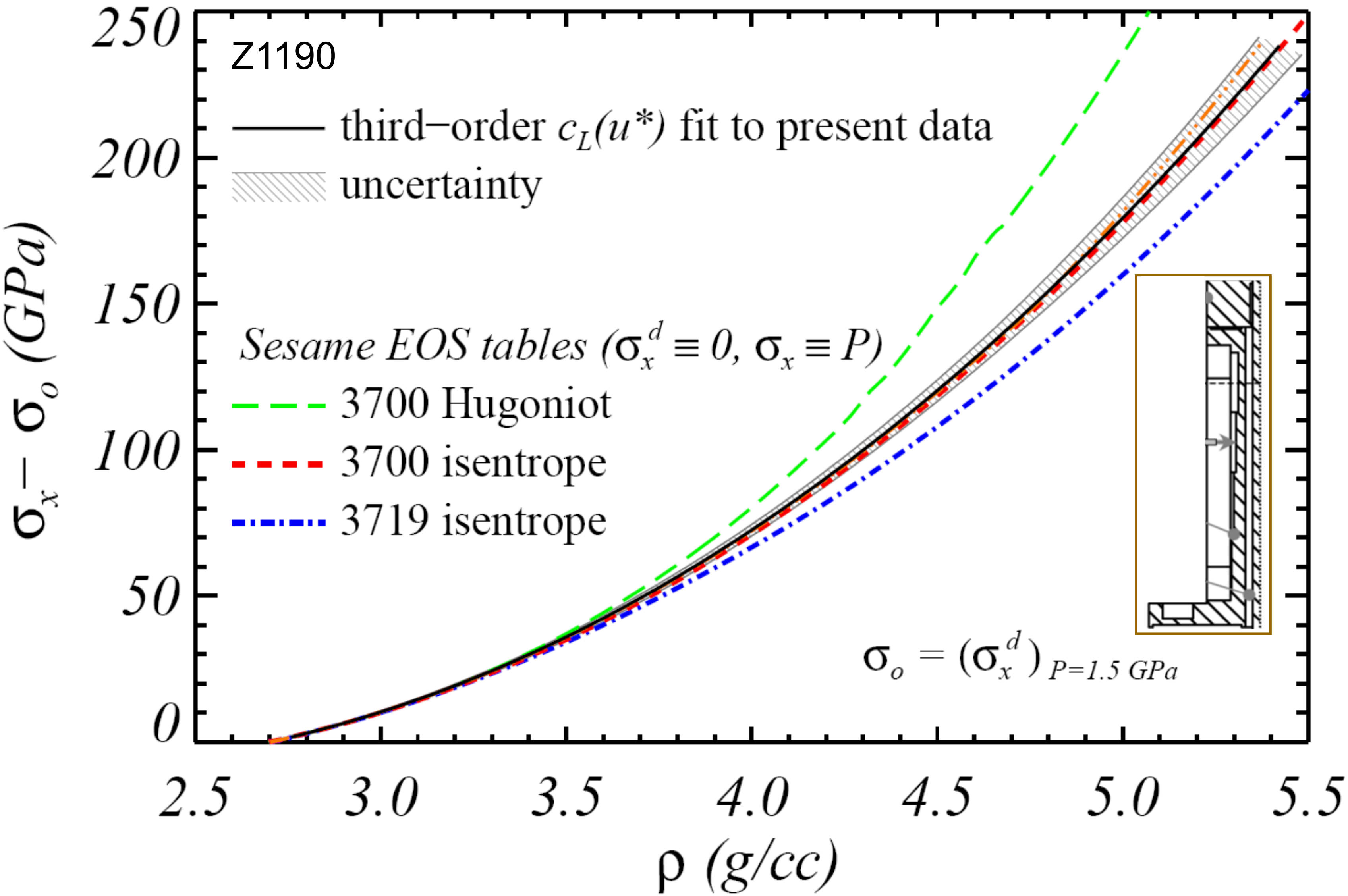


Quasi-Isentrope of Ta was measured to almost 400 GPa



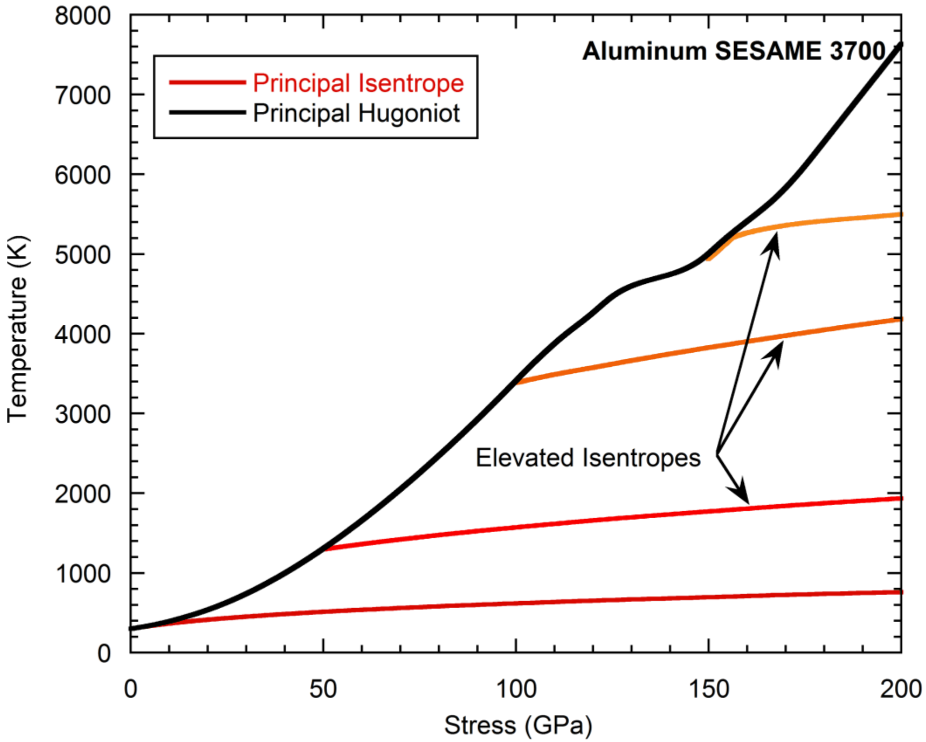
J.-P. Davis et al, J. Appl. Phys. ***116****, 204903 (2014)*

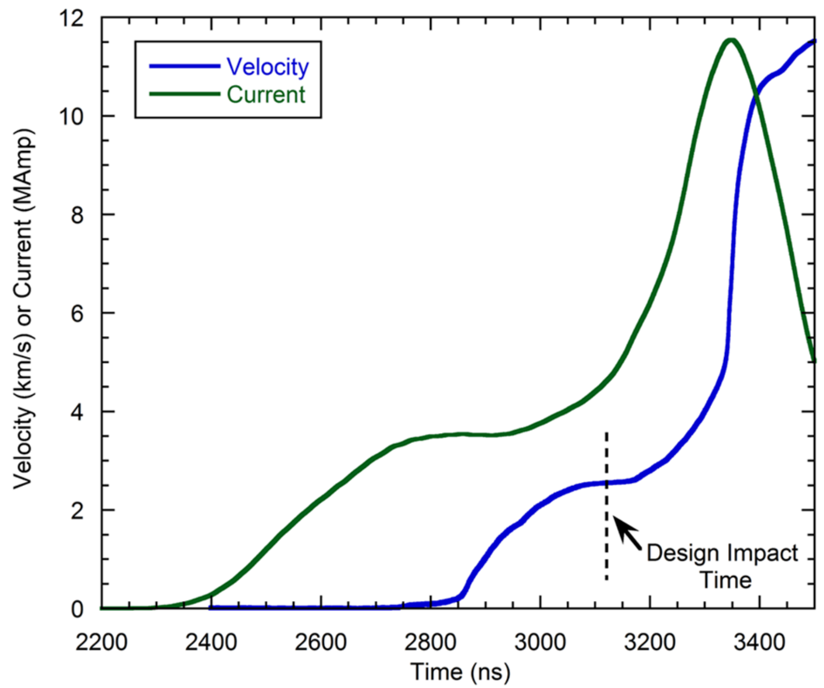
Quasi-isentrope of Al6061-T6 was measured to 240 GPa with 5% uncertainty



J-P. Davis, *J Appl Phys* **99**, 103512 (2006).

The Shock-Ramp technique probes between the principal Hugoniot and isentrope





Ramp compression from a Hugoniot state results in intermediate temperatures at high compression.

Flight gaps and pulseshape designed to enable impact at nearly constant velocity

This velocity plateau also generates a "hold" in the shock state

Liquid tin equation of state measured with the shock-ramp technique

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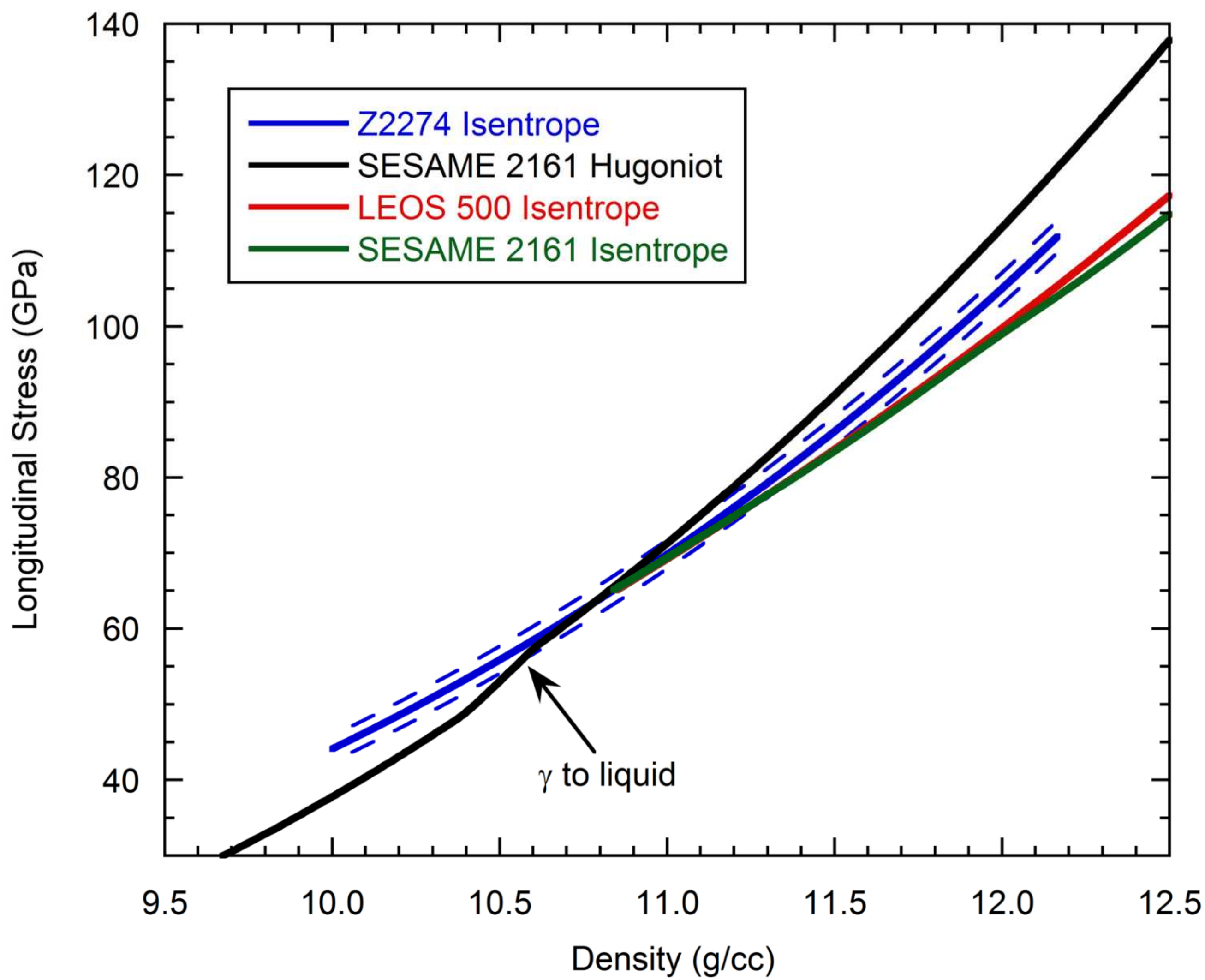
Liquid tin is stiffer than current EoS models



Seagle, et. al, Appl. Phys. Lett. 102, 244104 (2013)

Strength can be inferred from velocities in ramp-release experiments on Z using the self-consistent method

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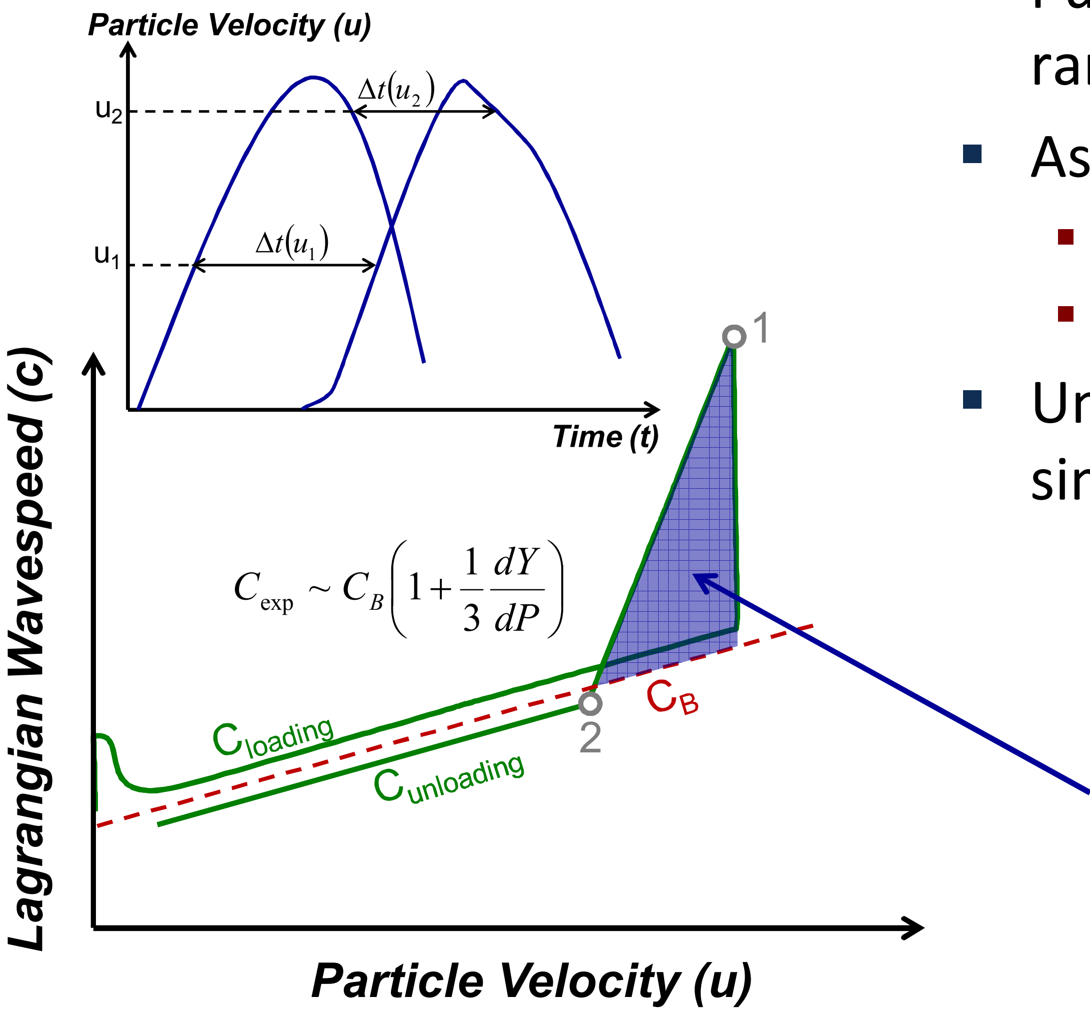


- Pulse shaping used to create ramp release loading
- Assumptions
  - Simple wave propagation
  - J2 plasticity (Von-Mises yield)
- Uniaxial strain results in simplified coupling:

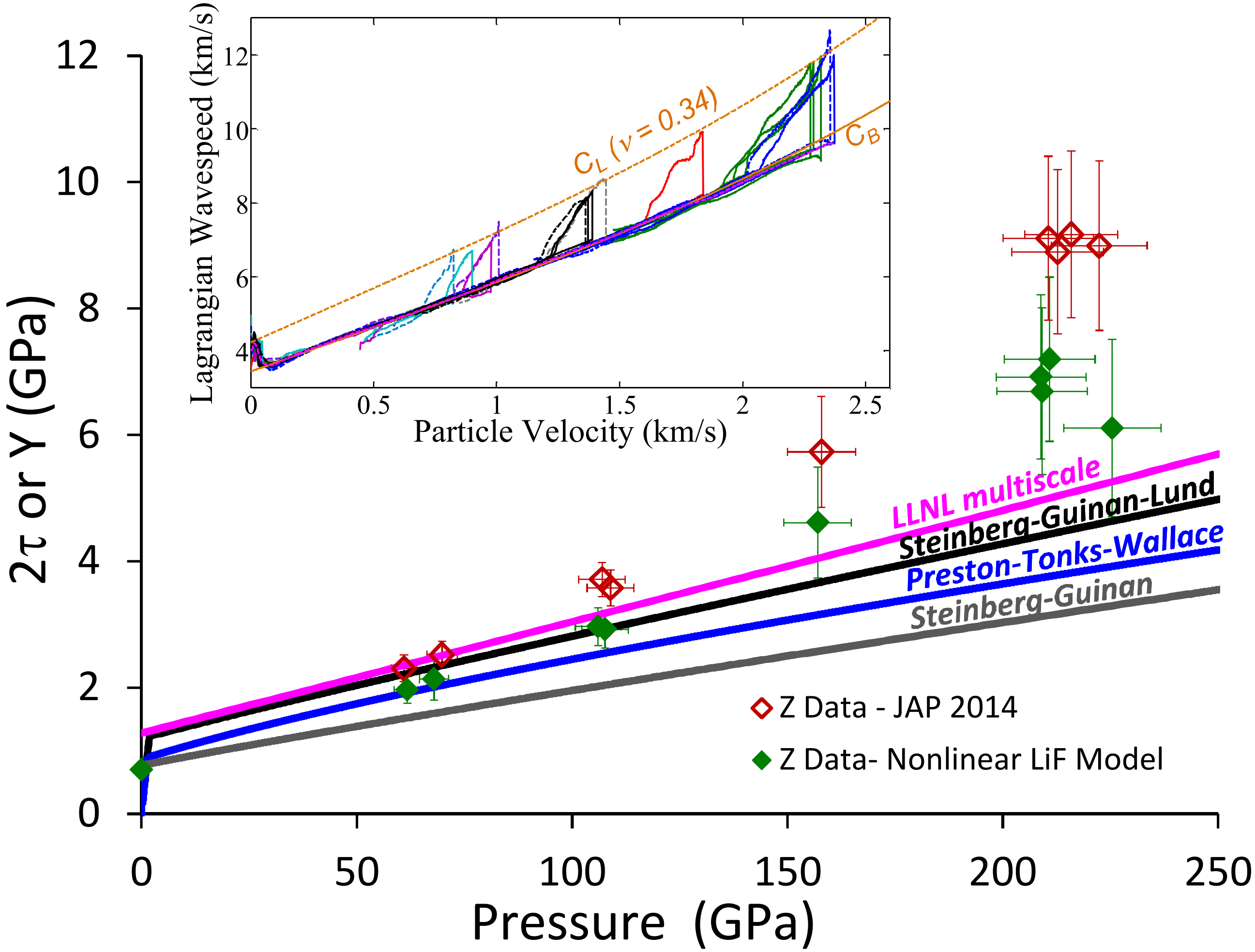
$$\sigma_x(\varepsilon) = P(\varepsilon) + \frac{4}{3}\tau(\varepsilon)$$

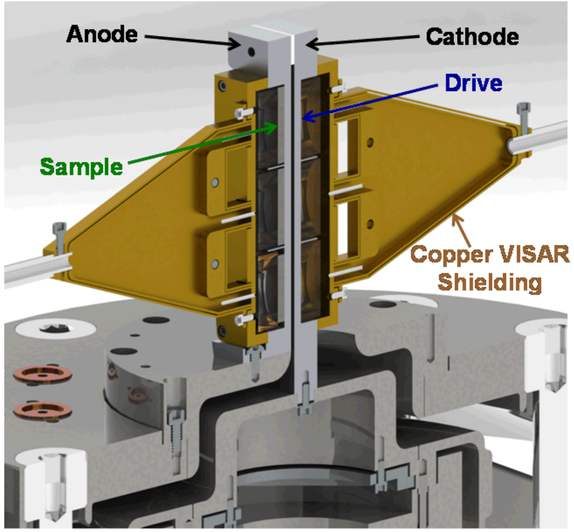
$$\frac{d\tau}{d\varepsilon} = \frac{3}{4}\rho_0\left[c_{exp}^2 - c_B^2\right]$$

$$\tau_2 - \tau_1 = \frac{3}{4}\rho_0\int_{u_1}^{u_2}\left[c_{exp}{}^2 - c_B^2\right]\frac{du}{c}$$

Brown, et. al, JAP 114, 223518 (2013); Asay and Chhabildas, 1981;

Z experiments on tantalum at strain rates of 10^5/s reveal higher than predicted shear stress near 200 GPa

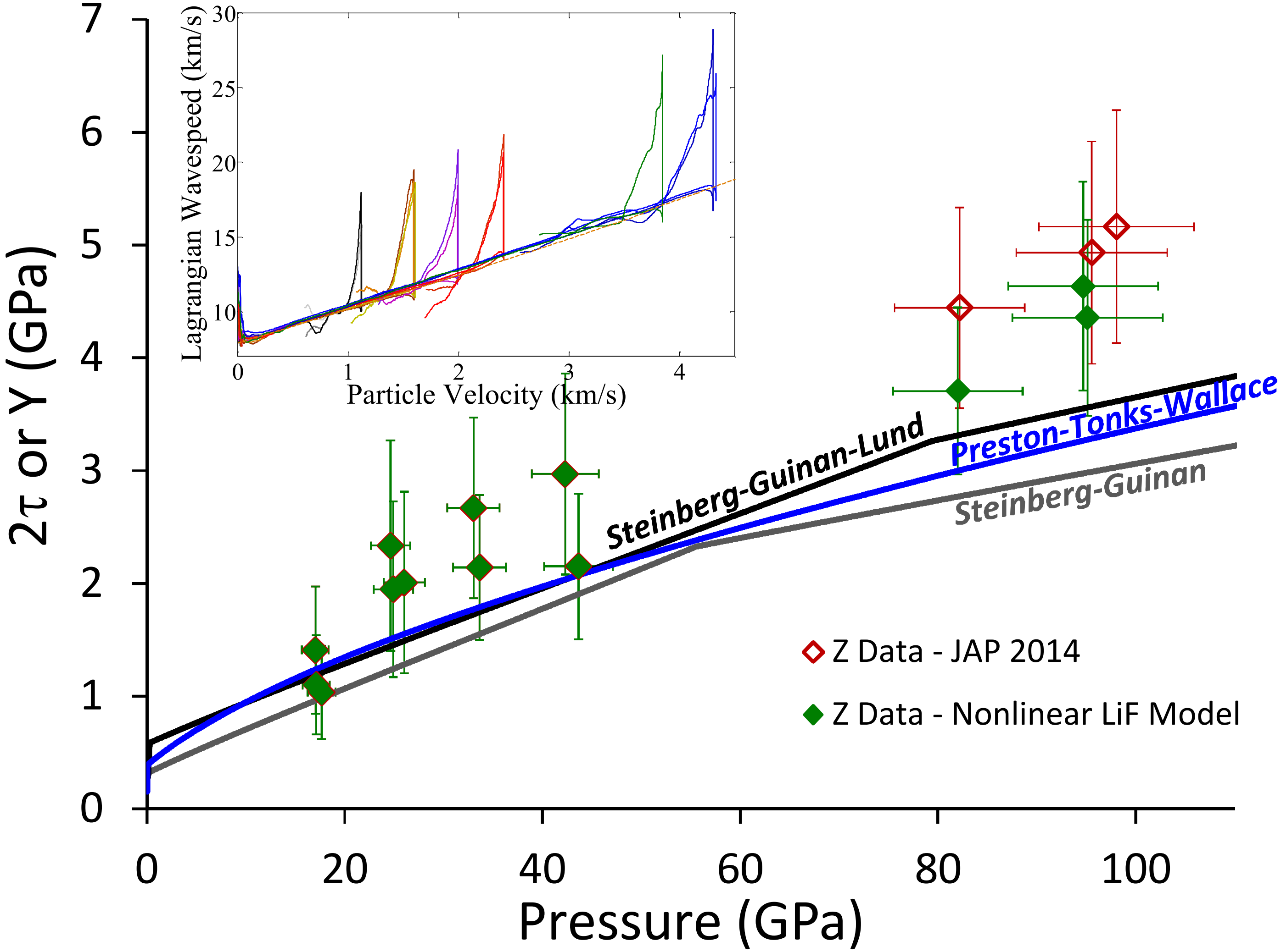




- LiF windows are used for both sample and drive measurements
  - It's important to correctly model its mechanical and optical properties

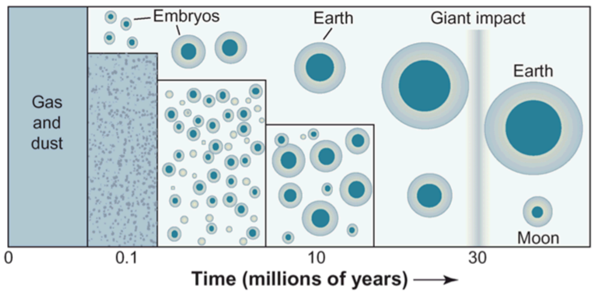
Brown et al., JAP 115, 043530, 2014

Z experiments on beryllium at strain rates of 10^5/s reveal higher than predicted shear stress near 100 GPa

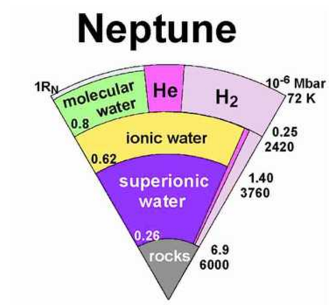


Brown et al., JAP 116, 033502, 2014

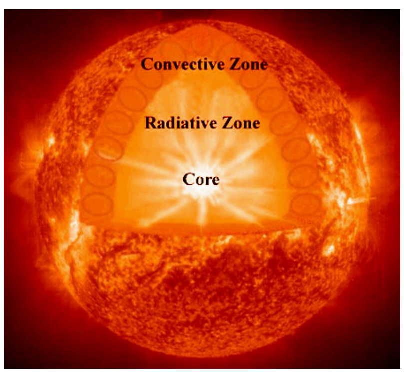
The Z Fundamental Science Program has created strategic partnership with leading institutions



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

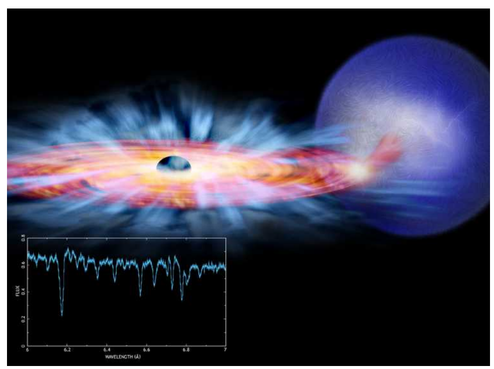


Photo-ionized plasmas
Range of ionization param. ξ

- Resources/shots on Z since 2010
  - 40 dedicated ZFS + 40 ride-along shots
- Science with significant impact
  - Bailey et al, Nature (2015)
  - Kraus et al, Nature Geoscience (2015)
  - 1 PRL, 3 PoP, 1 PRA, 1 PRB
  - 8 other peer-reviewed publications
- Popular outreach
  - National Public Radio, "All things considered", Joe Palca 3/6/2014
  - MIT Technology review, 10/4/2012
  - Discover Magazine, 9/16/2012
- Students and postdocs
  - 4 M.Sc. Exam, 2 Ph.D. exams
  - 5 postdocs
- Z and Sandia is a part of the international HED community

Pulse Power enables unique dynamic material science investigations

- Pulsed Power is a very effective driver for HED dynamic materials experiment
- The Z facility supports tailored delivery of very high currents
- A combination of load designs and pulse shaping enables experiments which reach many interesting regions of material phase space
- Precise, high pressure measurements are producing new insights in how materials behave under extreme conditions