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

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A large team has contributed to this work:

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**Sandia National Laboratories**
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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.

Ramp compression experiments **absolute measurements** of stress-density that are:

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

Electronic forces binding the atoms together at 0 K.
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


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(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).

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

Figures from Dayne Fratanduono
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

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

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

**Particle Velocity**

- **LiF**
  - VISAR A
  - VISAR B

**Math**

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

From measured step thickness difference

From arrival times for particle velocity

**Lagrangian Sound Velocity in LiF**

- N180501
- N181002
- N181205
- N190924

- Weighted Average
- Davis et al. (Z)
From the velocity and the known step thicknesses, we determine sound speed as a function of particle velocity.

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

From measured step thickness difference

From arrival times for particle velocity

Only true for \textit{in-situ} velocity, in reality analysis is more complex. See Rothman and Maw, 2006 for details.
Integrating the sound speed as a function of particle velocity, we obtain the stress-density path of the sample

### More Math

\[
P = \rho_0 \int C_L du_p
\]

\[
\rho = \frac{\rho_0}{1 - \int \frac{du_p}{C_L}}
\]
The magnitude of the thermal pressure corrections to reduce the ramp path to the isentrope is small.

\[ P_{\text{isen}} = \sigma_x - \frac{2}{3}Y - \gamma\rho \int \beta dW_p - \gamma\rho_{\text{Hug}} (E_{\text{Hug}} - E_{\text{isen}}) \]

Measured stress

Deviatoric stress

Thermal pressure from initial shock

Plastic work

heating

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

Work:

\[ \text{Stress Offset for LiF} \]

For LiF, total stress offset is \( \sim 8.5 \text{ GPa} \) or \( \sim 0.9\% \) at peak of 930 GPa.

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

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

Kraus, et al., PRB, 93, 134105 (2016).
Using the NIF, we measured the material response of copper to ~2300 GPa

Probing the material response of simple noble metals (Cu, Au, Ag) provides an excellent method to test first principal calculations at extreme conditions.
A revolution is underway in the diamond anvil cell community and researchers are accessing unprecedented conditions.

**New Static High-Pressure Apparatuses**

- **Toroidal DAC**
- **Micro-paired diamond anvils**

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

~1000 GPa in gold

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

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 modeling 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.