Overview and progress of materials experiments using the NIF ramp compression platform

HEDS Seminar Series

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Lawrence Livermore National Laboratory

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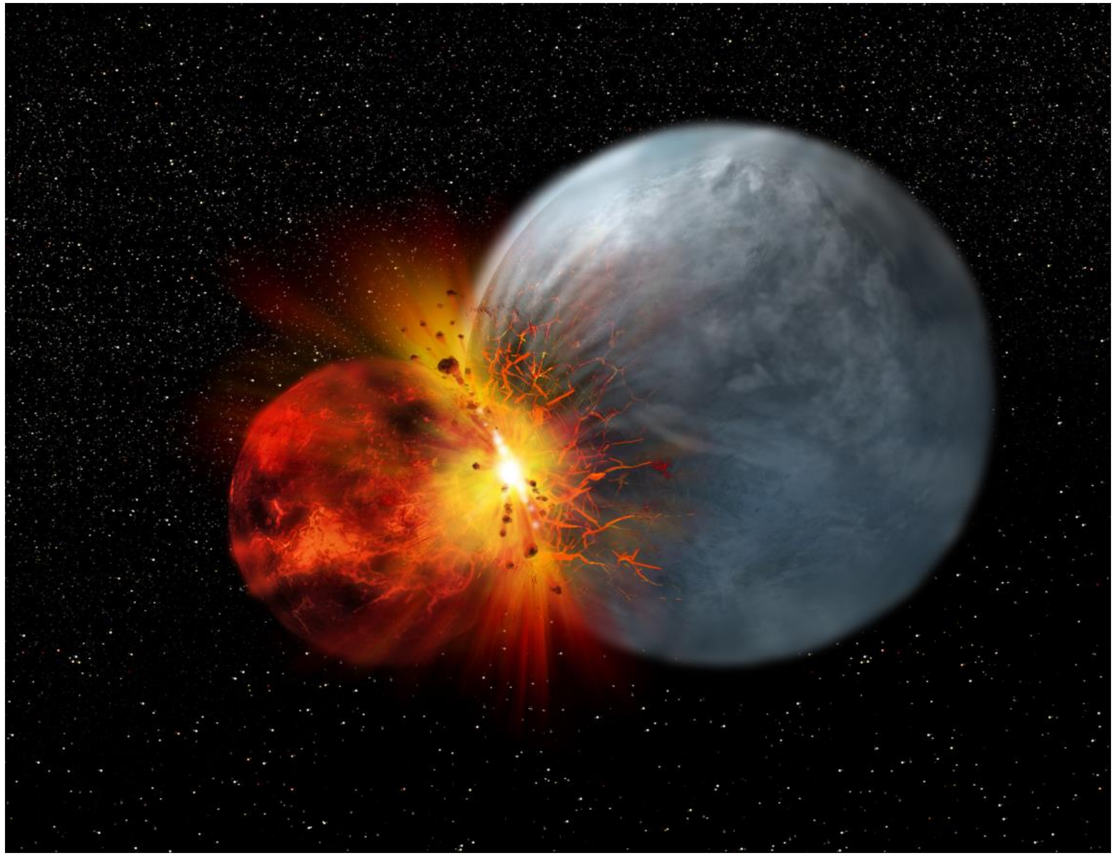
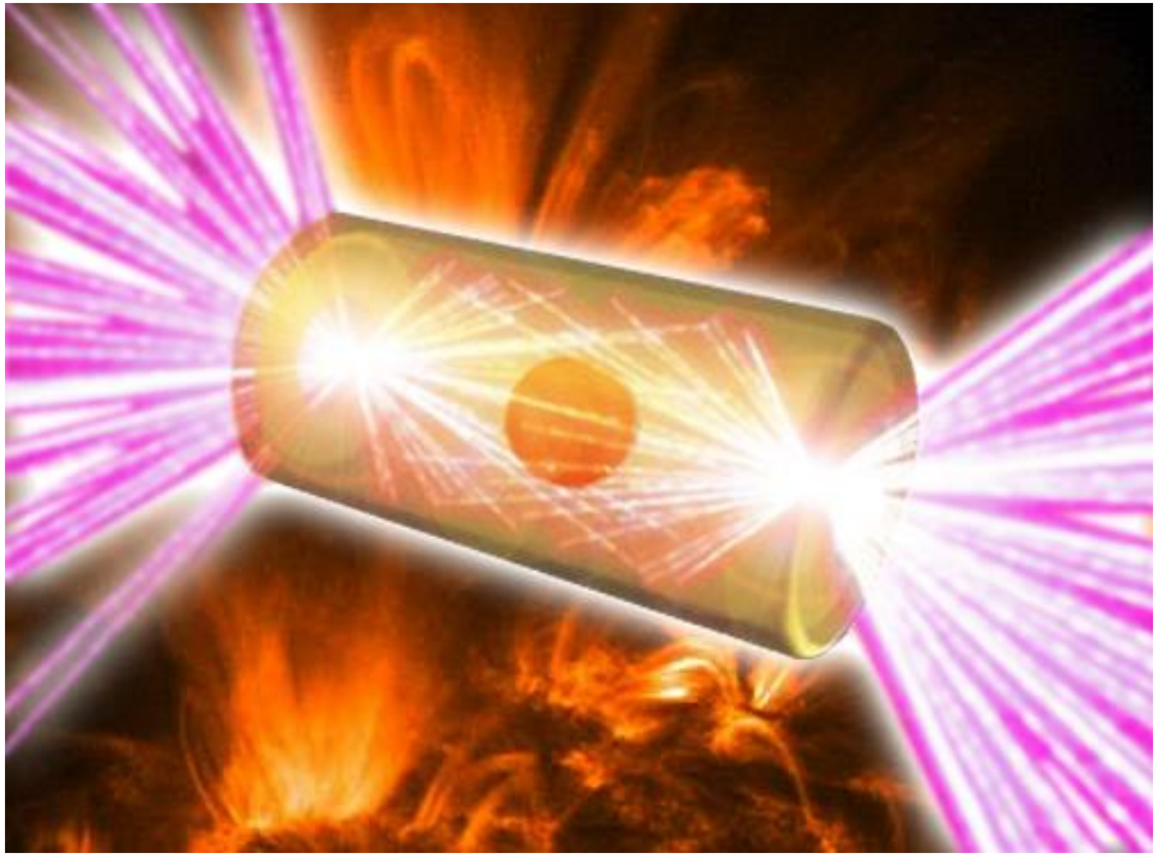
Sandia National Laboratories

Chris Seagle, Justin Brown, Jean-Paul Davis

Understanding the dynamics of planetary formation, giant impacts, and inertial confinement fusion implosions involves hydrocode simulations





Accurate equation of state models underpin the validity of all hydrocode predictions

An equation of state describes the thermodynamic relationship between temperature, density (or volume), and energy (or pressure) for a material

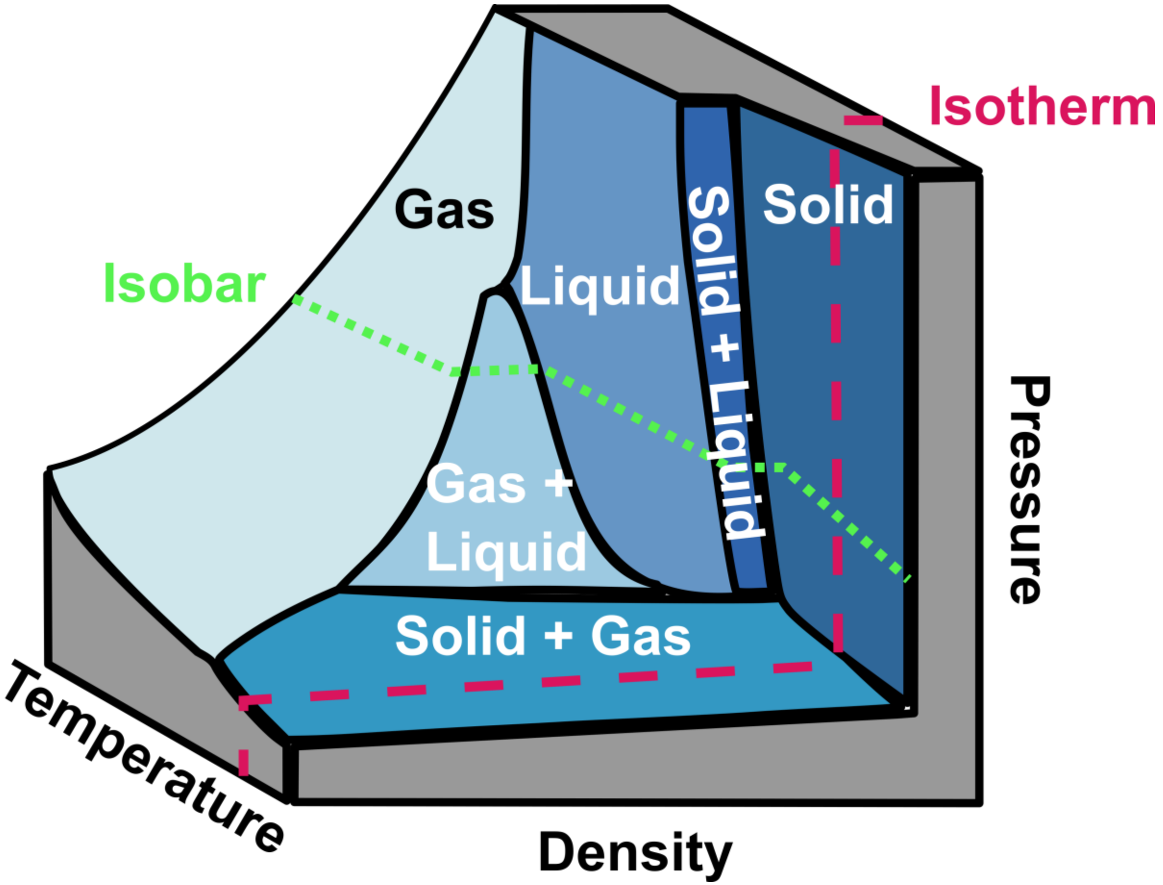


Figure based on a similar map from Hyperphysics

We have several tools available to constrain an EOS surface at specific points at elevated pressure, temperature, or density

Experimental:

- Static compression
  - Isotherms
- Dynamic compression
  - Isentropes
  - Hugoniots

Theory:

- Density Functional Theory, Quantum Monte Carlo, Molecular Dynamics, etc
- Limits (ideal gas, Fermi limit, etc)

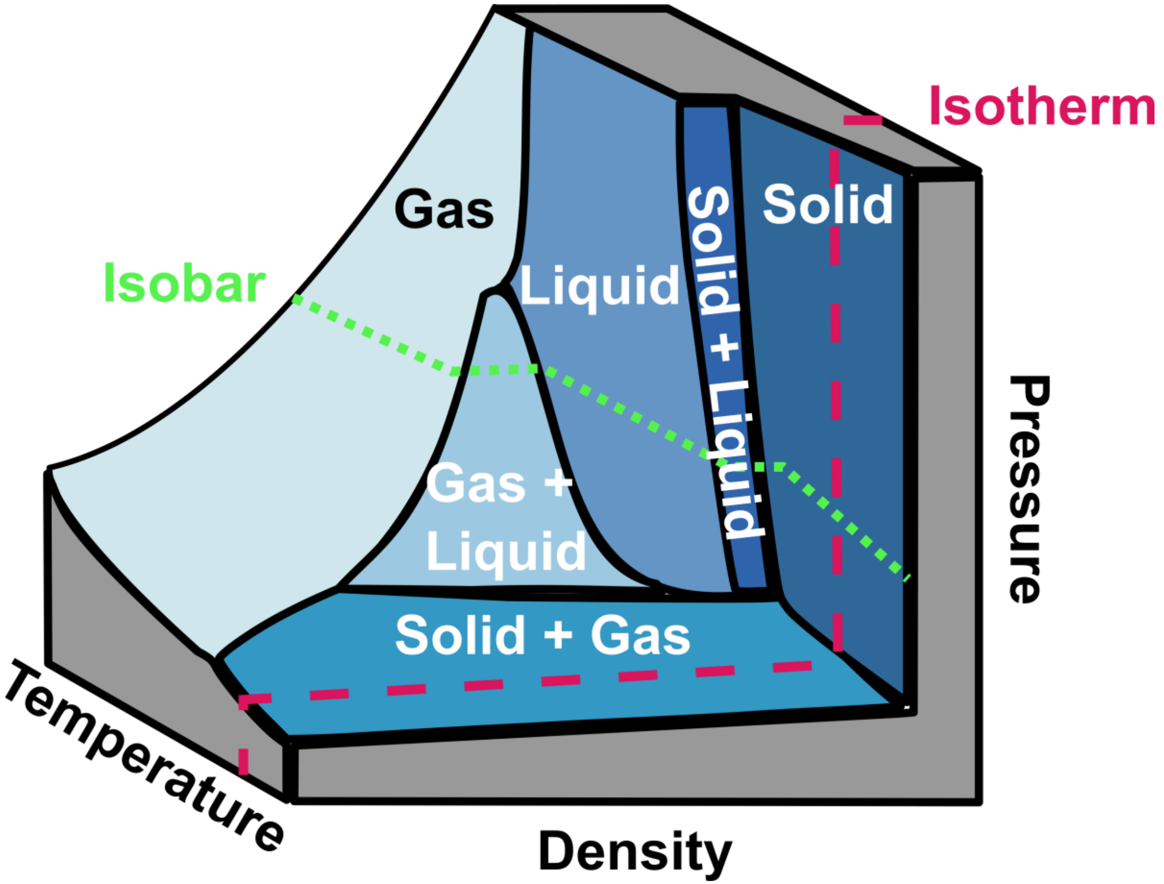
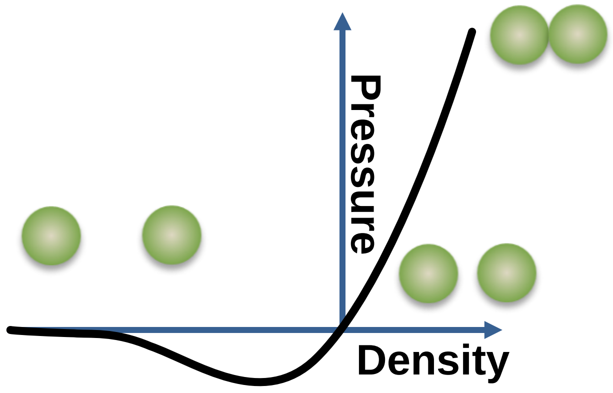


Figure based on a similar map from Hyperphysics

Equations of state are frequently constructed by separating the free energy contributions into distinct sources

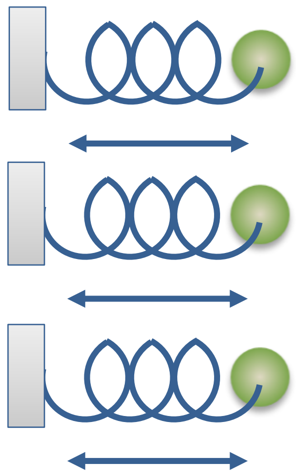
Free energy is frequently partitioned into three sources:

Cold Curve



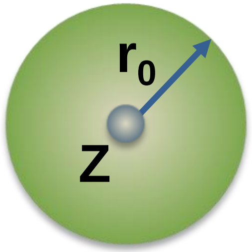
Electronic forces binding the atoms together at 0 K

Ion Thermal



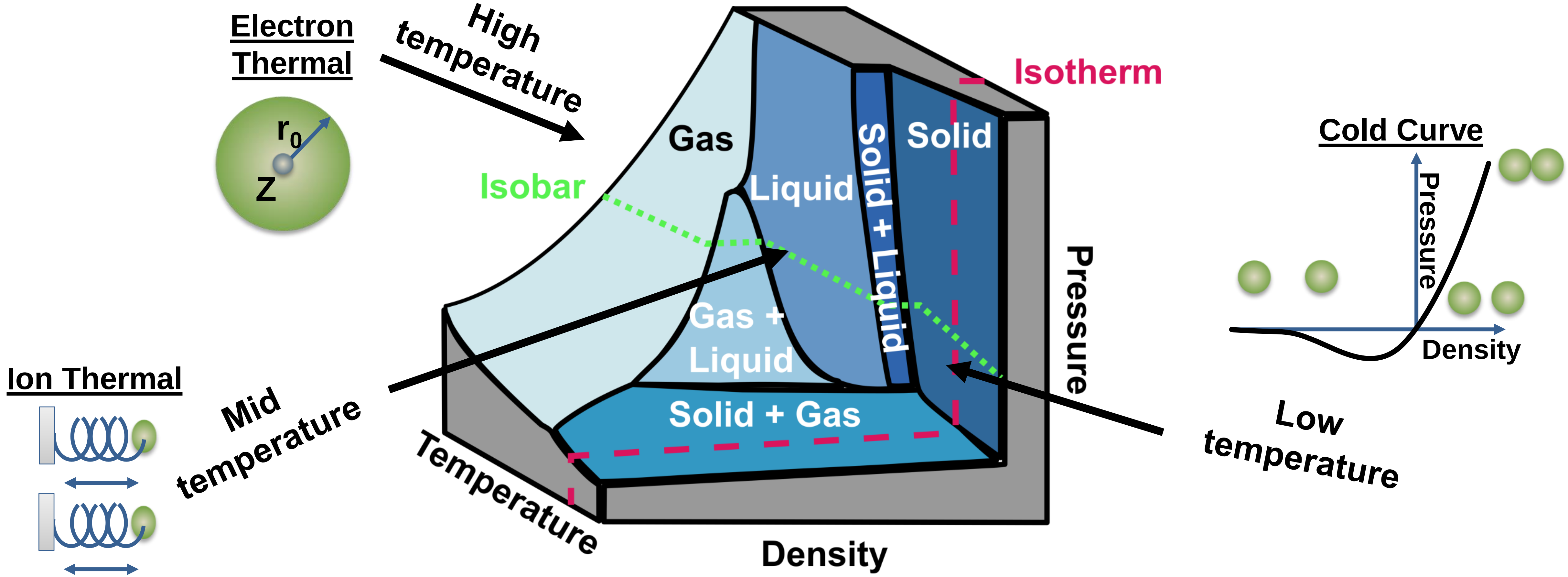
Vibrational excitation of the nuclei

Electron Thermal



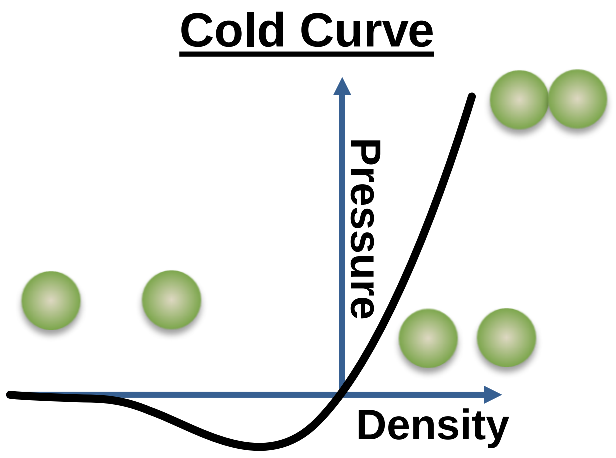
Thermal excitation of the electrons

The dominant free energy source varies across the equation of state



Each source has associated physics-based models and is constrained by different measurements

Constraining the cold curve is vital for building accurate equations of state



Electronic forces binding the atoms together at 0 K

Ramp compression experiments <u>absolute measurements</u> of stress-density that are:

- **within a few percent of the isentrope**
- **readily reduced to either an isentrope (or an isotherm) using established techniques**

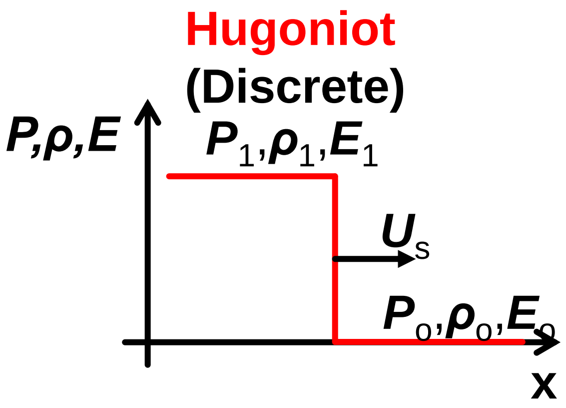
For absolute EOS measurements, shock and ramp compression are the canonical classes of dynamic loading experiments

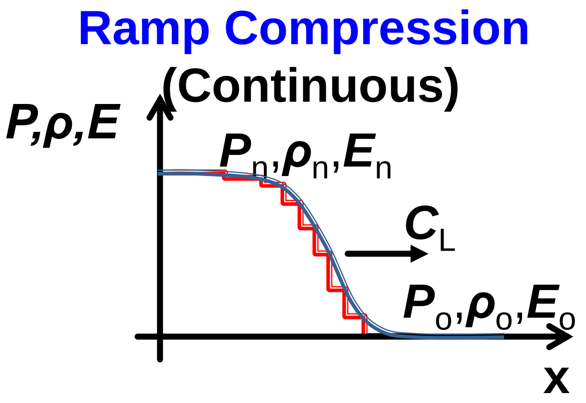
$$P = \rho_0 U_s u_p$$

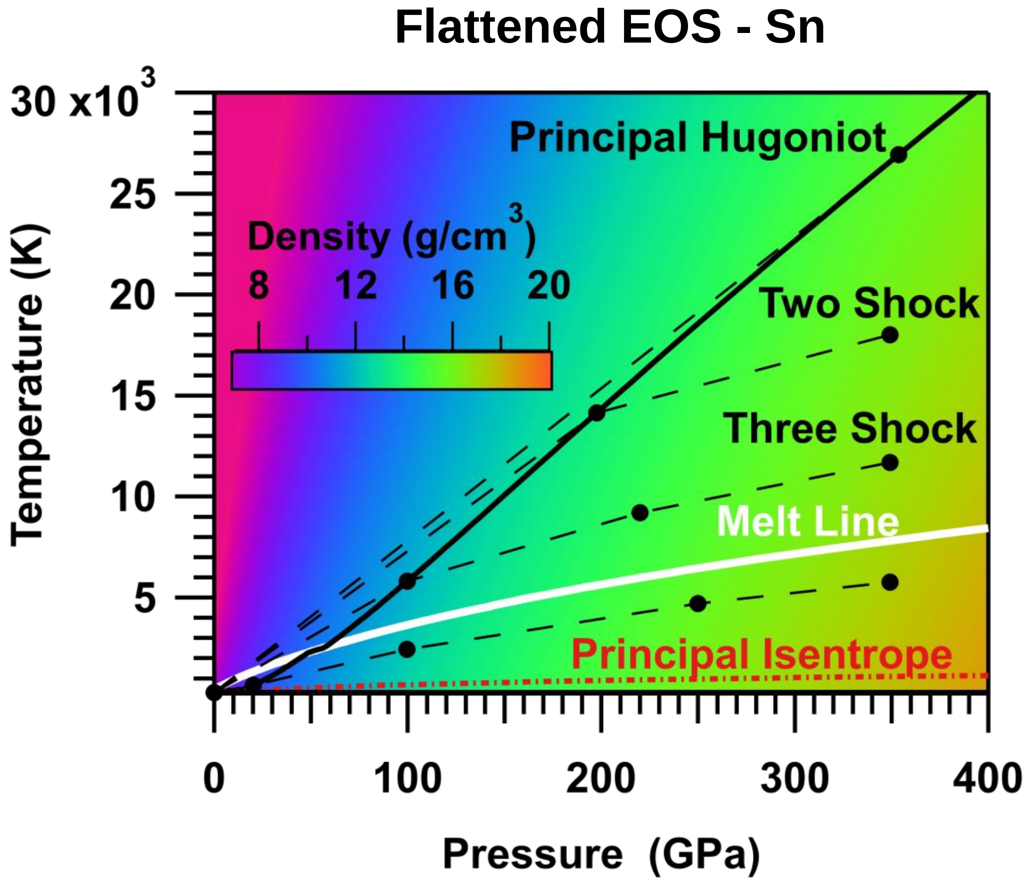
$$\rho = \frac{\rho_0}{1 - \frac{u_p}{U_s}}$$

$$P = \rho_0 \int C_L du_p$$

$$\rho = \frac{\rho_0}{1 - \int \frac{du_p}{C_L}}$$







Ramp compression experiments require smooth pressure loading (careful control over the applied loading rate)

The absolute measurements are done using multi-step targets, measuring velocities at multiple thicknesses

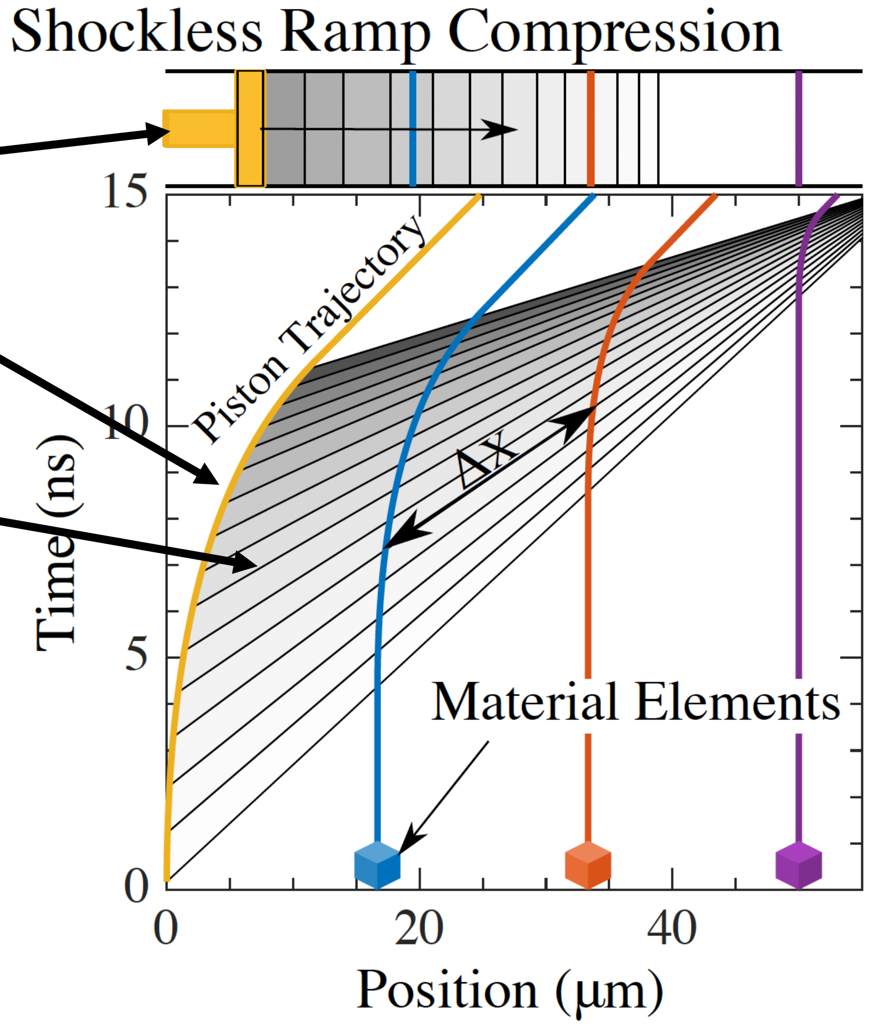
Piston launches compression waves into a material

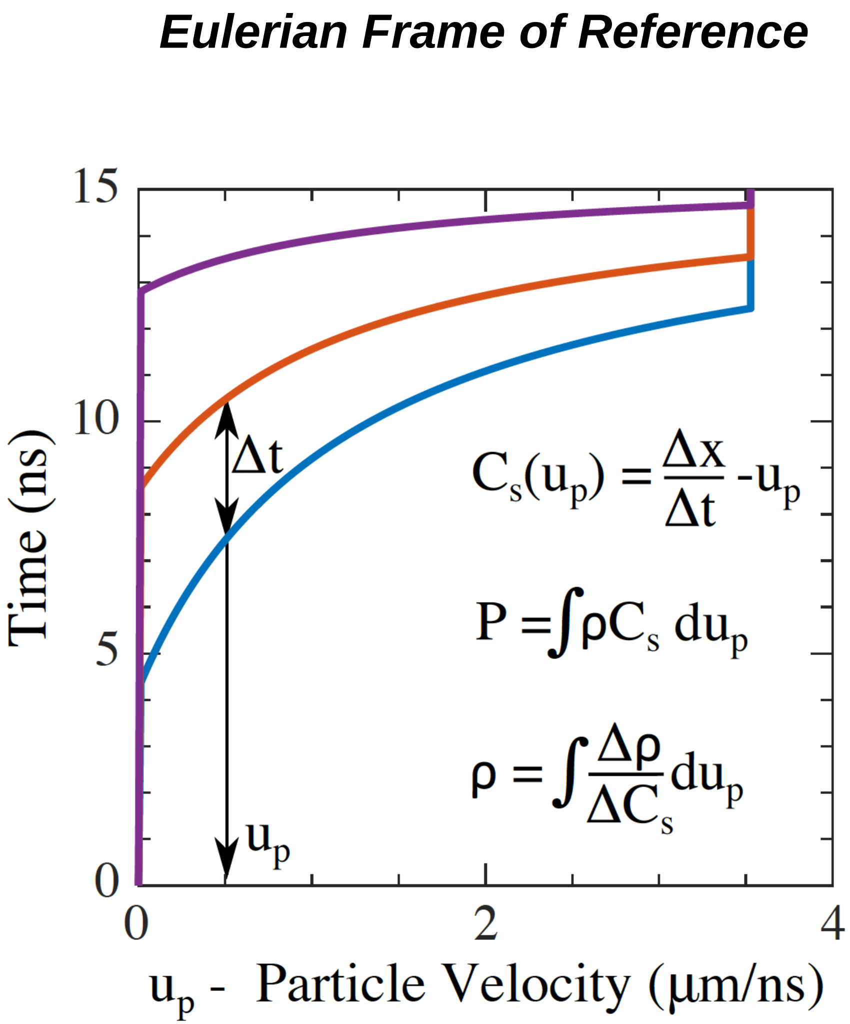
These are the characteristics with slope:

$$\frac{dx}{dt} = u \pm C_s$$

Along each line the following is conserved:

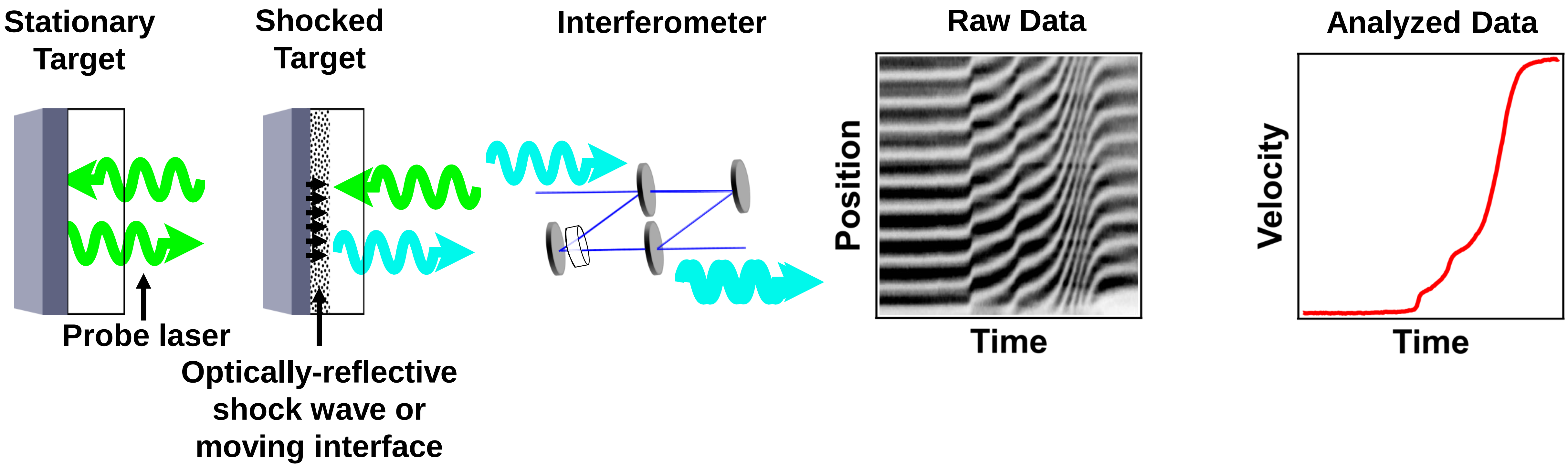
$$du + \frac{1}{\rho C_s} dP = 0$$





A quick digression: Introduction to the Velocity Interferometry System for Any Reflector (VISAR)

Measure phase shift due to Doppler effect vs. time using interferometer
Often implemented with one spatial dimension and one temporal



For more: Barker et al., *JAP* 1972; Celliers et al., *RSI* 2004; D. Dolan's 'Foundations of VISAR analysis' from 2006

Laser-driven ramp compression began with a mix of reservoir unloading (shown here) and direct drive experiments

Laser-Driven Plasma Loader for Shockless Compression and Acceleration of Samples in the Solid State

J. Edwards, K.T. Lorenz, B. A. Remington, S. Pollaine, J. Colvin, D. Braun, B. F. Lasinski, D. Reisman, J. M. McNaney, J. A. Greenough, R. Wallace, H. Louis, and D. Kalantar

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, USA

(Received 11 April 2003; published 18 February 2004)

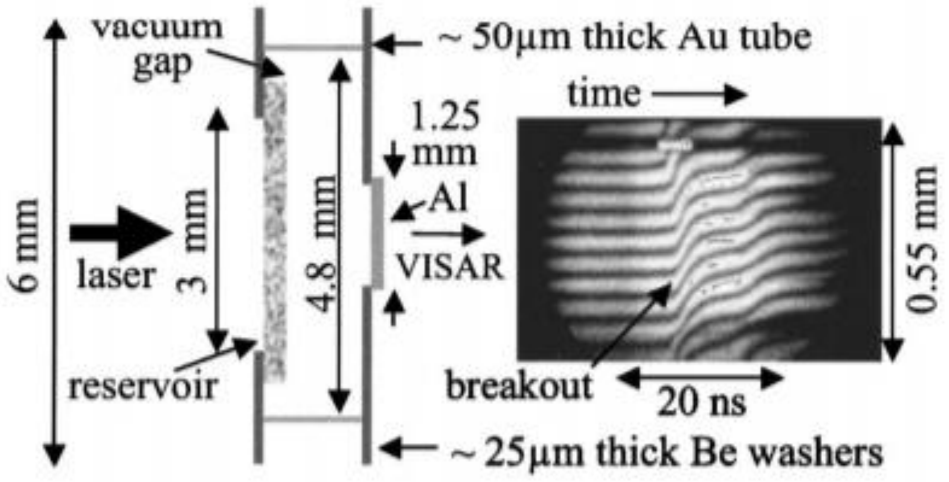
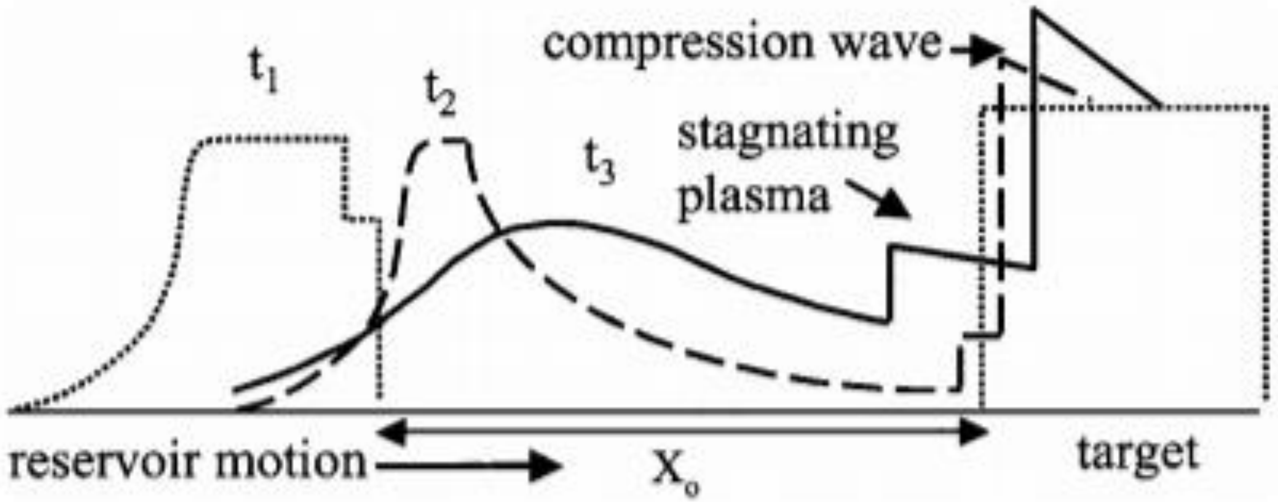


FIG. 2. Schematic of the target, and a typical VISAR record reflected from the rear of a 29.4 μm Al foil (Table I, B). Fringe motion indicates acceleration of the surface (1.65 km/s/fringe). Targets were axisymmetric about the laser axis.



Laser-driven ramp compression began with a mix of reservoir unloading and direct drive experiments (shown here)

PHYSICAL REVIEW E **71**, 066401 (2005)

Quasi-isentropic compression by ablative laser loading: Response of materials to dynamic loading on nanosecond time scales

Damian C. Swift and Randall P. Johnson
Physics Division, Los Alamos National Laboratory, MS E526, Los Alamos, New Mexico 87545, USA
(Received 13 October 2004; revised manuscript received 18 March 2005; published 3 June 2005)

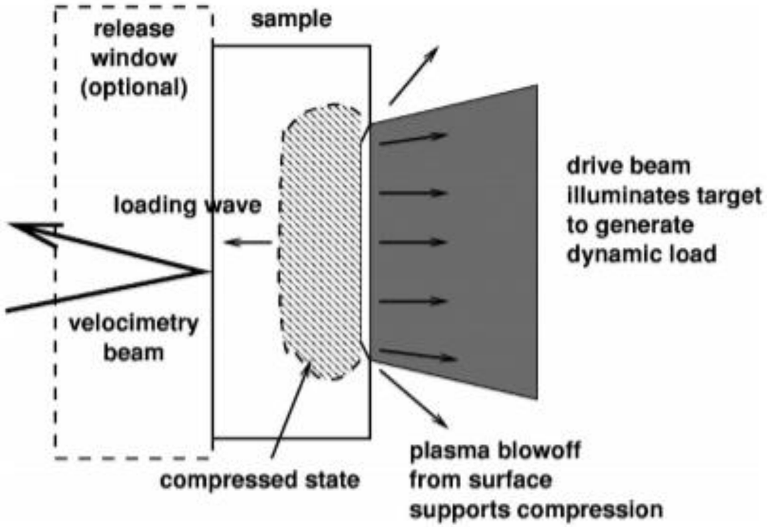


FIG. 1. Schematic of direct drive laser loading experiment (horizontal size exaggerated).

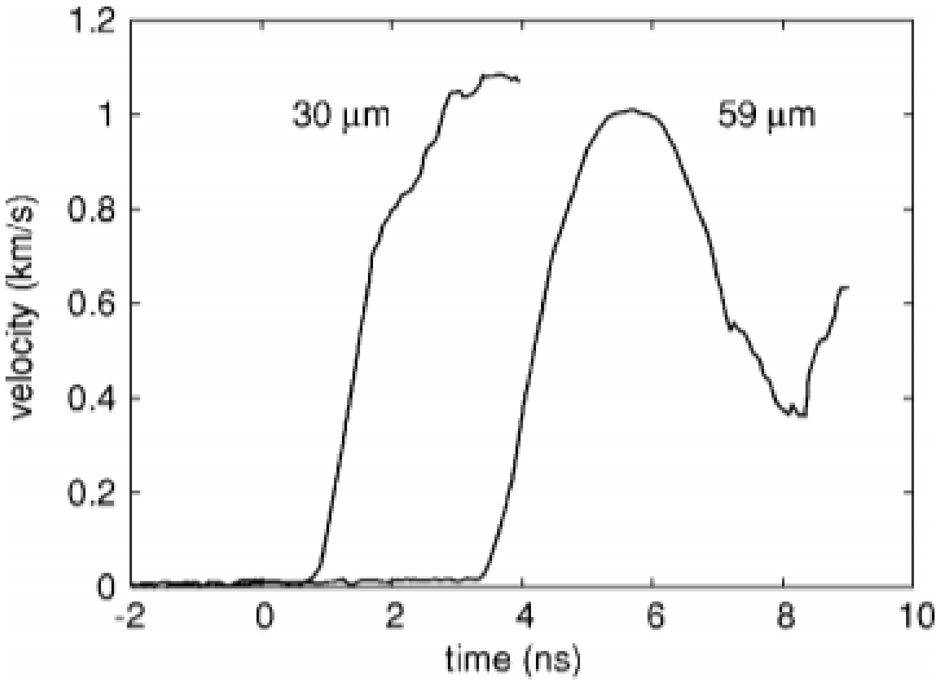


FIG. 6. Example surface velocity history for quasi-isentropic compression in Si (100) samples of two different thicknesses (TRIDENT shot 15 020). Lumpy structures near the peak velocity in the thin sample may be caused by noise in the VISAR record.

I think the first laser-driven EOS measurement was Ray Smith's 2007 Al paper, done on the Omega-60 laser facility

PRL **98,** 065701 (2007) PHYSICAL REVIEW LETTERS week ending 9 FEBRUARY 2007

Stiff Response of Aluminum under Ultrafast Shockless Compression to 110 GPA

Raymond F. Smith,[1] Jon H. Eggert,[1] Alan Jankowski,[1] Peter M. Celliers,[1] M. John Edwards,[1] Yogendra M. Gupta,[2] James R. Asay,[2] and Gilbert W. Collins[1]

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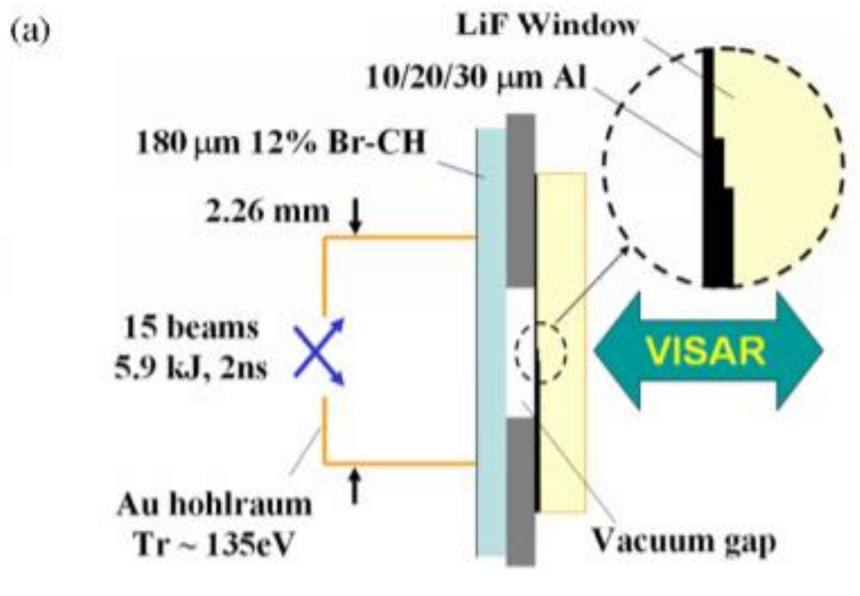
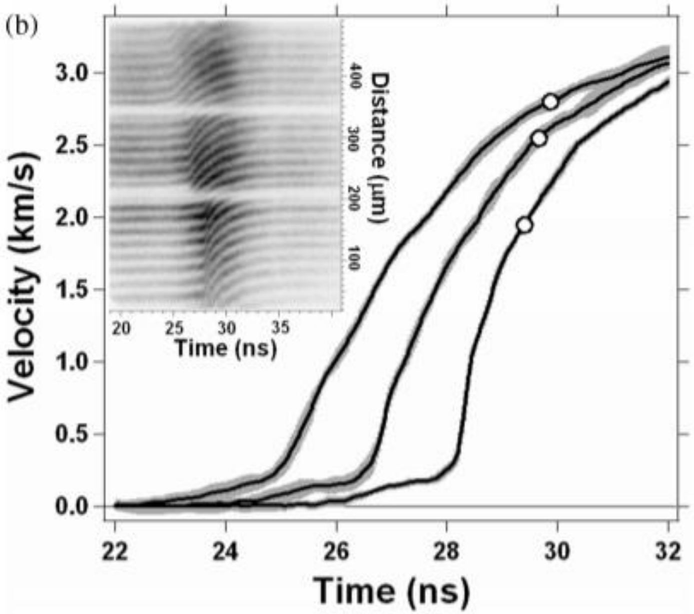
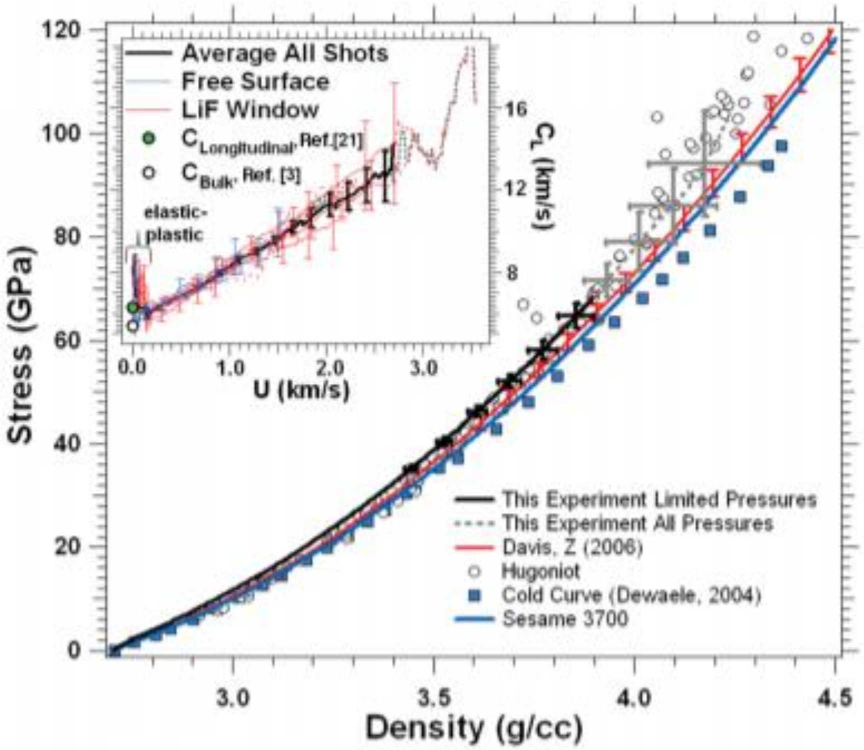
(Received 6 September 2006; published 6 February 2007)







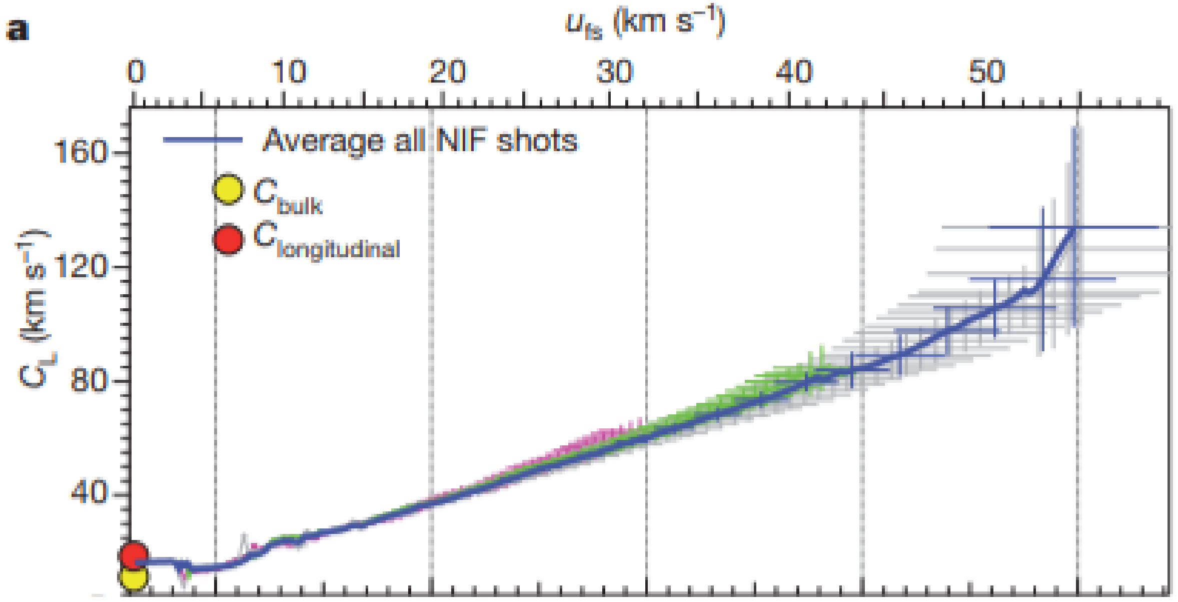
Development of ramp compression on NIF started about ten years ago, with a series of shots on diamond

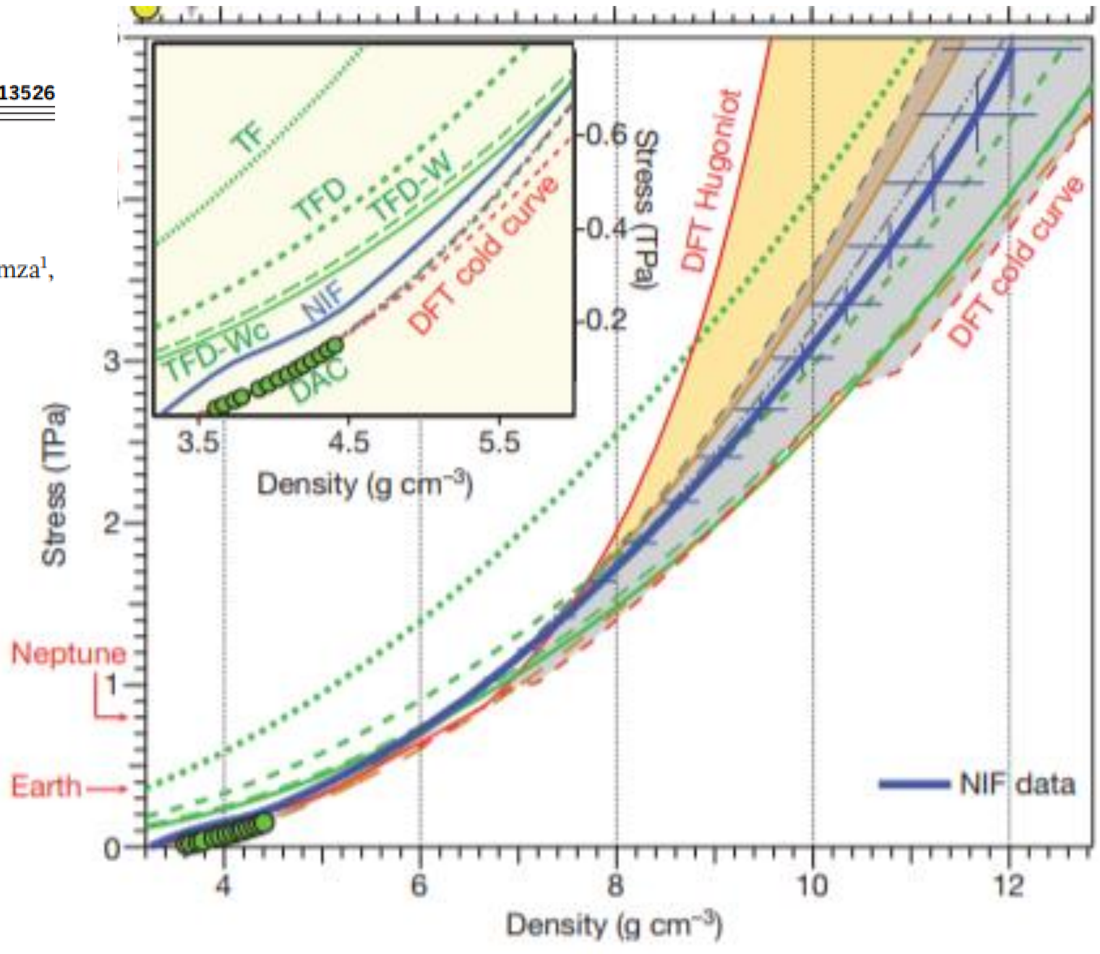

LETTER

doi:10.1038/nature13526

Ramp compression of diamond to five terapascals

R. F. Smith[1], J. H. Eggert[1], R. Jeanloz[2], T. S. Duffy[3], D. G. Braun[1], J. R. Patterson[1], R. E. Rudd[1], J. Biener[1], A. E. Lazicki[1], A. V. Hamza[1], J. Wang[2], T. Braun[1], L. X. Benedict[1], P. M. Celliers[1] & G. W. Collins[1]

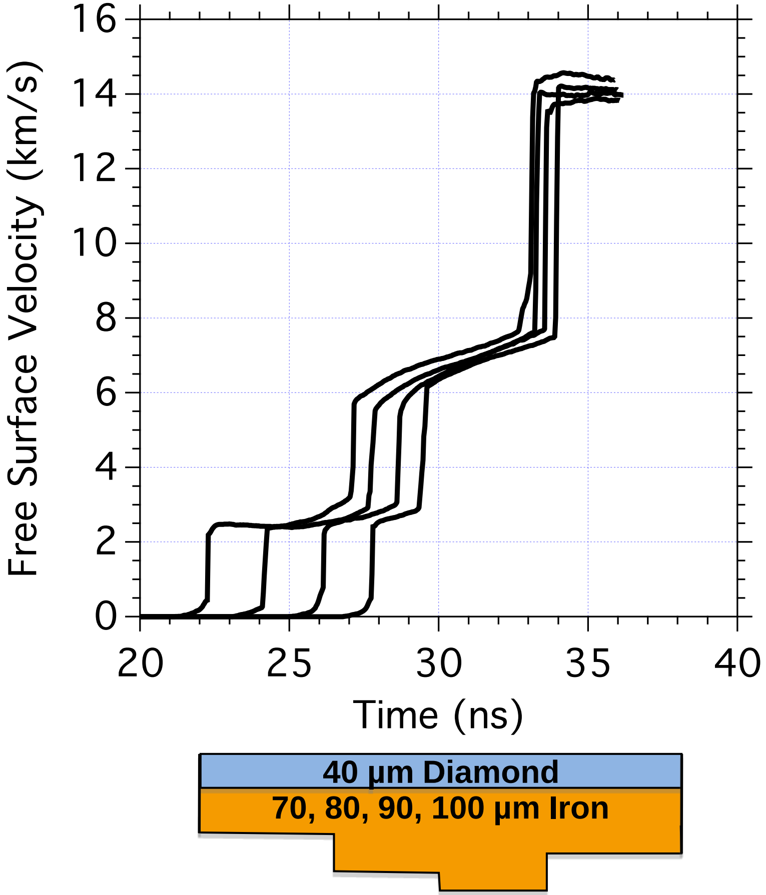




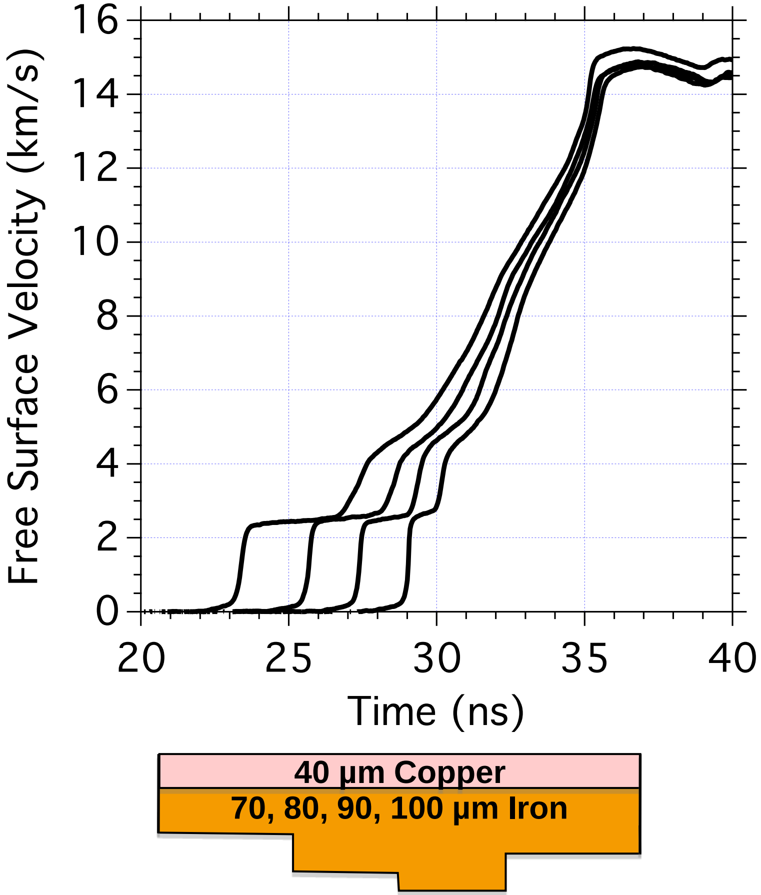
The programmatic goals for the platform involved more metal EOS measurements, and the HDC ablator didn't work as well

- Diamond strength is very difficult to model, particularly well enough to consistently avoid intermediate shock formation
- The switch from HDC to Cu ablators (c. 2015) significantly improved the quality of the ramp
- (This is also roughly when I joined, late 2015)

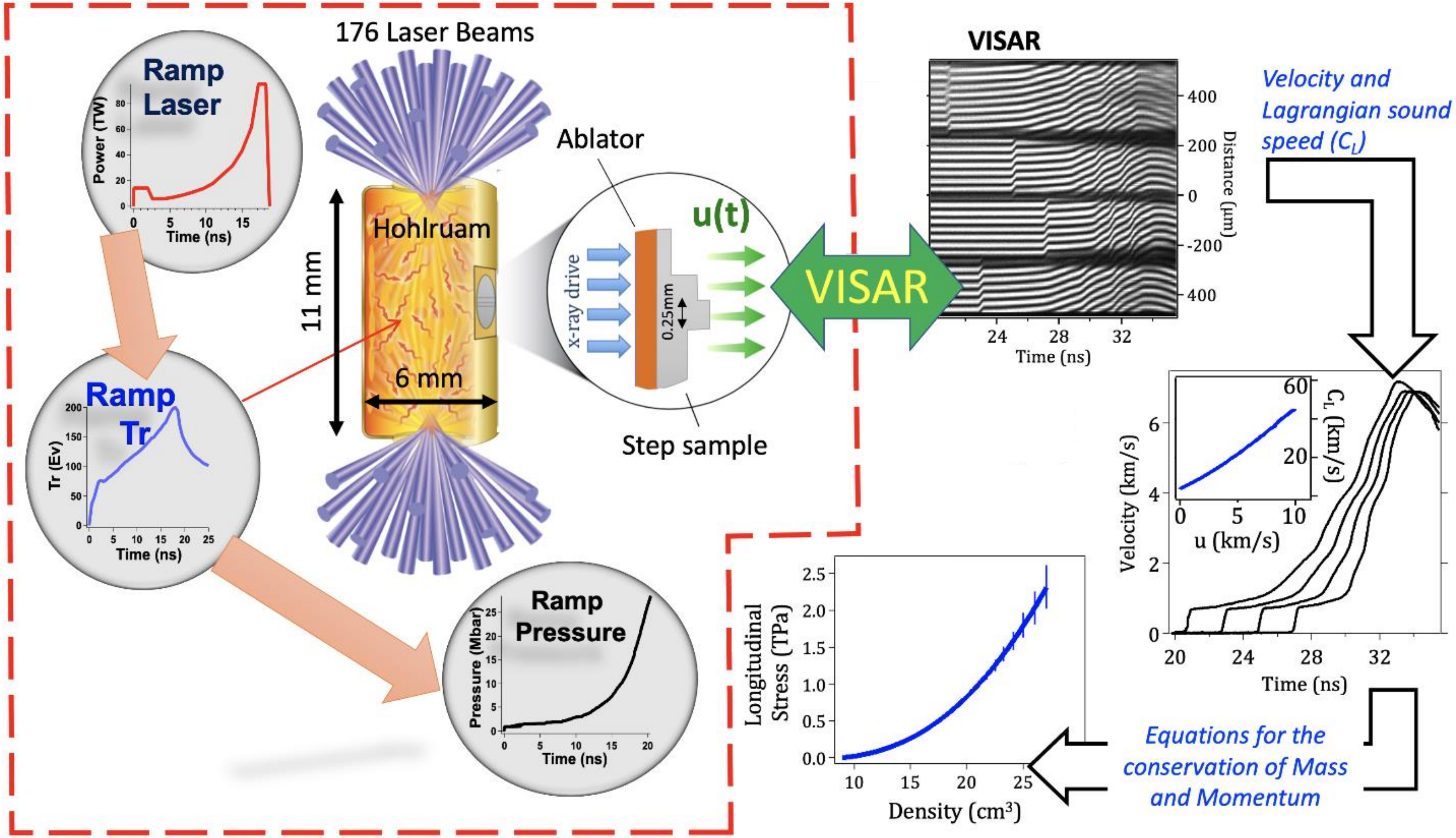
HDC Ablator



Copper Ablator

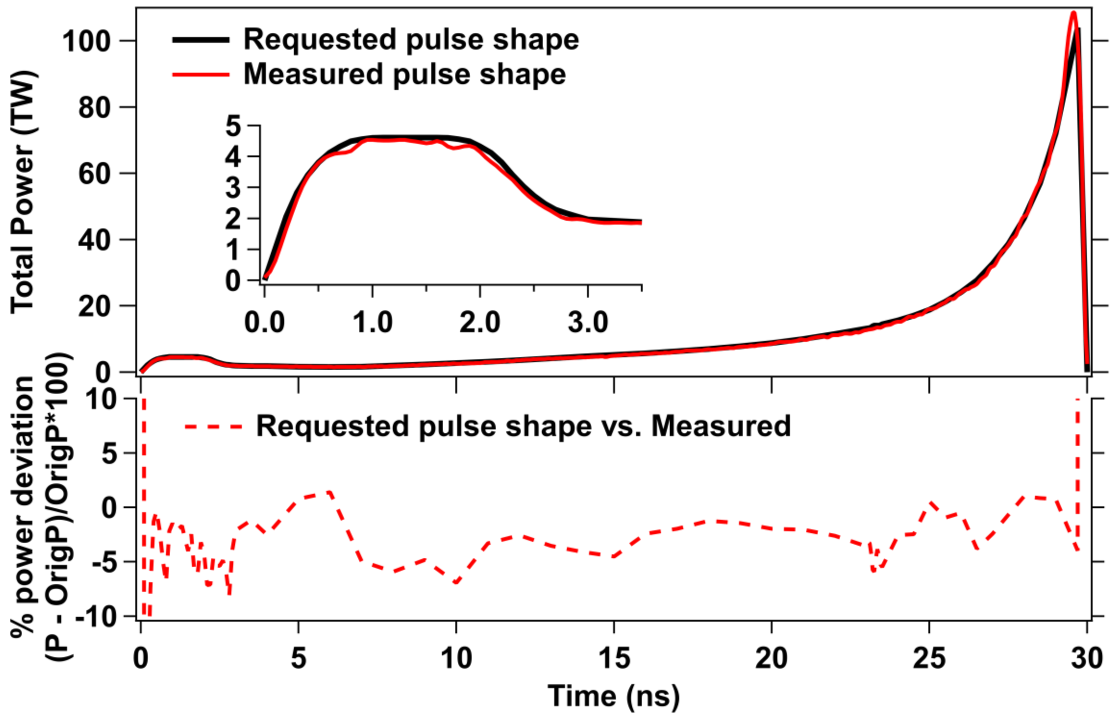


Incorporating lessons learned from early ramp campaigns and facility/diagnostic improvements, this is the current platform



The pulse shape control, high energy, and state of the art diagnostics make NIF the premier facility for ramp compression measurements

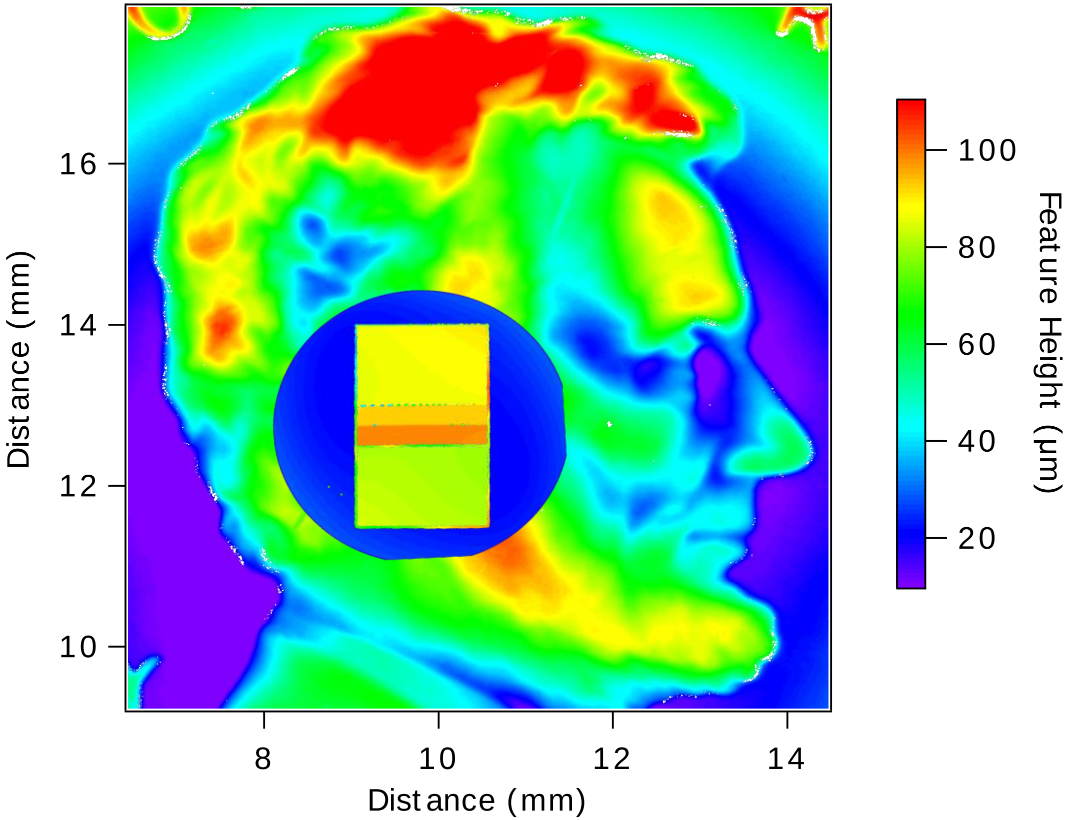
Comparison of Laser Request vs. Delivered

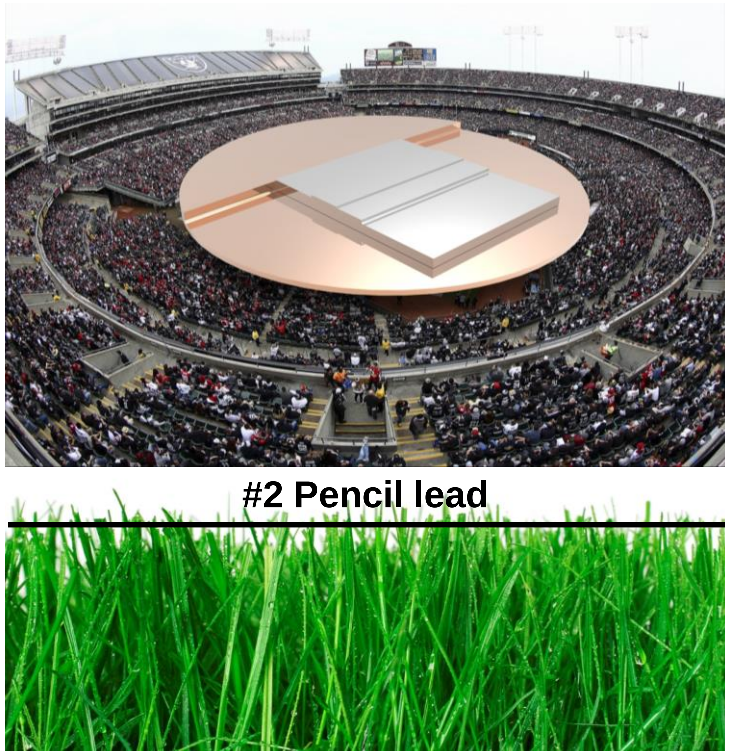


State of the art line VISAR Diagnostic

We routinely compress materials to pressures greater than 1000 GPa on the NIF

The physics uncertainty requirements demands target samples of extreme precision

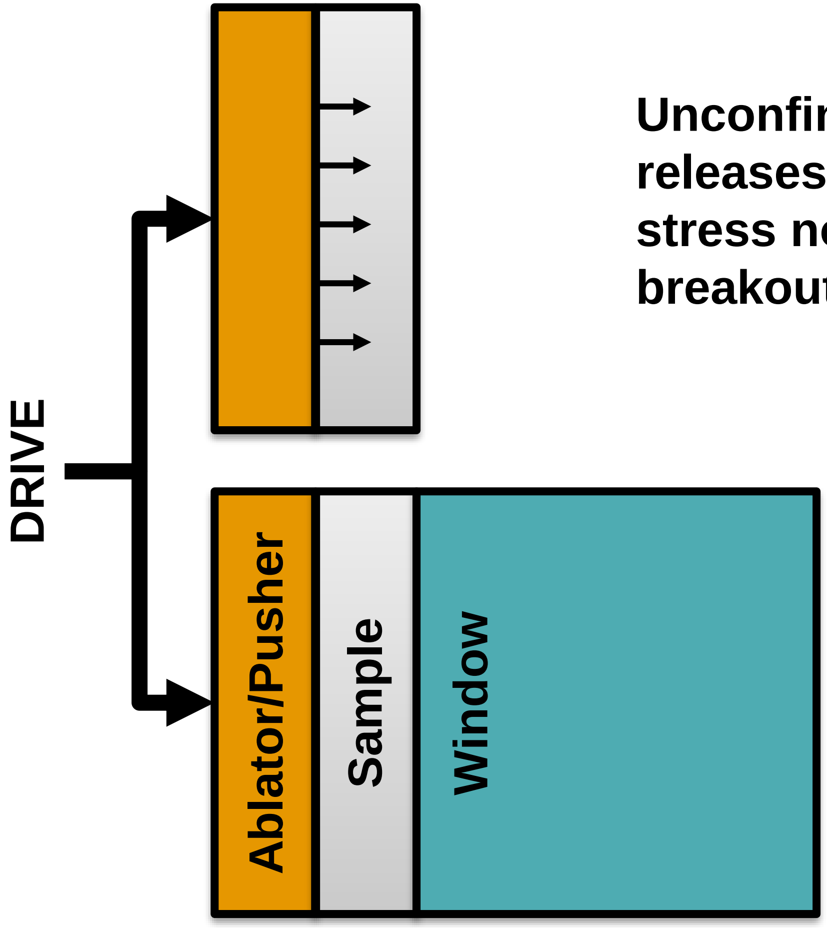




To reduce uncertainties our samples are precision diamond turned to < 50 nm RMS. Comparable to trimming the grass of a football field to the width of a #2 pencil lead.

As a brief example of the analysis process, I’m going to focus on lithium fluoride

- Lithium fluoride is used extensively as a window in dynamic compression experiments
- Tamping a sample surface with a window confines the material when the compression wave propagates, maintaining the stress
- LiF remains transparent in the visible at high pressures (>900 GPa on isentrope, ~<200 GPa on shock) making it highly useful as a window



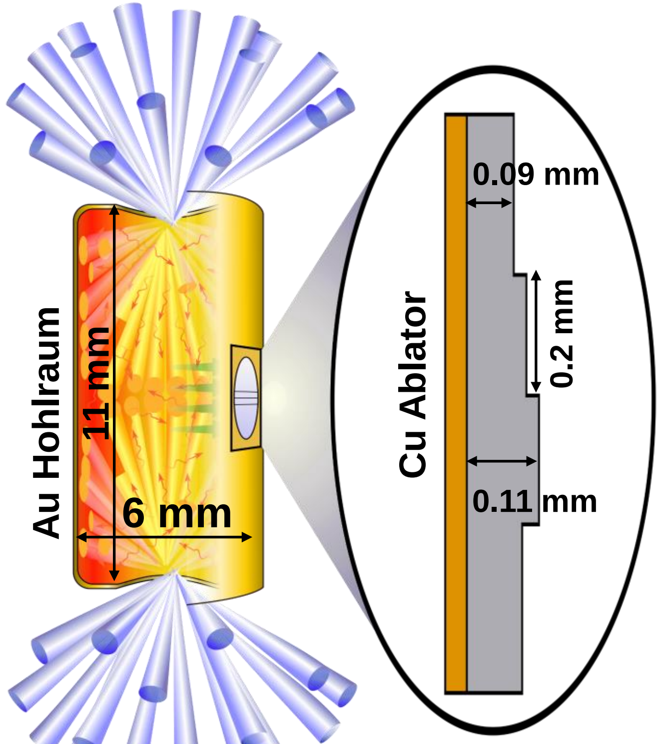
Unconfined: Sample releases into vacuum, stress not maintained after breakout

Confined: Compression transmits to window, stress is maintained in sample

A high-precision EOS for LiF is required to analyze these experiments

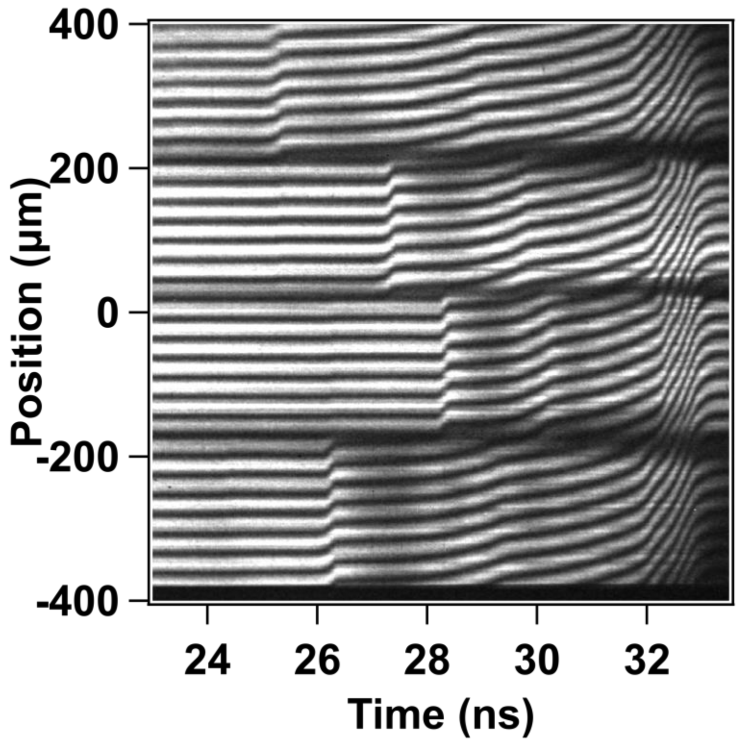
We determine velocity for each step using VISAR (Velocity Interferometry System for Any Reflector)

Target

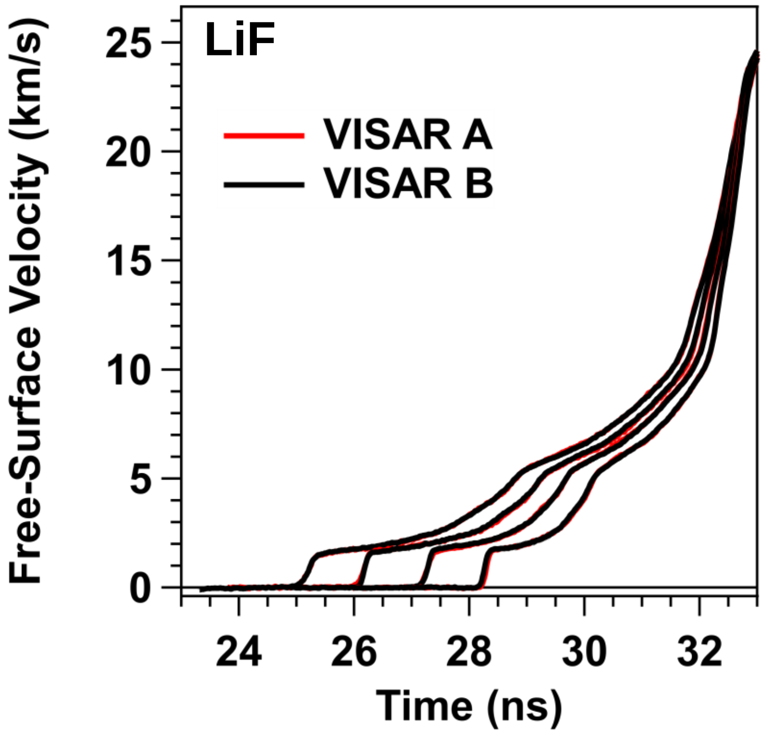


Stepped LiF sample w/ 200 nm Al or Ti coating

Raw VISAR

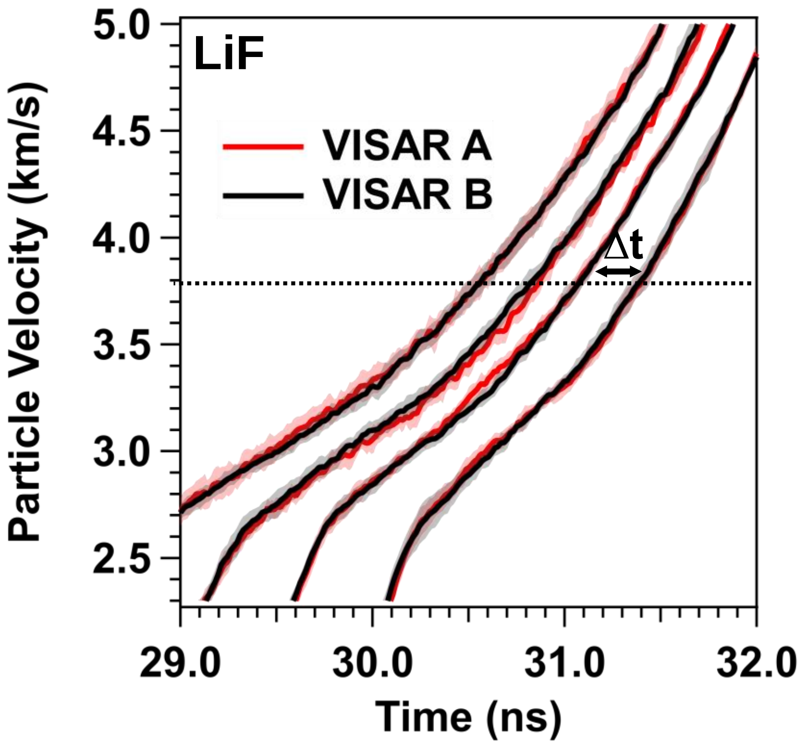


Free-surface velocity



From the velocity and the known step thicknesses, we determine sound speed as a function of particle velocity

Particle Velocity



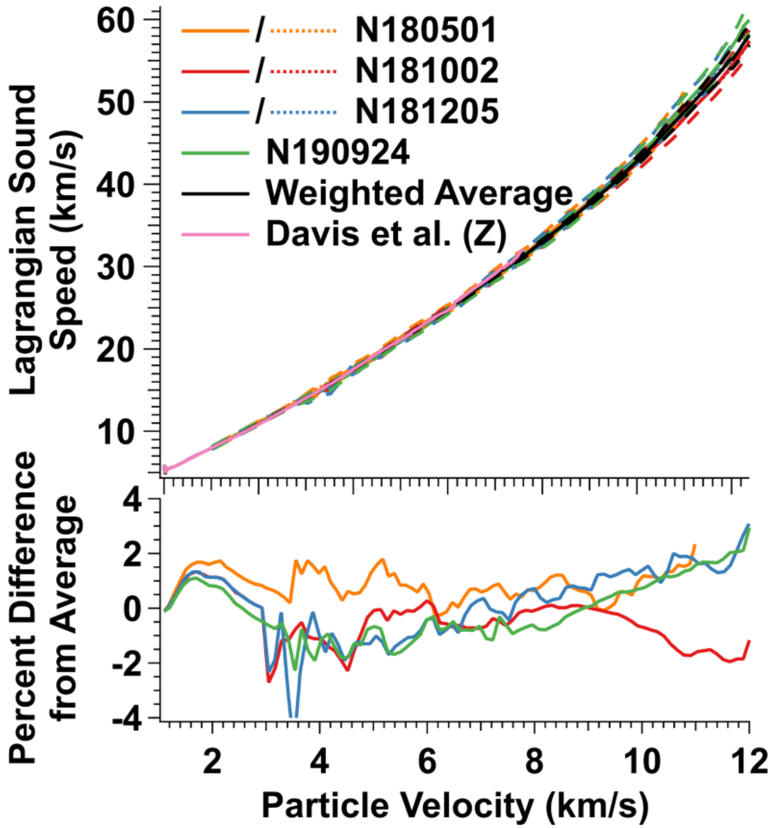
Math

From measured step thickness difference

$$C_L(U_P) = \frac{\Delta x}{\Delta t}$$

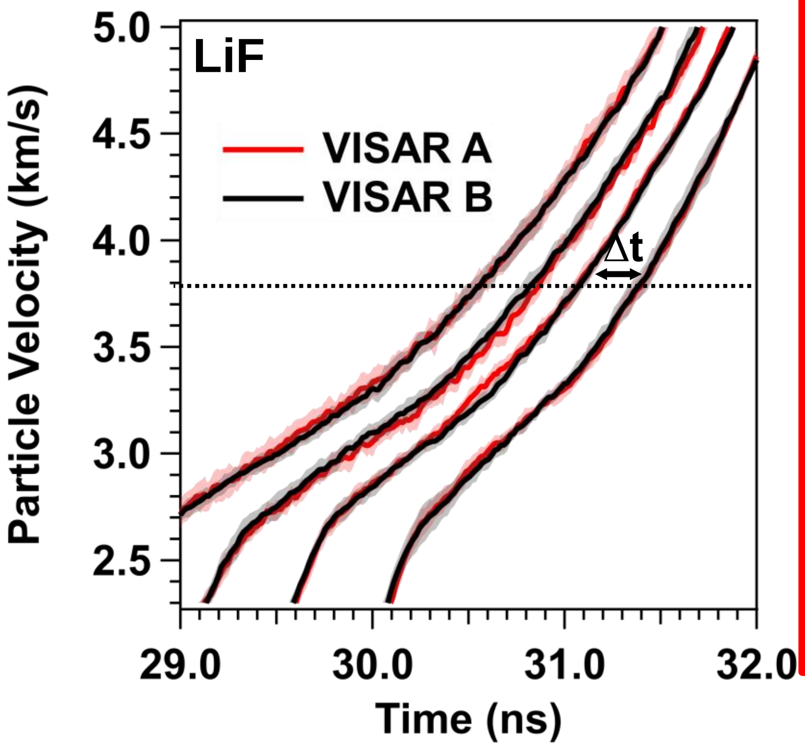
From arrival times for particle velocity

Lagrangian Sound Velocity in LiF



From the velocity and the known step thicknesses, we determine sound speed as a function of particle velocity

Particle Velocity



Math

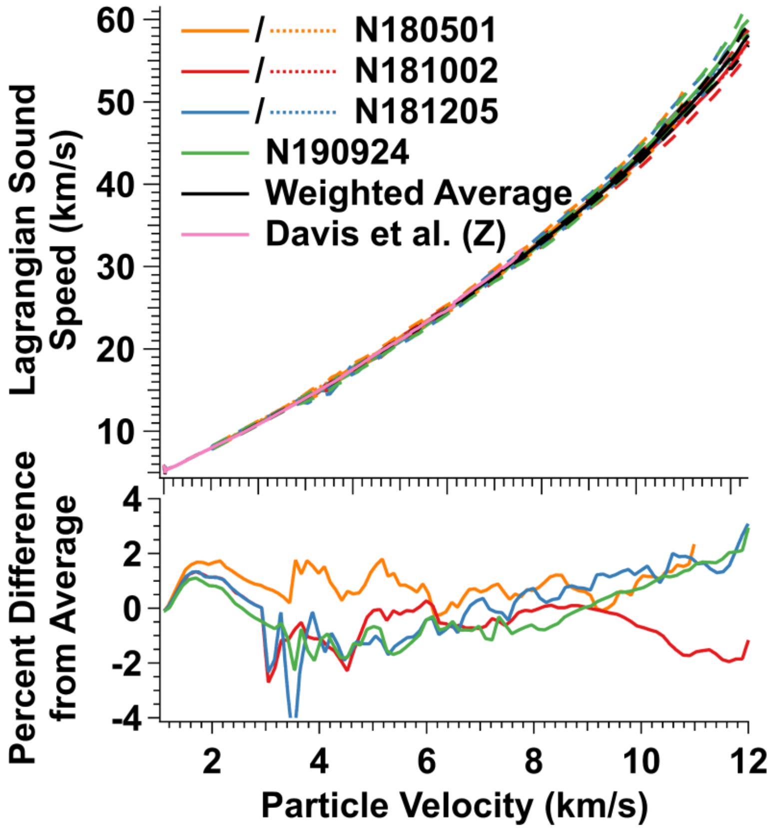
From measured step thickness difference

$$C_L(U_P) = \frac{\Delta x}{\Delta t}$$

From arrival times for particle velocity

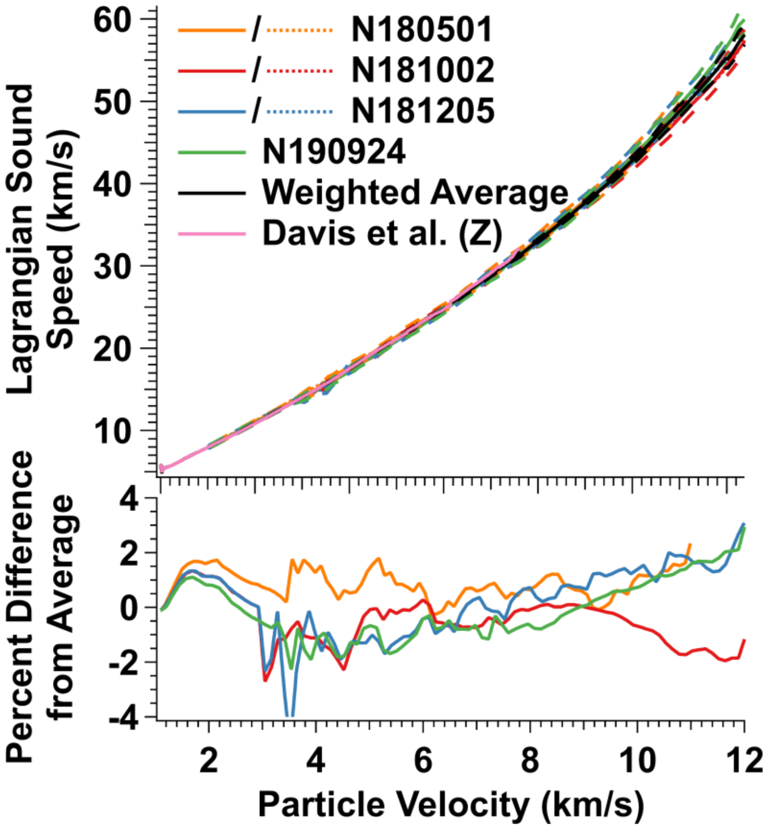
Only true for *in-situ* velocity, in reality analysis is more complex. See Rothman and Maw, 2006 for details

Lagrangian Sound Velocity in LiF



Integrating the sound speed as a function of particle velocity, we obtain the stress-density path of the sample

Lagrangian Sound Velocity in LiF

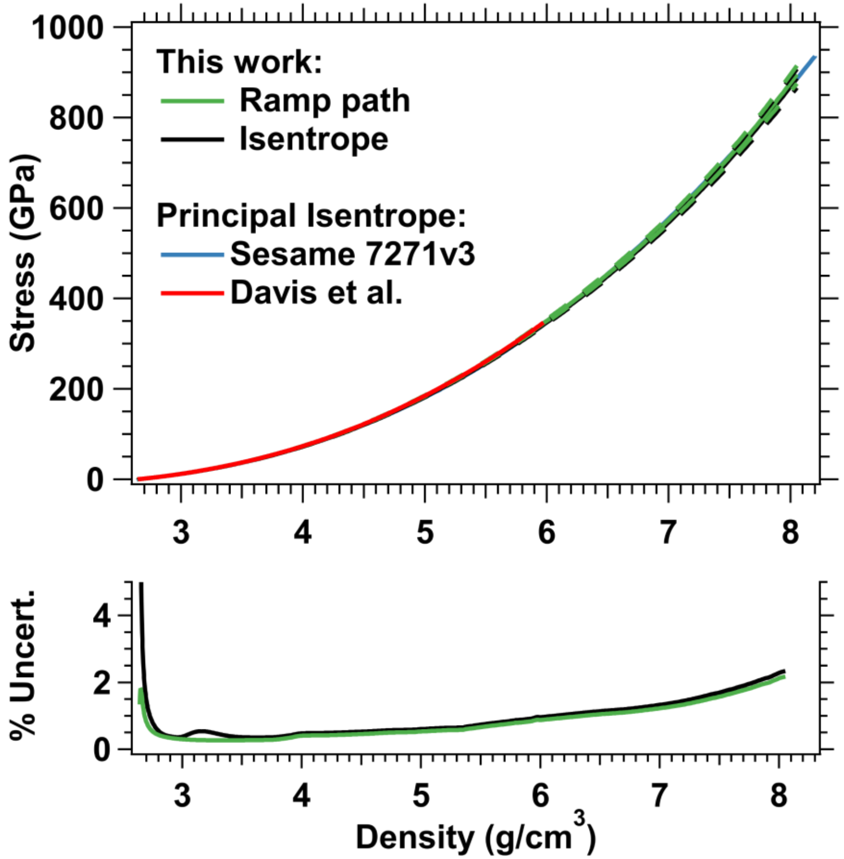


More Math

$$P = \rho_0 \int C_L du_p$$

$$\rho = \frac{\rho_0}{1 - \int \frac{du_p}{C_L}}$$

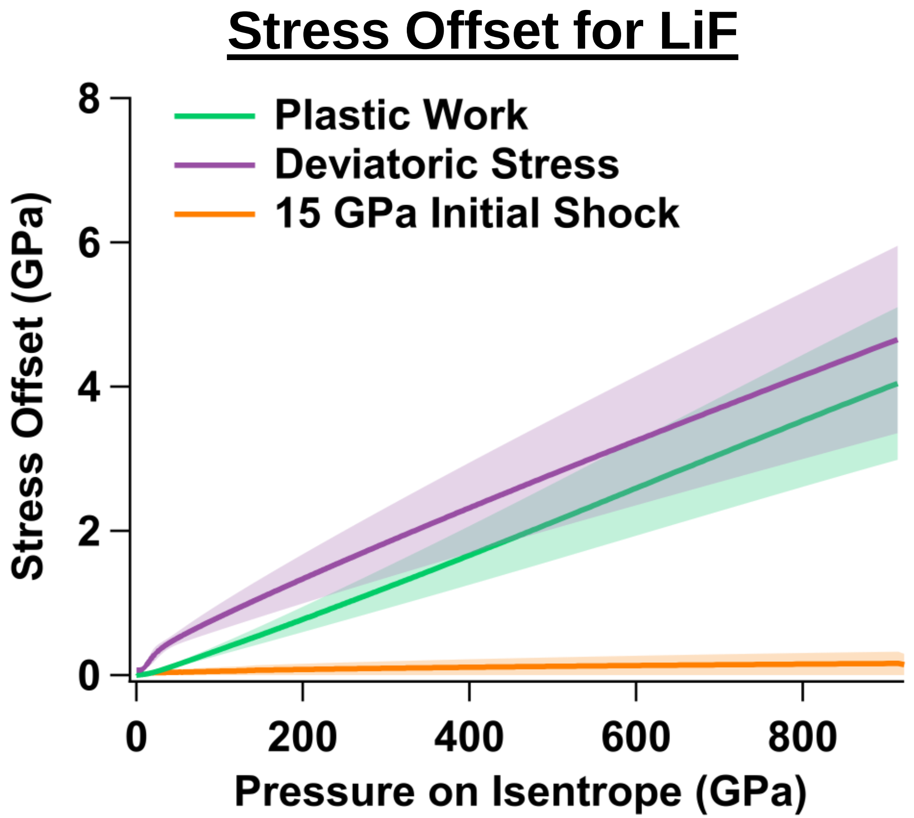
Stress vs. Density in LiF



The magnitude of the thermal pressure corrections to reduce the ramp path to the isentrope is small

$$P_{isen} = \underbrace{\sigma_x}_{\text{Measured stress}} - \overbrace{\frac{2}{3}Y}^{\text{Deviatoric stress}} - \underbrace{\gamma\rho\int \beta dW_P}_{\text{Plastic work heating}} - \overbrace{\gamma\rho_{Hug}(E_{Hug} - E_{Isen})}^{\text{Thermal pressure from initial shock}}$$

Work: $$dW_P = \frac{1}{\rho_0}\frac{2}{3}Y[d\epsilon_x - \frac{dY}{2G(\rho)}]$$



See Kraus et al., 2016 or Fratanduono et al., 2020 for detailed discussion of corrections

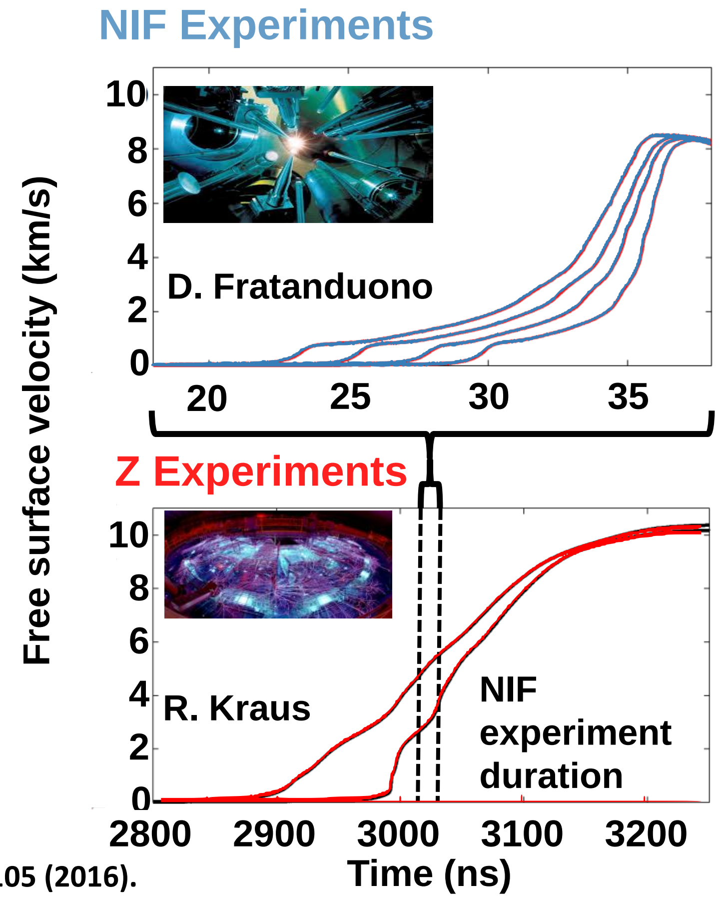
For LiF, total stress offset is ~8.5 GPa or ~0.9% at peak of 930 GPa

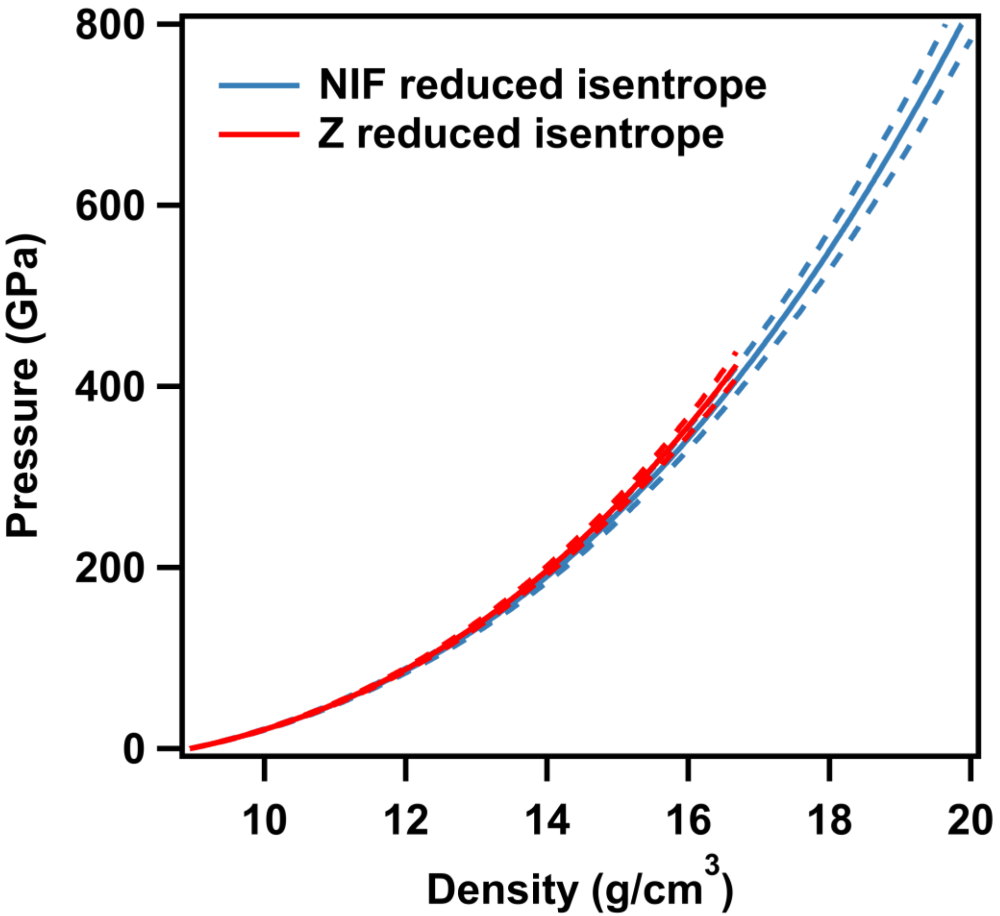
We have several completed and ongoing campaigns using the ramp compression platform

- **We have conducted several successful campaigns:**
  - Conducted cross platform experiments on a simple materials to validate the NIF platform against Z
  - Measured the material response of copper to ~2300 GPa
  - Measured the response of Pt and Au to provide absolute pressure standards for static compression
  - As a Discovery Science campaign, measure isentrope of iron to ~1400 GPa

- **Some current campaigns (that I don't have time to discuss, but happy to talk about later!)**
  - Liquid Sn adiabat
    - Demonstrate ability to obtain data on liquid samples, constrain thermal response between Hugoniot and isentrope
  - Deviatoric stress measurement development
    - Important for reducing ramp stress-density to pressure-density
  - EOS of Ta > 2000 GPa

Cross platform experiments on simple materials (Cu, Pt, Au, and LiF) were performed to validate the NIF platform

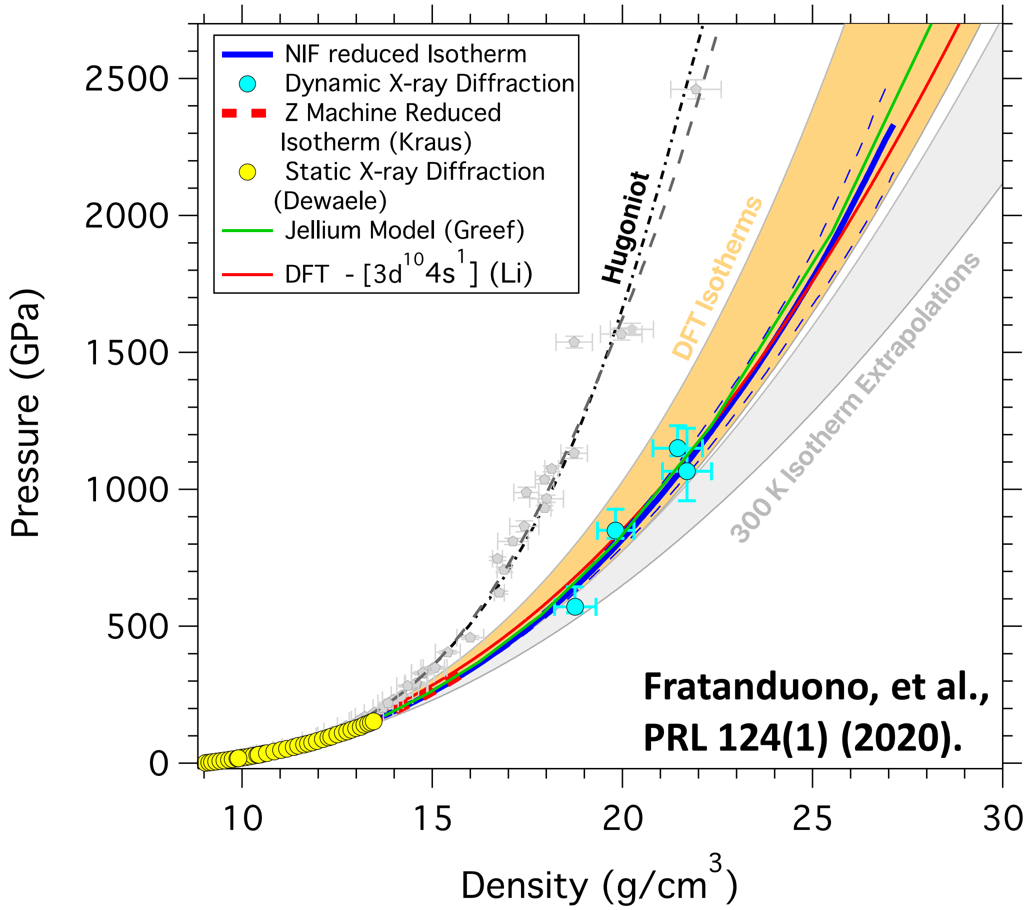




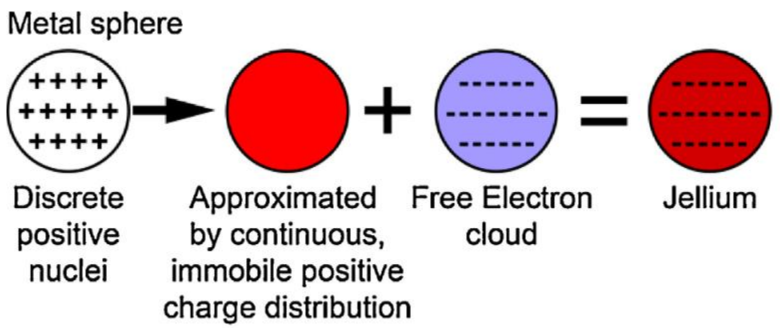
Kraus, et al., PRB, 93, 134105 (2016).
Fratanduono, et al., PRL 124(1) (2020).

Good agreement between NIF and Z on such simple materials suggests that discrepancies could indicate rate-dependent response

Using the NIF, we measured the material response of copper to ~2300 GPa



Jellium Model in Metals



Assumes interacting electrons in a smeared potential of ions (no lattice structure considered)

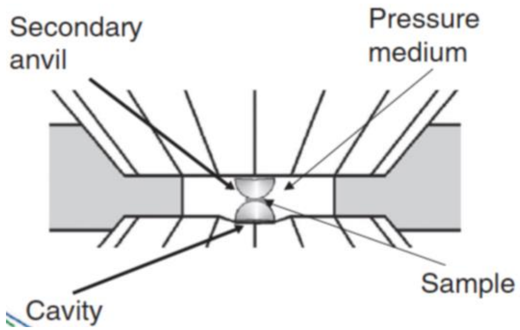
Probing the material response of simple noble metals (Cu, Au, Ag) provides an excellent method to test first principal calculations at extreme conditions

Chandra, A., et al. (2014). "Role of surfaces and interfaces in solar cell manufacturing." CIRP Annals **63**(2): 797-819.

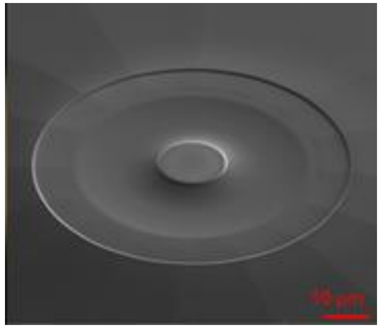
A revolution is underway in the diamond anvil cell community and researchers are accessing unprecedented conditions

New Static High-Pressure Apparatuses

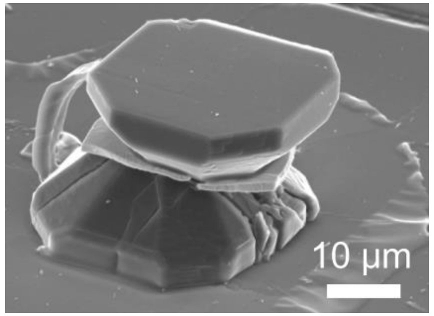
Double DAC with microspheres[1]



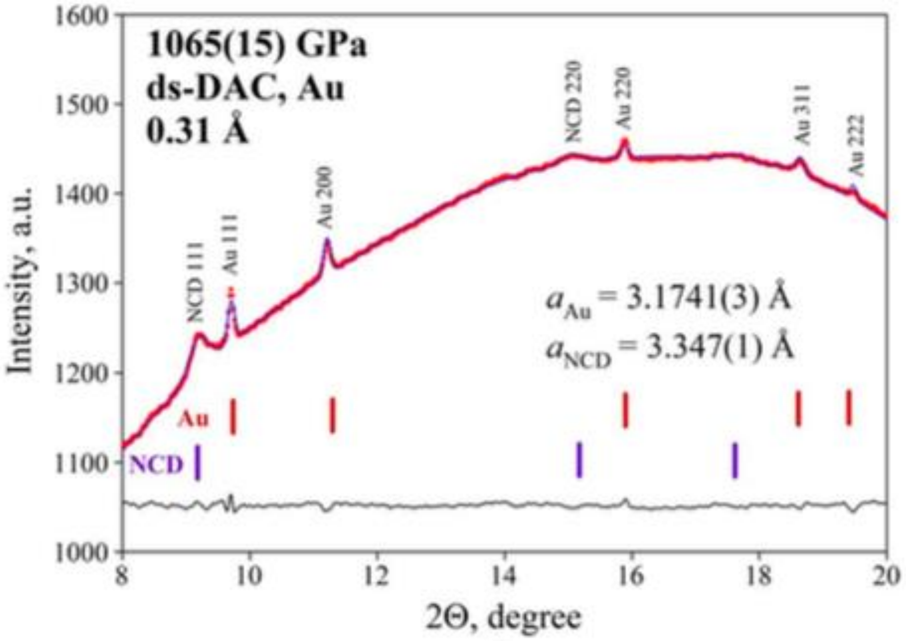
Toroidal DAC



Micro-paired diamond anvils[2]



Peak pressures (3x higher) than conventional DAC have been reported

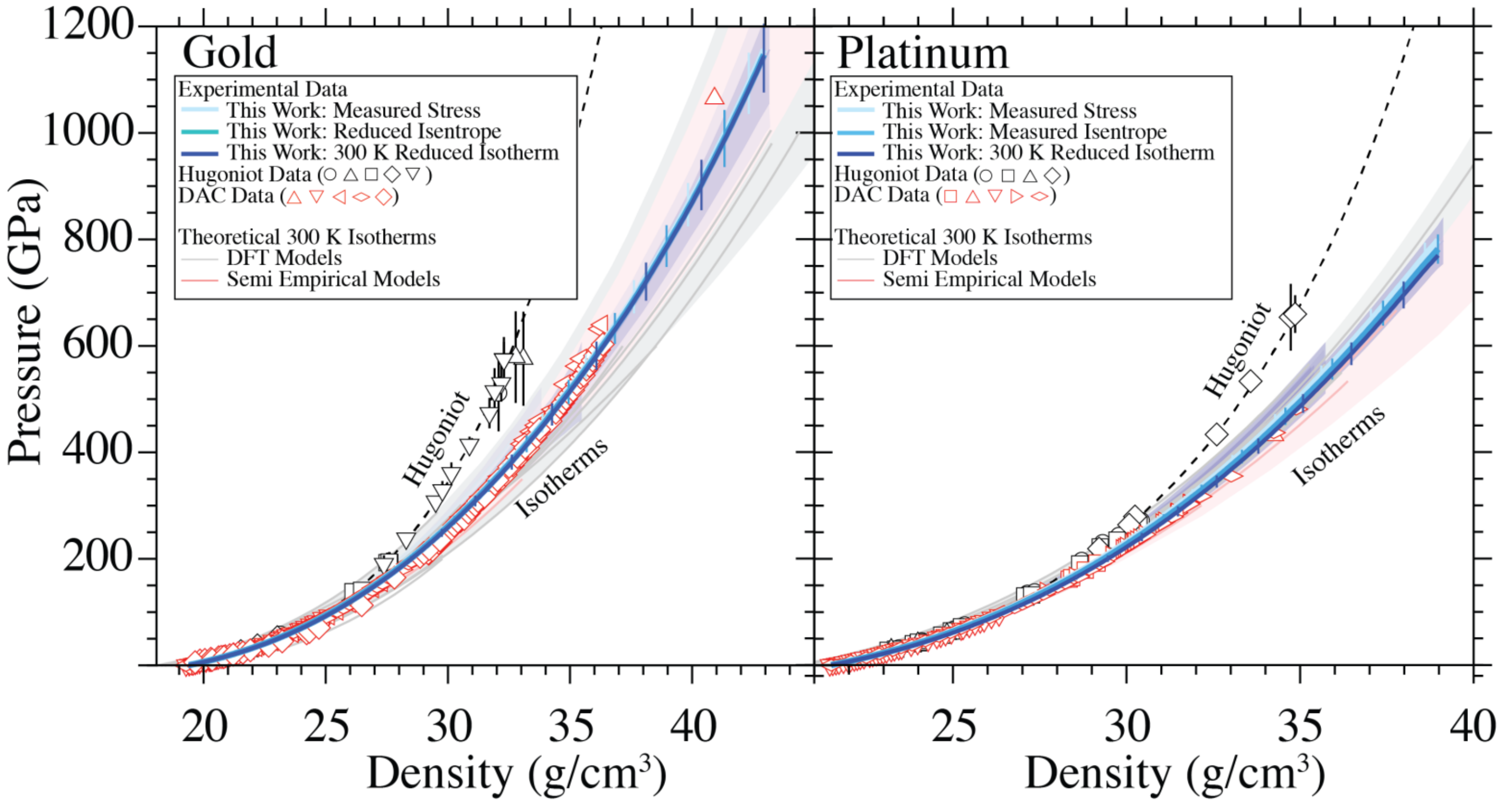


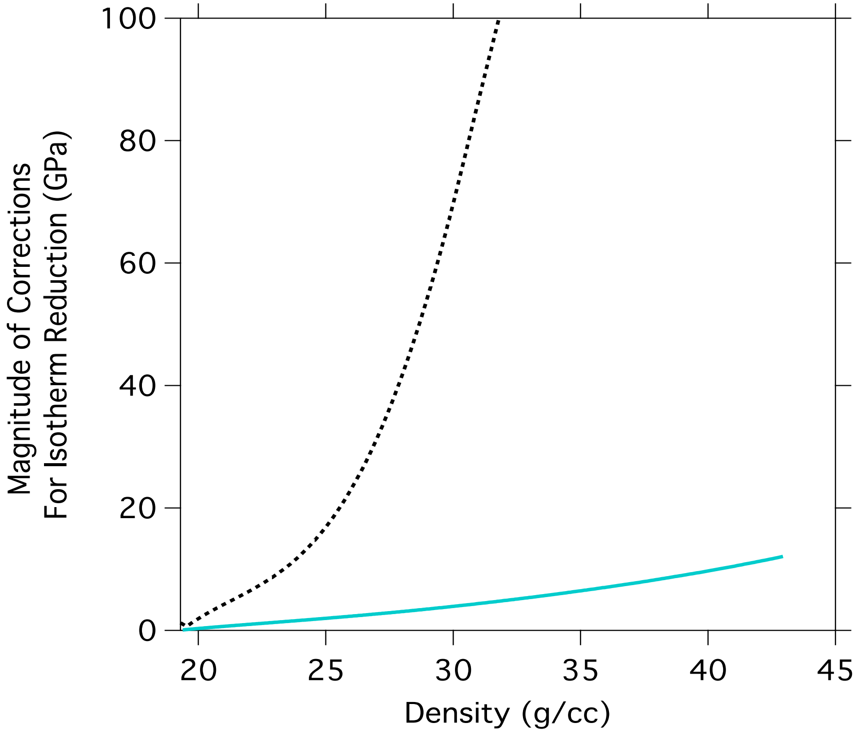
~1000 GPa in gold[1]

Our NIF experiments can provide the high-pressure (>500 GPa) standard required to calibrate these measurements

1-Dubrovinsky, *Nat Commun* 3: 1163 (2012) and *Nature* 525: 226 (2015)
2-Sakai, T., et al. (2015). Review of Scientific Instruments 86(3): 033905.

Our measurements on Pt and Au will underpin the emerging high-pressure diamond anvil cell community



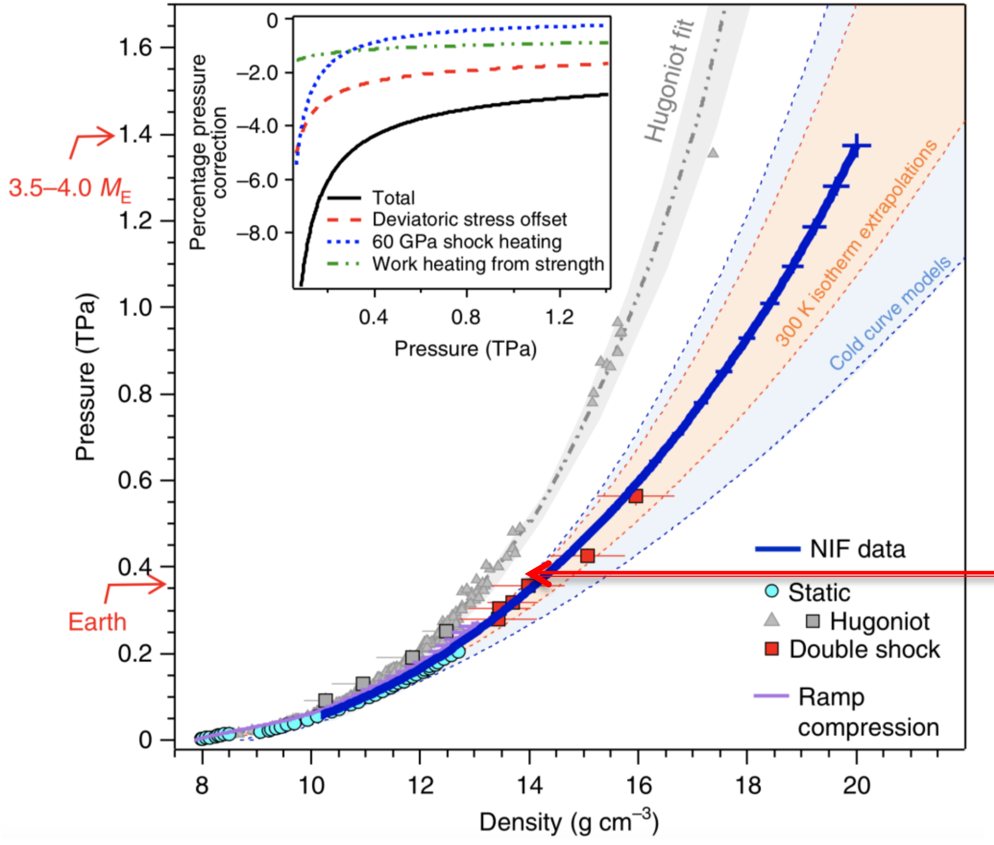


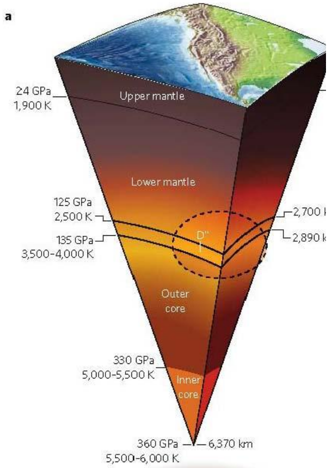
Shockwave data requires a 30% thermal reduction to get to isotherm
Ramp compression requires a 1% reduction

Figures from D. Fratanduono et al., Science, in production 2021

Fe

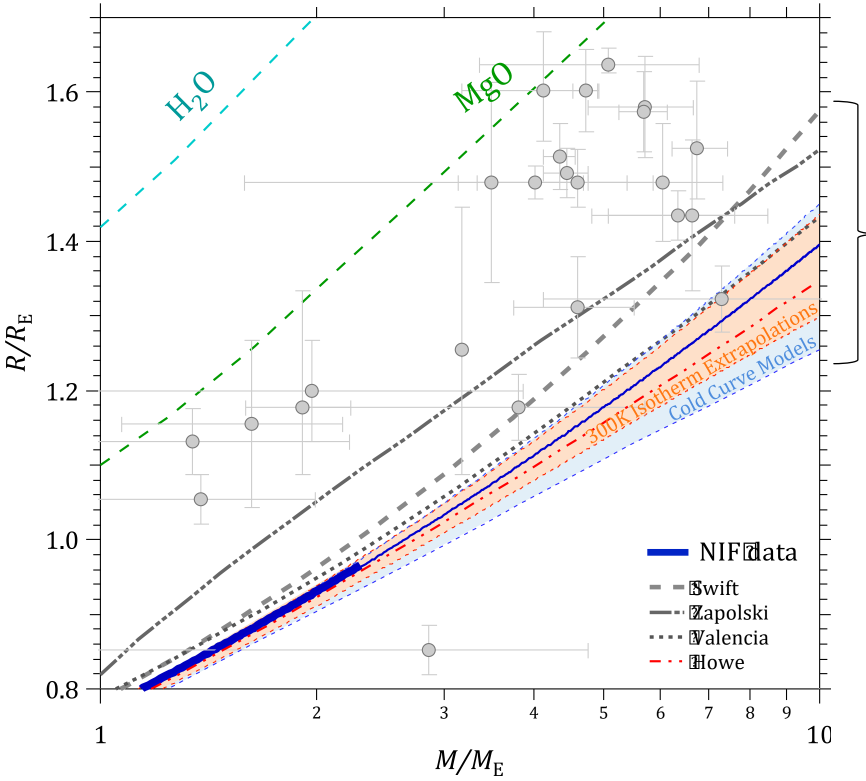
NIF Discovery Science experiments on iron aids in the modeling of rocky planets



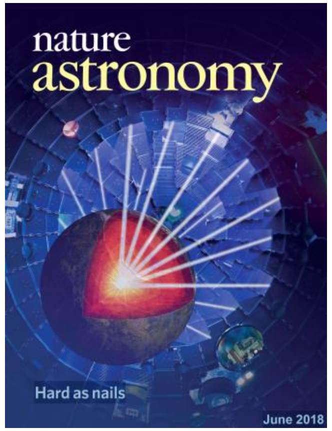


Earth's Core Pressure

Exoplanet Mass-Radius Plot



Spread in Fe Models



Smith, et al., Nature Astronomy, 452, 452 (2018).

Determining the interior structure and composition of these *super-Earth* planets is crucial to understanding the diversity and evolution of extrasolar planetary systems.

The NIF ramp compression platform has allowed us to make nearly absolute measurements up to incredible pressures

- **Using the NIF, we measured the material response of:**
  - Copper to 2300 GPa, important as both a standard and a relatively simple material for platform validation
  - Iron to 1400 GPa, vital for modelling rocky planets
  - Platinum and Gold to 800 GPa, providing a high precision, absolutely determined reference for increasing high pressure DAC experiments
  - A number of other materials currently being analyzed, including Al, Pb, Sn, LiF, and Ir
- **These data are important for understanding material behavior under extreme conditions, calibrating relative measurements, and creating accurate material models**

Lawrence Livermore National Laboratory