Shock and ramp compression experiments: recent developments

J. H. Eggert

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European XFEL HED instrument user workshop
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Shock and ramp compression experiments: recent developments

European XFEL HED instrument user workshop

January 30, 2014

Jon Eggert
Team

- **Lawrence Livermore Laboratory**

- **Los Alamos Laboratory**
  - C. Bolme

- **University of California, Berkeley**
  - R. Jeanloz

- **Stanford University**
  - A. Gleason, W. Mao

- **Princeton University**
  - T. Duffy, J. Wang

- **University of Rochester**
  - T. Boehly, B. Yaakobi

- **Commissariat a l’Energie Atomique, France**
  - P. Loubeyre, S. Brygoo

- **University of Oxford, UK**
  - J. Wark, A. Higginbotham, M. Suggit

- **National Research Council of Canada**
  - D. Klug, Y. Yao

- **University of Edinburgh, Scotland**
  - M. McMahon, E. McBride, R. Briggs

- **Additional Collaborators / Consultants**
  - Andrew Comley, Brian Maddox, Hye-Sook Park, and Bruce Remington

- **Plus target fabrication, Omega and NIF facility and diagnostic teams**
Matter at extreme $P, T$ are found throughout our universe (1 Mbar = 100 GPa = $10^6$ atm.)

- Earth: 3.6 Mbar, 6000 K
- Jupiter: 77 Mbar, 16000 K
- 55cnce: ~7.5 Mbar
- NIF capsule, pre-ignition: ~300,000 Mbar, ~50,000,000 K = ~4 keV

**C. J. Hamilton**
A Common Definition for “High-Energy Density” is $10^{11} \text{ J/m}^3 = 1 \text{ Mbar}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Pressure at 2-Fold Comp. (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>18</td>
</tr>
<tr>
<td>Mg</td>
<td>$\sim$120</td>
</tr>
<tr>
<td>Pb</td>
<td>180</td>
</tr>
<tr>
<td>Sn</td>
<td>180</td>
</tr>
<tr>
<td>Al</td>
<td>240</td>
</tr>
<tr>
<td>Zn</td>
<td>$\sim$250</td>
</tr>
<tr>
<td>Ag</td>
<td>$\sim$460</td>
</tr>
<tr>
<td>Ta</td>
<td>470</td>
</tr>
<tr>
<td>Cu</td>
<td>$\sim$500</td>
</tr>
<tr>
<td>Mo</td>
<td>$\sim$640</td>
</tr>
<tr>
<td>Au</td>
<td>$\sim$810</td>
</tr>
<tr>
<td>W</td>
<td>$\sim$820</td>
</tr>
<tr>
<td>Diamond</td>
<td>900</td>
</tr>
</tbody>
</table>

High-Energy Density allows us to clump high temperatures and high densities together.

Here I will concentrate on Extreme Compression Physics: $\rho/\rho_0 > 2$. 
Within the past 15 years complex structures for alkali metals have been predicted

Predictions for Lithium structures:

Predictions for Sodium structures:
Hanfland, Syassen, Loa, Christensen, Novikov, Gordon Conference Poster (2002).

Low symmetry structures are stable at high pressure

Structure Matters:
oC8 has v/v₀=0.1 at 950 GPa.
BCC has v/v₀=0.1 at 1500 GPa.
Christensen and Novikov (2002)
Above 200 GPa Sodium becomes a large band-gap insulator! -- Electride --

Traditional view that all materials become simple at high pressure is incorrect!

“... what the present results most assuredly demonstrate is the importance of pressure in revealing the limitations of previously hallowed models of solids”

FCC, 65 GPa
cI16, 108 GPa
oP8, 119 GPa
tl19, 147 GPa
hP4, 190 GPa

Incommensurate
Insulating, Transparent Electride

Increasing Structural Complexity

Gatti, PRL (2010)

Ma, Nature (2009)
High pressure phases of aluminum are also predicted to be complex


Host-Guest structure of Ba-IVa (Incommensurate Electride) 32-88 Mbar

Simple Hexagonal Electride 88 – 100 Mbar

CMMA Electride > 100 Mbar

ΔV~1.8%

ΔV~2.8%

ΔE ~ -8 eV

“All structures near 300 Mbar are far from close packed”
At even higher pressures carbon is also predicted to adopt electride phases.


At LLNL, Sebastien Hamel has predicted that fluid carbon at 80 and 250 Mbar also show electron clustering.
Rousseau and Ashcroft proposed fundamental Quantum-Mechanical drivers for complex structures

Valence electron localization due to hard-sphere exclusion potential with Pauli exclusion and orthogonal wave functions

“When the cores are induced to occupy an increasingly larger fraction of the unit cell the indications are that a new paradigm, as suggested here, may be appropriate.”

--Rousseau and Ashcroft, PRL (2008)
We currently use very large lasers to study materials at extreme compression. Lawrence Livermore National Laboratory (CA) uses Janus, with 2 beams of 700 J each. Omega at the University of Rochester (NY) has 60 beams of 30 kJ each. N.I.F. at Lawrence Livermore National Lab has 192 beams, 2 MJ total energy. Stewart McWilliams.
NIF
Inside the Target Chamber
Using NIF we want to explore the new paradigm of Extreme-Compression Science

We want to measure:
- Stress-Density
- Structure
- Solid-Solid Phase Transitions
- Texture
In order to study the physics of extreme compression we need to keep temperature low.

Strong shocks probe high-temperature EOS states

Ramp compression waves probe EOS at lower temperatures than shocks

Ramp and shock compressions follow different paths on EOS surface.
Laser pulse shaping capability is critical for ramp compression experiments.

- **Design constraints:**
  1. Identical drive
  2. No reverberation
  3. No shock
We successfully ramp compressed nano-crystalline diamond to nearly 50 Mbar.

We use this data to determine the stress in our diffraction experiments.
Using Omega we want to explore the new paradigm of Extreme-Compression Science

We want to measure:
- Stress-Density
- Structure
- Solid-Solid Phase Transitions
- Texture
In situ diffraction gives critical data:

- Crystal structure / phase diagram
- EOS
- Phase-transition mechanisms
- Deformation texture / microstructure
- Potential to determine liquid structure

- Target and diagnostics are simple
- We have done 6 NIF TARDIS shots
Raw image-plate data is self-calibrating with ambient as well as high-pressure diffraction:

Quasi-monochromatic beam by thermal emission of Cu He-α line.

- $10^{11} - 10^{12}$ photons incident on sample
- 3.5% bandwidth
We use diamond-sandwich targets to obtain uniform stress density conditions after ramp compression.

We determine stress by backward propagation of the diamond free-surface velocity, assuming that we know the EOS of diamond.

Ramp drive: 197J ($t_{BL} = 5.0$ ns) $P = 3.2$ Mbar
Raw image plates contain 360° azimuthal scattering.

*In situ* diffraction provides conclusive crystal structure. Demonstrated at Omega

80 GPa, Ta

We observe a new phase in Tantalum above ~300 GPa.

If BCC is assumed phase the stress density disagrees with NIF, Z, GDI stress-density data.
We have measured diffraction in materials to nearly 10 Mbar.

**New Phases:**
- **MgO**: B1-B2 transition at 500 GPa
- **Sn**: A new phase at 200 GPa
- **Ta**: A new phase at 300 GPa
- **Fe**: No new phase

**Materials:**
- **Tantalum**
- **Iron**

**Graphs:**
- D-spacing vs. Stress for MgO, Sn, Ta, and Fe.
- D-spacing vs. Pressure for Ta and Fe.
Using NIF we want to explore the new paradigm of Extreme-Compression Science

We want to measure:

- Stress-Density
- Structure
- Solid-Solid Phase Transitions
- Texture
We are fielding diffraction on NIF (6 shots so far) TARDIS (TARget Diffraction In Situ) diagnostic.

Three image plates will collect the diffraction data.
N130806: Ta target, Ge x-ray source, 2.5 Mbar drive

- Diffraction was observed on Ta at 2Mbar
- Large transmission through AERMET body
- Due to large amount of high-energy background (FFLEX: E=216J, T=33keV)
- Phase plates did not eliminate background
Using new synchrotron facilities we want to explore the new paradigm of Extreme-Compression Science

We want to measure:

- ✓ Stress-Density
- Structure
- Solid-Solid Phase Transitions
- Texture
Using a 5ns ramp and a 100 J laser we should be able to achieve uniform 10 Mbar with a 200 µm spot.

\[ I(\text{TW/cm}^2) = \frac{2E(J)}{\Delta t(\text{ns})\pi R^2(\mu\text{m}^2)} \times 10^5 \]

\[ P(\text{GPa}) = 42(\pm 3)[I(\text{TW/cm}^2)]^{0.71(\pm 0.01)}. \]

Fratanduono, et al. JAP (2011)
LCLS: What does the MEC chamber look like?

MEC target chamber is modeled after the Titan chamber at the Jupiter Laser System at LLNL

- ~2.5 m diameter, made of 1"-thick Al.
- Vacuum up to 10^{-6} torr.
- 10 top-ports, 8 side-ports, and 6 doors.
- Internal Al breadboard ~2 m diameter.
- Motorized target alignment stage with 6 degrees of freedom.

MEC long pulse laser:
- Continuum Agilite laser. Nd:Glass system, doubled to 527 nm.
- 2-20 J beams with 10 minute rep rate.
- 2-20 ns pulse shaping.
LCLS: Recent experiment: MEC - LA11, Shock-compressed Ti, Cindy Bolme, and Amy Lazicki, 10/06/2013
LCLS: Recent experiment: MEC - LA11, Shock-compressed Ti, Cindy Bolme, and Amy Lazicki, 10/06/2013

- 4-panel Target array,
- 7x7 targets per panel, (196 total)
- 4mm separation

- 5 CS PAD detector arrays:
  - 1 4x4,
  - 4 1x2.

- 4-panel Target array,
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Photograph of LCLS setup

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Cindy Bolme, and Amy Lazicki
Fused Silica to Stishovite at MEC, LCLS

Gleason et al., High-Power Laser Workshop 2013

Gaussian profiles
- assume symmetric strain profile
- slope $\rightarrow$ strain
- intercept $\rightarrow$ grain size

Ungar et al., 1998
Ribarik et al., 2001
Hawreliak et al., 2007

Ungar et al., 1998
Ribarik et al., 2001
Hawreliak et al., 2007
Fused Silica to Stishovite at MEC, LCLS

32 J & 16 J:
Onset of nucleation = 3 ns
3 to 4 ns, growth rate ~ 2 nm/ns
Plateau, 4 ns at ~ 2.3 nm

→ At these conditions, all grains are nucleating at once – system has reached heterogeneous nucleation threshold!!
- lower energy shots to be examined

Gleason et al., High-Power Laser Workshop 2013
Laser Hutch is being designed for APS, Dynamic Compression Sector (DCS)

- Small target chamber
- Ports hold detectors, diagnostics and driver

- Proposed laser: 100 J, 15 min. rep. rate
- First light as soon at Summer 2015.
Results from APS -- BIOCARS Beamline

Diamond (20 µm) -- Tantalum (3 µm) -- Diamond (40 µm) Sandwich
Peaks are very broad, due to finite size effects.

Comparison of LCLS and APS data

Peaks are very broad, due to finite size effects (~2 nm).
Diode Pumped Optical Laser for Experiments (DIPOLE) at XFEL, HED Instrument

- 100 J scaleable DPSSL
- 10 Hz

10 J system as demonstrated

100 J based on scaling DiPOLE, auto align, pointing stab

Cooling TBD

Shaped Front End, Booster, Auto align
Flexibility and innovation in target area are important

LCLS Targets

Cindy Bolme, 
and Amy Lazicki
Flexibility and innovation in target area are important.

LCLS Targets

Cindy Bolme, and Amy Lazicki

DCS Target Concepts

Jim Hawreliak
Flexibility and innovation in target area are important.
Our expanding experimental reach in extreme-compression physics

1. Ramp-compressed, absolute stress-density relations can be made up to 50 Mbar

2. Dynamic diffraction provides evidence for new phase transitions at extreme densities

3. 3rd and 4th generation light sources offer great potential for extreme compression experiments