Results on laser compression experiments for warm dense matter study in the domain 1-10 Mbar

A. Benuzzi-Mounaix
LULI Laboratory, Ecole Polytechnique, Palaiseau, France

Workshop ESRF: studies of Dynamically COmpressed MAter with X-rays 29-30 March 2017
Goal of the talk

✓ To give a short overview of results and works in progress of our team using laser compression

✓ To give a good basis for discussions to establish future directions in the context of High Power Laser Facility at ESRF
✓ Context (WDM -> planetology).
   Main challenges: microscopic studies and get-off Hugoniot states

✓ Electronic and ionic structural changes study: Laser shock coupled to XANES diagnostic

✓ Detection of phase transitions: decaying shock using visible diagnostics and laser shock coupled with X-ray diffraction

✓ Brief review of different techniques to get-off Hugoniot states

✓ Perspectives in the context of HPLF
Warm Dense Matter regime

WDM is the state at the intersection between plasma physics and condensed matter physics.

Difficult to simulate -> today ab initio calculations, but they must be validated experimentally.

An accurate study of WDM matter has important repercussions in high pressure physics and planetology.
The challenges ......

In the last 20 years, a lot of Hugoniot data

-> Microscopic studies (i.e. phase transitions, structural information etc..) are today necessary

Test calculations approximations

High pressure physics and planetary models

-> Develop compression techniques to reach extreme states of matter off the principal Hugoniot to span a large region of the phase diagram is today necessary

<table>
<thead>
<tr>
<th>Temperature (eV)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-4</td>
<td>1</td>
</tr>
<tr>
<td>10^-2</td>
<td>10</td>
</tr>
<tr>
<td>10^-1</td>
<td>10^2</td>
</tr>
<tr>
<td>10^0</td>
<td>10^3</td>
</tr>
<tr>
<td>10^1</td>
<td>10^4</td>
</tr>
<tr>
<td>10^2</td>
<td>10^5</td>
</tr>
<tr>
<td>10^3</td>
<td>10^6</td>
</tr>
</tbody>
</table>

Classical plasma
Dense plasma
High density matter
Condensed matter
WDM
Intérieurs Planétaires
Electronic and ionic structural changes study
(laser shock coupled to XANES diagnostic experiment)
Work on shocked SiO$_2$ with XANES diagnostic

LULI and LLNL experiments
X-rays Absorption Near Edge Spectroscopy

Many probed conditions in WDM range
Work on shocked SiO$_2$ with XANES diagnostic

LULI and LLNL experiments

X-rays Absorption Near Edge Spectroscopy

Many probed conditions in WDM range

Metallization mechanism: allowed energy levels become available in the gap → pseudo-gap is formed

Denoeud et al PRL 2014

In the liquid phase the coordination number increases with density

Detection of phase transitions
(decaying shock using visible diagnostics and laser shocks coupled with X-ray diffraction)
Decaying shocks to detect phase transitions

With one shot you explore a segment of the Hugoniot

If the shock crosses a phase boundary:

(e.g. Hicks et al PRL 2006; Millot et al. Science 2015; Spaulding et al etc..)
Recent results on MgSiO$_3$, MgO, Mg$_2$SiO$_4$

One liquid single phase

MgSiO$_3$

Mg$_2$SiO$_4$

MgO

Melting at 4.7 Mbar

Bolis et al. GRL 2016

Experimental P-T curves:
- Shot 44
- Shot 83
- Shot 81
- McWilliams

Theoretical phase boundaries:
- DaKoker and Stixrude, 2000
- Baoles and Bonov, 2013
- Cabella et al., 2014
- Root et al., 2015
- Miyarnishi et al., 2015

Spaulding Glass

Results:
- Gekko
- LULI

Experimental P-T curves:
- Zann et al., 1998
- Lyzenga and Athens, 1980
- Lu et al., 2004

Gekko et al.

BL

no dissociation signatures
Recent results on MgSiO$_3$, MgO, Mg$_2$SiO$_4$

Good results, but
- phase transitions with small volumes changes could be missed
- it is necessary to be very careful to hydrodynamics effects

--> X-ray diffraction is essential to have a direct information on phase
X-ray diffraction experiment using X-ray laser sources

Previous works on iron: Kalantar et al PRL 2005

Backlighter: 9 beams (2.5 ns) $E_{\text{tot}} = 1.1$ kJ ($3\omega$)
Drive beams: 3 beams (2.5 ns) $E_{\text{tot}} = 400$ J ($3\omega$), 1 mm focal spot, $10^{12}$-$10^{13}$ W/cm$^2$

The results show the presence of hcp iron up to 1.7 Mbar along the Hugoniot.

A. Denoeud et al. PNAS (2016)
X-ray diffraction experiment using X-ray laser sources

Previous works on iron: Kalantar et al PRL 2005

Backlighter: 9 beams (2.5 ns) $E_{\text{tot}} = 1.1 \text{ kJ} \ (3\omega)$
Drive beams: 3 beams (2.5 ns) $E_{\text{tot}} = 400 \text{ J} \ (3\omega)$, 1 mm focal spot, $10^{12}-10^{13} \text{ W/cm}^2$

The results show the presence of hcp iron up to 1.7 Mbar along the Hugoniot.

A. Denoeud et al. PNAS (2016)
X-ray laser sources

Main constraint for X-ray laser source: to have enough photons -> high energy laser

Some examples: X-ray diffraction at Omega 4-10 beams ($\approx 400$ J each), 1ns (Rygg et al. RSI 2012)

: EXAFS at Omega on iron -> 50 laser beams ($\approx 400$ J each) in implosion configuration (Ping et al. PRL 2013)

Critical points: divergence, max energies limited to 10keV

-> Today Synchrotron radiation or XFEL are a great opportunity to have very clean X-ray data on Warm Dense Matter
Main constraint for X-ray laser source:
**to have enough photons -> high energy laser**

Some examples:
- X-ray diffraction at Omega 4-10 beams ($\approx 400$ J each), 1ns  
  (Rygg et al. RSI 2012)
- EXAFS at Omega on iron -> 50 laser beams ($\approx 400$ J each) in implosion configuration  
  (Ping et al PRL 2013)

Critical points: divergence, max energies limited to 10keV

-> **Today synchrotron radiation or XFEL are a great opportunity to have very clean X-ray data on Warm Dense Matter**

How to span a large part of the phase diagram?
Getting off Hugoniot states
(different techniques and constraints)
Techniques to reach off the principal Hugoniot states

Techniques to reach high pressure states colder than Hugoniot

✓ Quasi-isentropic compression

✓ Laser shock on Diamond Anvil Cell (DAC) precompressed target

✓ Double shock, reverberation, reshock, ramp on confined targets
Quasi-isentropic compression

long pulses and high laser energy (>kJ) are necessary
Quasi-isentropic compression

Temperature vs. density

Principal Hugoniot

Single shock

Isentrope

long pulses and high laser energy (>KJ) are necessary

EXPERIMENT at LIL on iron and SiO₂

Laser

Diamond

Quartz or Iron

LIF or Saphire

LIL -> 6-8 Mbar iron and SiO₂

(N. Amadou PoP 2015; A. Benuzzi et al Phys Scripta 2014)

Other works: NIF -> 50 Mbar in the diamond (Smith et al. 2014) OMEGA -> 8 Mbar in the diamond (Bradley et al. PRL 2009)
Laser shock on DAC precompressed target

OMEGA laser-> precompression up to several tens of kbar (Loubeyre et al. 2014)

LULI, recently tested with NH₃ precompression up a few kbar

Constraint: **high laser energy (≥ 1 kJ)**

ANR Pompei
In collaboration with CEA and IMPMC
Double shock, reverberation technique or reshock

Principal Hugoniot

Double shock

« Dynamic precompression »:
Constraints: an excellent control of timing and of precompressed matter

Temperature
Principal Hugoniot
Double shock

ρ₀
Density

Complex thermodynamical path. Thermodynamics conditions can be obtained using rear side diagnostics coupled to hydrodynamical simulations.

Reverberation or reshock

Ramp compression on confined target

Temperature
Principal Hugoniot

ρ
Density

Windows impedance > material impedance

target

these techniques can be used with a laser of moderate energy (100 J)
Some perspectives for HLPF
GeO$_2$ is chemical and structural analogue of SiO$_2$, a major component of earth’s interior

- phase transitions
- metallization
- Re-crystallation

R. Torchio, S. Pascarelli, O. Mathon
LULI and CELIA
Perspectives at short term: EXAFS experiment on shocked GeO$_2$

GeO$_2$ is chemical and structural analogue of SiO$_2$, a major component of earth’s interior

R. Torchio, S. Pascarelli, O. Mathon
LULI and CELIA

- phase transitions
- metallization
- Re-crystallation

Other materials interesting to investigate: olivine (Mg$_2$FeSiO$_4$) or MgFeO
Perspectives at long term: study of $\text{H}_2\text{O}/\text{NH}_3/\text{CH}_4$

The context -> icy giant planets, Uranus and Neptune (2/3 of their mass)

The states of matter, equations of state, transport, chemical and structural properties of the $\text{H}_2\text{O}/\text{CH}_4/\text{NH}_3$ system are basically unknown at extreme conditions.

$$g(r)$$

Ab initio calculations predict polymerization of shocked $\text{CH}_4$

$$\text{Target are the challenge}$$

$\text{ Sherman et al. 2012}$

$\text{-> shock + X-ray diffraction/scattering}$
Some points for discussion

HLPF opens a great opportunity for Warm Dense Matter microscopic characterization

Beside X-ray diagnostics, laser compression must be characterized by independent diagnostic (SOP and VISAR)

Interesting data along the Hugoniot states up to \( \approx 10 \) Mbar will be "easily" obtained with 100 J laser.

Concerning off Hugoniot states, some constraints exist. To keep low temperatures and high pressures is not trivial, but possible with reverberation, multiple shocks etc... The range of pressures is specific to each design of target

It is important to have different X-ray diagnostics simultaneously
Thank you for your attention and thank you to collaborators

R. Bolis, A. Ravasio, T. Vinci, A. Denoeud, E. Brambrink, M. Guarguaglini, M. Koenig

LULI

F. Dorchies, J. Gaudin, P.M. Leguay CELIA

G. Morard, F. Guyot, F. Datchi, S. Ninet, M. Harmand, G. Fiquet IMPMC, UMPC

S. Brygoo, F. Occelli, P. Loubeyre CEA

N. Ozaki, R. Kodama, Un of Osaka

T. Sekine Un of Hiroshima

S. Mazevet, R. Musella LUTH

J. Bouchet, F. Remus, V. Recoules CEA

S. Le Pape, R. Smith LLNL

S. Pascarelli, R. Torchio, O. Maton ESRF

Thank you to the laser and technical staff of laser facilities

ANR SECHEL, PLANETLAB and POMPEI