Laser-induced Ramp Compression of Tantalum and Iron to Over 300 GPa: EOS and X-ray Diffraction

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Laser-induced ramp compression of tantalum and iron to over 300 Gpa: EOS and x-ray diffraction

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Laser Facilities

Janus
Lawrence Livermore National Lab (CA)
2 beam
1 kJ

Omega
University of Rochester (NY)
60 Beams
30 kJ

100 meters

N.I.F.
Lawrence Livermore National Lab
192 Beams, 2 MJ
Outline

Laser-Driven Ramp Compression Experiments

• Introduction

• Ramp-Compression EOS on Tantalum to 320 GPa
  – Cold Sample
  – Absolute Stress-Strain

• X-ray Diffraction on Iron to 470 GPa
  – Far Above Shock Melting on Hugoniot
  – Still Solid
  – Consistent with HCP

• On to NIF . . .
We ramp compressed diamond to 1500 GPa

Diamond Steps

Apply this drive to Tantalum
Ramp-Wave EOS

--Design Requirements--

No reverberation

--and--

No Shock.
Target Metrology and Pulse Shape

Tantalum deposition: Paul Mirkarimi and Kerry Bettencourt.

\[\begin{align*}
  d_A &= 11.24 \pm 0.05 \, \text{µm} \\
  d_B &= 13.83 \pm 0.05 \, \text{µm} - 2.59 \, \text{µm} \\
  d_C &= 16.54 \pm 0.05 \, \text{µm} - 2.71 \, \text{µm} \\
  d_D &= 19.35 \pm 0.05 \, \text{µm} - 2.81 \, \text{µm}
\end{align*}\]
VISAR Wave Profiles
Shot 54777

12 µm
21 µm
18 µm
15 µm

Time (ns)
Free-Surface Velocity (km/s)

Tantalum
We collect data using a line visar and use an iterative Lagrangian Analysis (Rothman, et al., 2005)

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

Since we measure free surface velocity, not \( u \) we must use an iterative correction developed by Rothman (2005)

\[ \rho(u) = \rho_0 \left(1 - \int \frac{du}{C_L}\right)^{-1} \]

\[ p_x(u) = \rho_0 \int C_L \, du \]
We propagate uncertainties throughout the iterative analysis.

Errors in Lagrangian sound speed, $C_{L,i}$, arise from uncertainties in $U_{FS}$, $t$, and $d$:

$$\delta \varepsilon_j = \Delta U_p \left( \frac{\rho}{\rho_0} \right)^2 \sum_{i=0}^{j} \frac{\delta C_{L,i}}{C_{L,i}^2}$$

$$\delta P(U_p) = \rho_0 \Delta U_p \sum_{i=0}^{j} \delta C_{L,i}$$

Dominant uncertainties are not independent as a function of $U_{FS}$ (e.g. thickness, streak camera warping, visar laser speckle). Thus the errors propagate linearly to strain and stress:

Uncertainties continue to grow at high pressure.
8 Shots—Highly Consistent Results

Tantalum

Lagrangian Sound Speed (km/s) vs Free Surface Velocity (km/s)

Stress (GPa) vs Density (g/cc)

8 Shots on the Omega Laser in 2009
100% Data Return
Ramp Compression Tantalum Equation of State

- Stress-density on 8 shots to over 300 GPa.
- Very consistent with previous Z shots.

Next Year: NIF experiments to 500 GPa and more . . .
To Estimate Plastic Work Heating We Estimate Deviatoric Stress or “Stress"

We equate the deviatoric stress with the strength,

\[ Y = \frac{3}{4} \left[ \sigma(\rho) - P(\rho) \right] \]

For simplicity, we will compare our with CALE Form 4, EOS 77, and with two sets of DAC isothermal EOS measurements:
Data falls within theoretical bounds on strength.  (Moriarty, 1998)
We estimate the temperature due to Plastic-Work Heating assuming the Dulong-Petite limit for specific heat. Iterative approach used to correct strength for thermal pressure.
Future Directions

• We are currently working to compress Iron to 300 GPa at Omega.
• Analysis that accounts for kinetics.
• Separation of EOS and strength.
• Determination of crystal structure.
• Temperature determination.
X-Ray Diffraction

• Diffraction -- Most direct way to determine crystal structure

• Laser Drive -- Ideal for X-ray diagnostics

• Ramp Compression -- limits shock heating, very high pressures in solid phase.
• Diffraction above the shock melting pressure?
X-Ray Diffraction at Omega Laser

- Back Plate
- Kapton Shields
- Image Plates
- Fe backlighter
  - 6.69 keV
As long as the sample is hydrodynamically thin, $P$ and $u$ at the LiF or Diamond interface is the same as in sample.

If we know the EOS of LiF or Diamond we can find the Pressure in the sample using the VISAR diagnostic.

Proof of principle already demonstrated for XRD and XAFS on iron.

Using this target design, we believe we can ramp compress samples to $\sim$30 Mbar, Hold the state for several ns, Determine the pressure, and Make a measurement.

XRD, XAFS, XANES, Reflectivity, . . . .

*Temperature remains the most important parameter that we do not know how to measure.*
Strain rate is very high, $\sim 10^8$ s$^{-1}$. Looks like temperature is low. What does diffraction look like?
Shot 54203

\[ P = 185^{+6}_{-17} \text{ GPa} \]

Raw Data

Wavelet-FT Background Subtraction

Two High Pressure Lines
We see 2 strong, 1 weak reflections.

We will assume a structure and fit.
Likely Structures:
HCP (variable $c/a$), FCC

Guided by static experiments, potential structures are hcp with $c/a=1.61$ and fcc. (Ma, et al. 2004)

Previous shock experiments on single crystals found hcp ($c/a=1.73$) (Kalantar, et al. 2005)
Triplet, peak positions fit well for this shot, but significant basal texture required to get agreement with doublet structure observed.
Results and Comparison

Diffraction on solid Fe to 472 GPa
- Highest pressure X-ray diffraction ever.
- Far above Hugoniot melt (~250 GPa).
- Structure appears to be HCP with c/a~1.61.
- More analyses / experiments still needed.
We can also fit $c/a$ ratio

Our data is in good agreement with previous static data: $c/a = 1.61$ (Ma, et al. 2004).
We have also measured Tin and Diamond.
X-ray Diffraction

• Highest pressure diffraction data ever recorded.
• Far above Hugoniot melt for Irong (250 GPa).

Future Directions
• Higher pressure.
• More diffraction lines.
• More accurate temperature determination.
The last 20 years have seen fantastic advances in DAC techniques, measurements, and diagnostics.

Our biggest challenge is to make similar progress in the next 20 years on laser-compression experiments.

The most important experimental advance will be the ability to produce a uniform sample state and perform in-situ measurements.

Unfortunately, transparent windows are needed (although LiF is transparent to at least 900 GPa under ramp compression).

Temperature diagnostics are critically needed (EXAFS?).
On to the NIF
We Have a Concept for Xray Diffraction on the NIF

Hohlraum: 60 beams from top and bottom using quads, Q12T, Q16T, Q34T, Q43T, Q44T, Q45T, Q46T, Q11B, Q12B, Q35B, Q36B, Q41B, Q43B, Q45B, Q46B.

Plus ARC, Q35T

Visar is pointed at TCC.
We have a design for an 8Mbar drive for tantalum on NIF using less than 200 kJ of power. We will use this design this spring.
Velocity drive is at 25 microns so 80 micron step has reverb at 55. Note that the 80 reverb goes back to -25 microns so that only the 90 micron thick step will avoid reverb.

Thus, we should use this drive with 80, 90, 100, and 110 micron steps. These are the steps I used in the analysis.
We believe that we can achieve better than 6% uncertainty in a single NIF shot to 800 GPa.

Red curve is this analysis using errors of 0.03 km/s, 50 ps, and 100 nm. Reverberations are marked at the 25 micron position, Steps used are 80, 90, 100, and 110 microns.

We believe that we can achieve better than 6% uncertainty in a single NIF shot to 800 GPa.
Conclusions

Ramp Compression Tantalum Equation of State

- Stress-density on 8 shots to over 300 GPa.
- Very consistent with previous Z shots.

Next Year: NIF experiments to 500 GPa and more . . .

Diffraction on solid Fe to 470 GPa

- Highest pressure X-ray diffraction ever.
- Far above Hugoniot melt (~250 GPa).
- Structure appears to be HCP.
- More analyses / experiments still needed.

No obvious limit on pressure
Current method requires both reverse and forward propagation steps.

Shocks are created by phase transitions.

Phase transitions and EP transitions both require time-dependent analysis.

We need to develop a forward only analysis method.
We are developing a Forward-Only Analysis Method

Repeat for all velocities, $U_{FS,i}$

• This method still requires a model for time-dependent phase transitions.
• Exact methods being developed by Evan Reed and by Bryan Reed potentially offer a very attractive alternative.
Iterative Analysis:
Correction for free-surface wave interactions.

Absolute Stress-Density Measurement

 EOS, $C_L(U_{FS})$

**Reverse** propagate $U_{FS,j}(t)$ to find drive pressure, $P_j(t)$, for all steps, $j$

 Iterate to convergence

 Update $C_L(U_{FS})$ by linearly fitting $d_j$ vs. $t_{FS,j}$

 Forward propagate $P_j(t)$, with no interface to the step thickness $d_j$ for all steps, $j$