From quasi static to dynamic compression: A unique opportunity to study the influence of kinetics on various physical phenomena

A. Sollier , F. Occelli, E. Lescoute, C. Pepin, A. Dewaele, S. Brygoo, L. Videau, V. Recoules, J. Bouchet, J. Bontaz, L. Soulard, and P. Loubeyre

Workshop on Studies of Dynamically Compressed Matter with X-rays, 29 and 30 March 2017 - ESRF

Outline

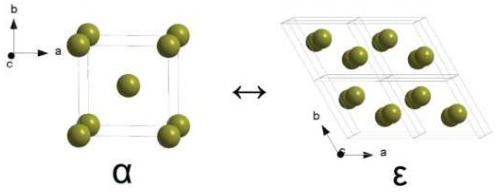
- Why do we want to perform dynamic compressions experiments in front of synchrotrons?
- What is our experimental strategy to do it ?
- First results and examples of possible future experiments

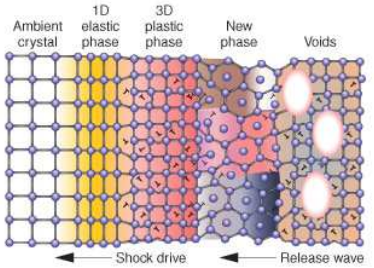
Relevance of synchrotron X-Ray measurements for dynamic compression studies

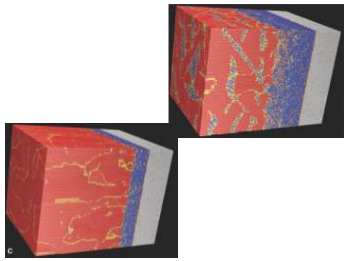
Understanding the dynamic behavior of materials require experiments that provide real-time, in-situ, spatially resolved measurements on relevant length and timescales

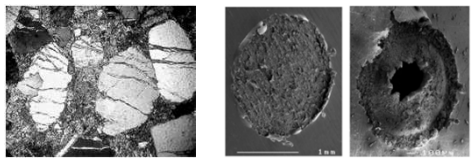
Topics of interest:

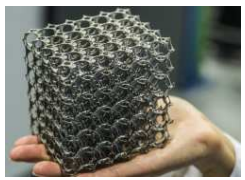
- Phase transitions, chemical reactions
  - Kynetics
  - Nucleation & growth, diffusion
  - Atomic rearrangement, microstruture evolution
- Metastability, intermediate phases
  - Metastable phases
  - Over heating / Over compression
- Plasticity
  - Dislocations dynamics
- Damage & Failure
  - Nucleation & growth
- Real, Complex Materials
  - Role of grains interfaces
  - Void compaction
- …

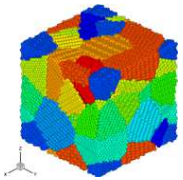












Diagnostics such as X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS) and Phase contrast imaging (PCI) available at ESRF offer unique opportunities for such ultrafast spatially resolved measurements

A strategy for Studies of Dynamic Behavior of Materials at ESRF

Apply dynamic loadings at different time scales on the same material and characterize it with different X-ray techniques

Samples + Loading platforms + Synchrotron

High purity (>99.9%)
Which impurities ?
Grain size ?
Oxydation layer ?
Compatible with X-rays !

Different loading paths
and time scales

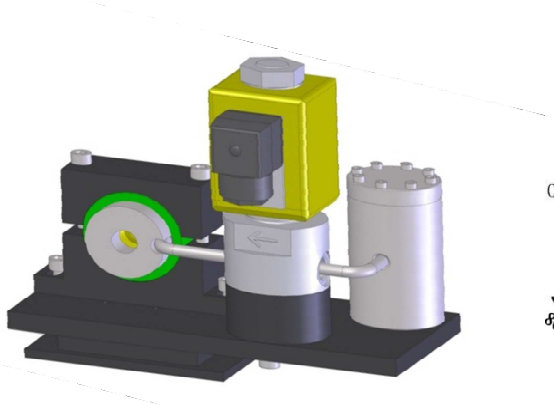
P/T measurements with
relevant time resolution

XRD, XAS, PCI
XMCD and CDI ?

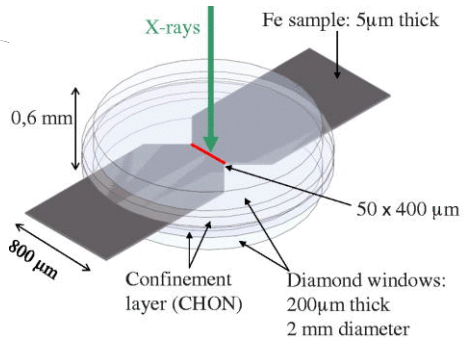
- Need to adapt the sample and the loading device to the beamline environment
- Need to adapt the beamline to the time-resolved conditions
- Need to implement P/T measurements

A strategy for Studies of Dynamic Behavior of Materials at ESRF

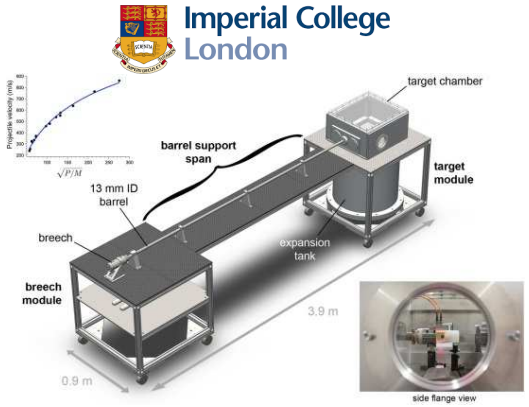
- Various dynamic loading facilities available or in development at ESRF
  - Different loading paths & strain rates
  - Large P/T range



GPa/ms

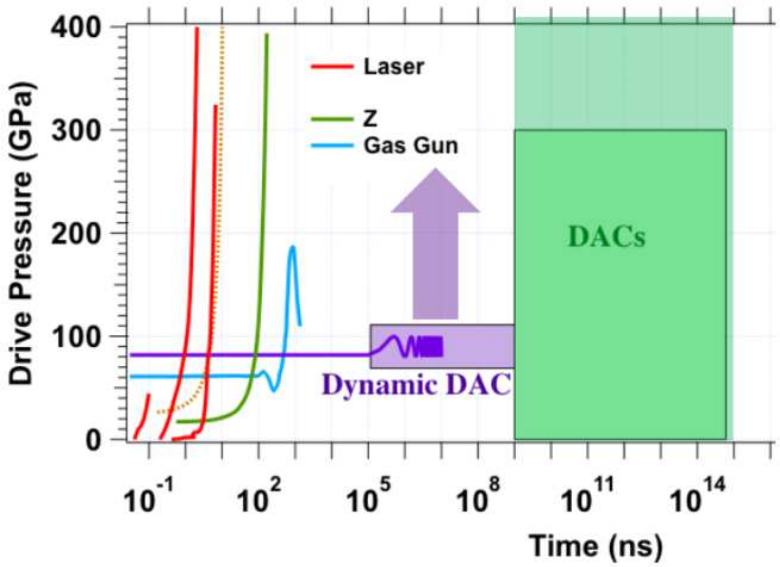


GPa/100µs



GPa/µs

GPa/ns



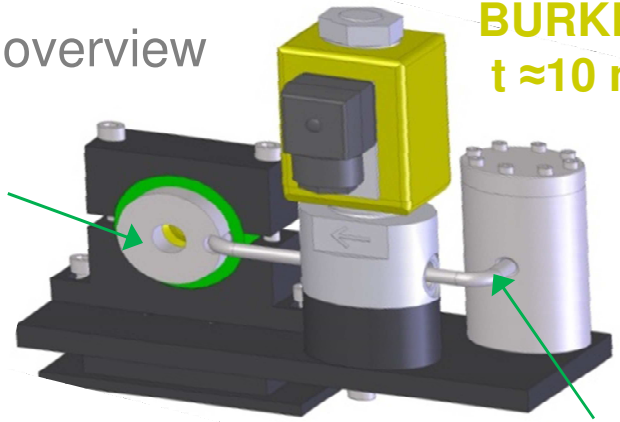
A unique opportunity to investigate a phenomena at various time scales with the same microscopic information from X-ray measurements (XRD, XAS, PCI, …)

ms dynamic membrane DAC

Setup overview

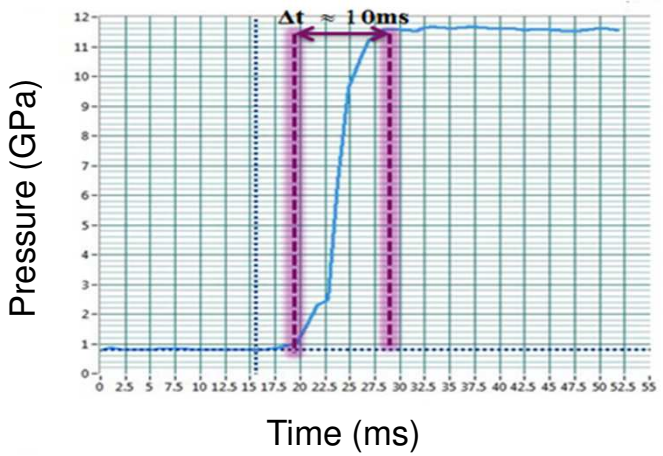
Electrovalve
BURKERT
t ≈10 ms

Membrane DAC



Gas tank

¼" tubing: large gas flow rate

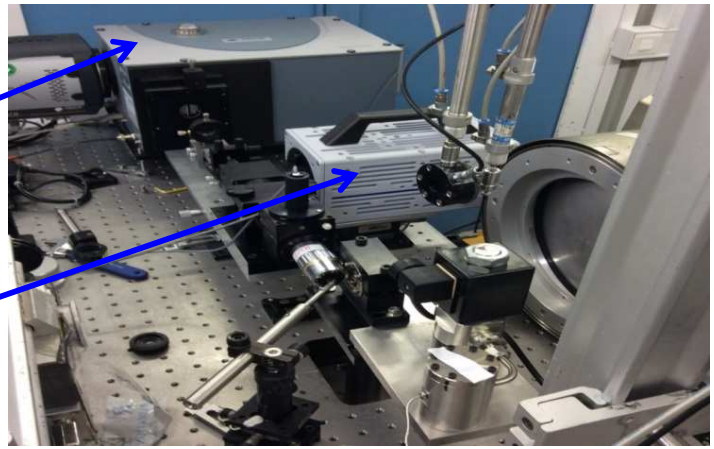


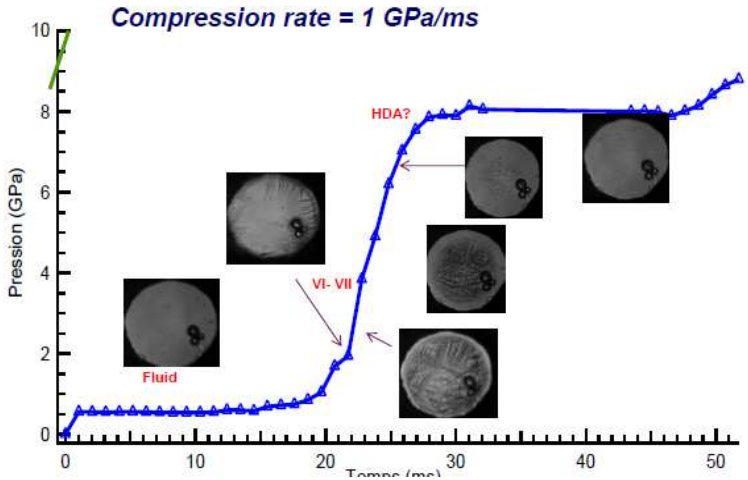
Pressure increase
0.1 to 1 GPa/ms

Proposal HC-2183 on ID27: Dynamic compression of water probed by XRD (30 keV, 5x5µm)

Monitoring of P(t) by Ruby luminescence

Monitoring of the sample evolution with a rapid camera (2000 frames/s)





ms time resolved EXAF measurement of the α→ω transition in Zr

The α → ω phase transformation in zirconium followed with ms-scale time-resolved X-ray absorption spectroscopy

A. Dewaele ✉, R. André, F. Occelli, O. Mathon, S. Pascarelli, T. Irifune & P. Loubeyre

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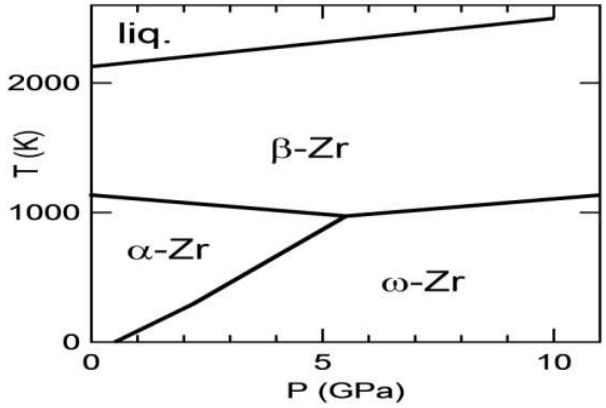
Journal
High Pressure Research ›
An International Journal
Volume 36, 2016 - Issue 3: Special Issue: Frontiers of High Pressure X-ray Absorption Spectroscopy

Earlier work:

Zr polycrystal of 99.98 % purity
Non-hydrostatic or quasi-hydro-static
in methanol+ethanol pressure medium

MK Jacobsen *et al.*, J Appl. Phys. **118**, 025902 (2015).

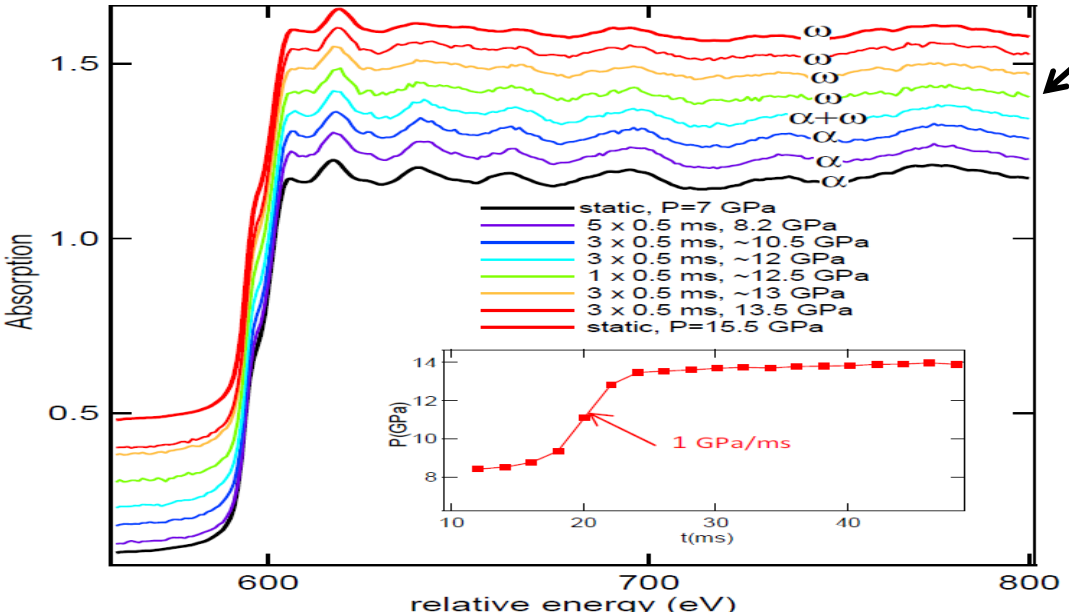
Sluggish kinetics with transition times reaching several minutes

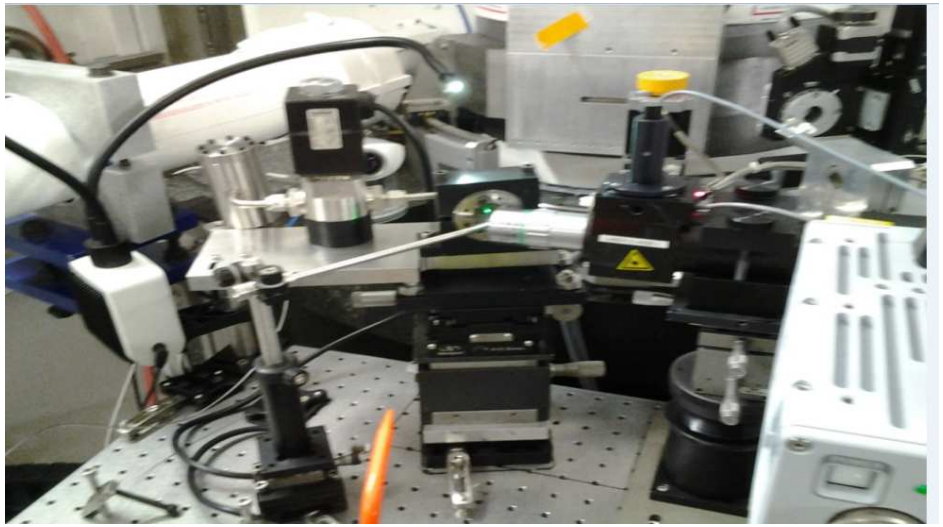


Experiment performed on ID24

Zr polycrystal of 99.9+ purity
Hydrostatically compressed in neon
Zr Kedge (18,0 keV)
Nanopolycristal DAC
Frelon detector

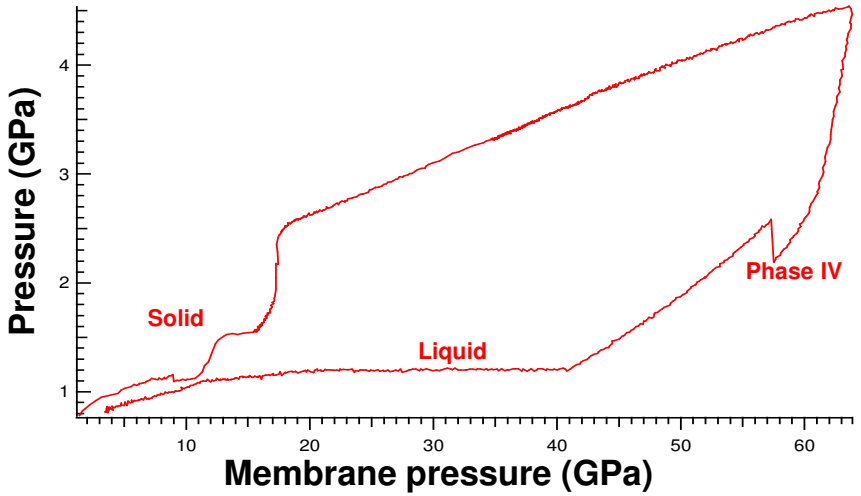
$P_{\alpha\rightarrow\omega}$ = 11 GPa (static) vs 12±1 GPa (dynamic)
The transition is achieved in less than a few ms !

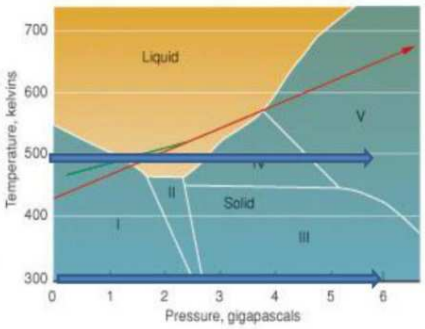




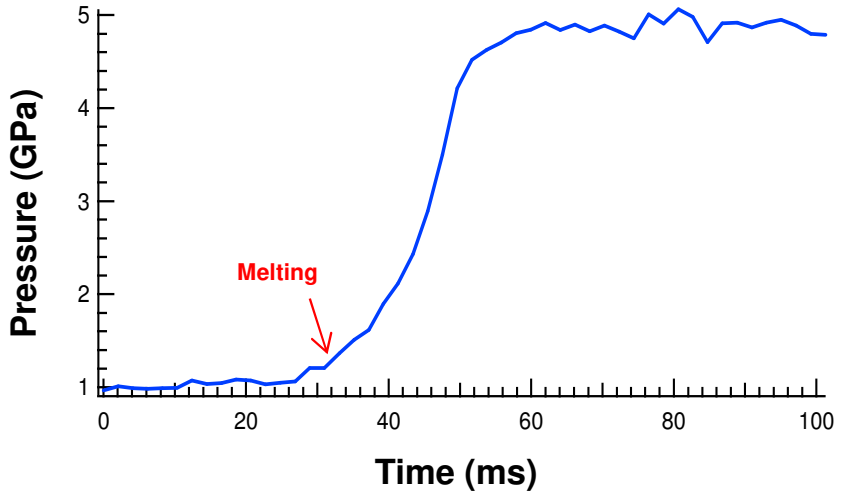
First trials on Bi

Static DAC experiment @ 498 K





Dynamic DAC experiment @ 498 K



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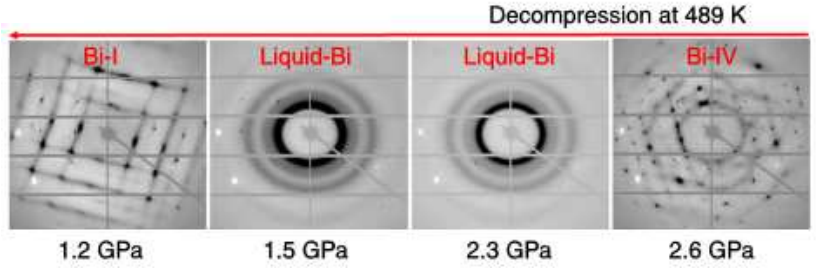
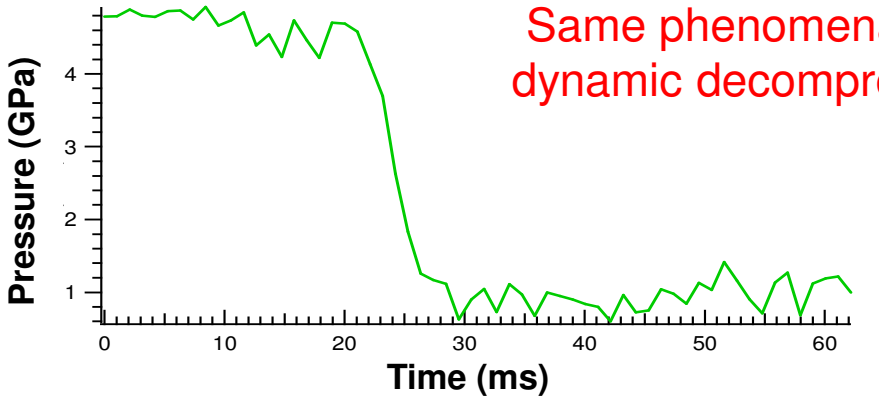
A metastable liquid melted from a crystalline solid under decompression

Chuanlong Lin[1], Jesse S. Smith[1], Stanislav V. Sinogeikin[1], Yoshio Kono[1], Changyong Park[1], Curtis Kenney-Benson[1] & Guoyin Shen[1]





Same phenomena under dynamic decompression ?

Ability to probe different isotherms of Bi both under compression and release

µs Ohmic ramps

JOURNAL OF APPLIED PHYSICS **115**, 093513 (2014)

A microsecond time resolved x-ray absorption near edge structure synchrotron study of phase transitions in Fe undergoing ramp heating at high pressure

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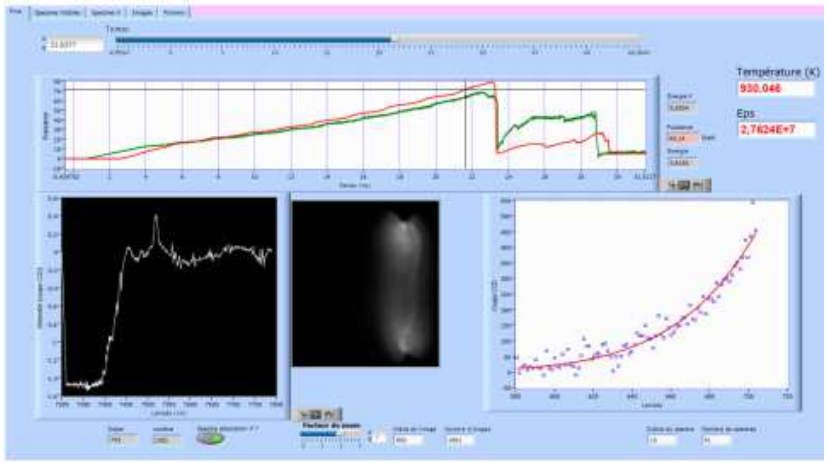
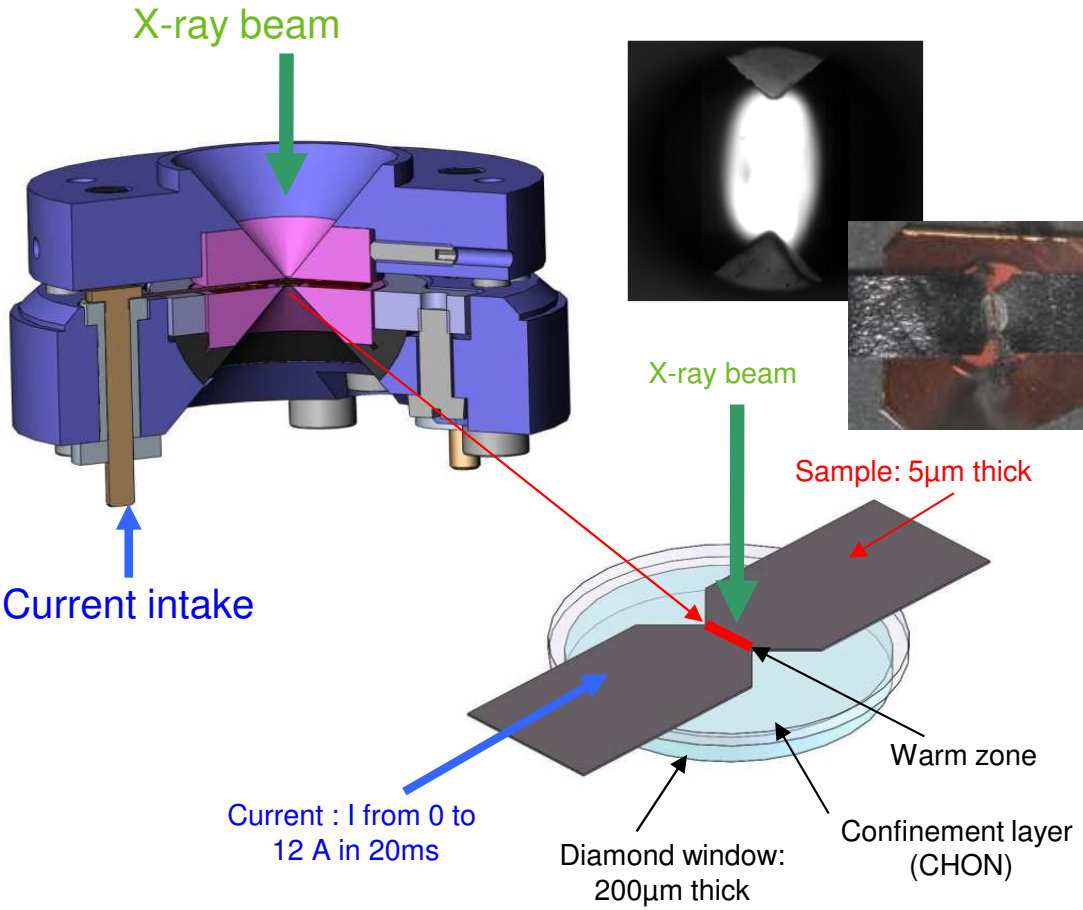
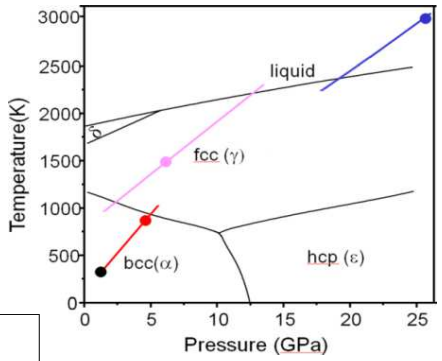
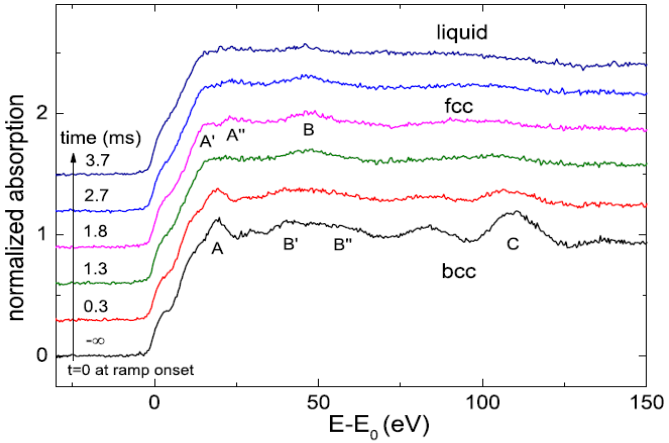


Monitoring of T(t) by time resolved spectral pyrometry



Quasi-isochoric heating



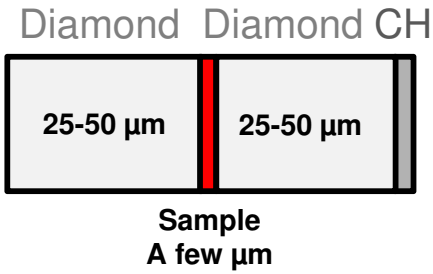


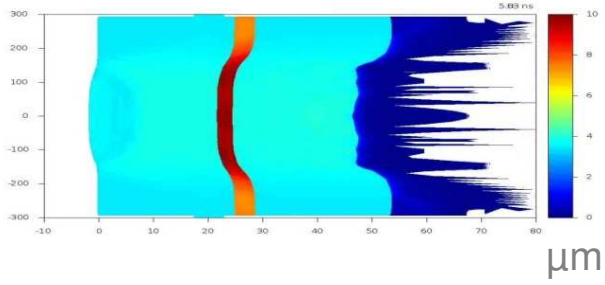
ns Laser shock compression

Portable high power laser systems

E ~ 20-50 J, τ ~4-100 ns

Up to 3 Mbar with ablator and small diameter PZP



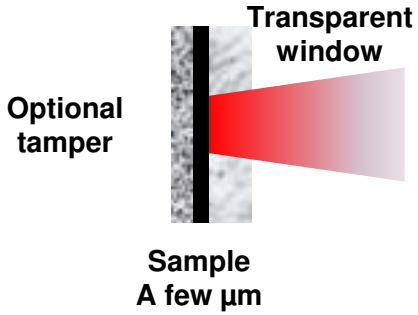


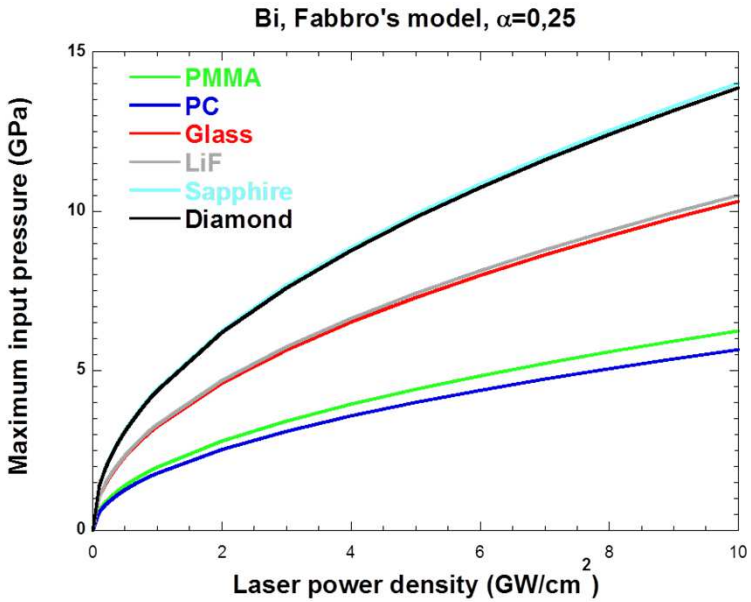
~2D, scalable pressure, poor reproducibility

Tabletop low power laser systems

E < 1 J, τ ~5-10 ns

Up to 10 GPa in confined geometry

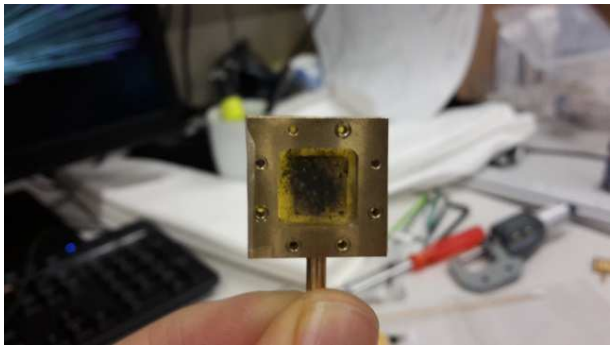




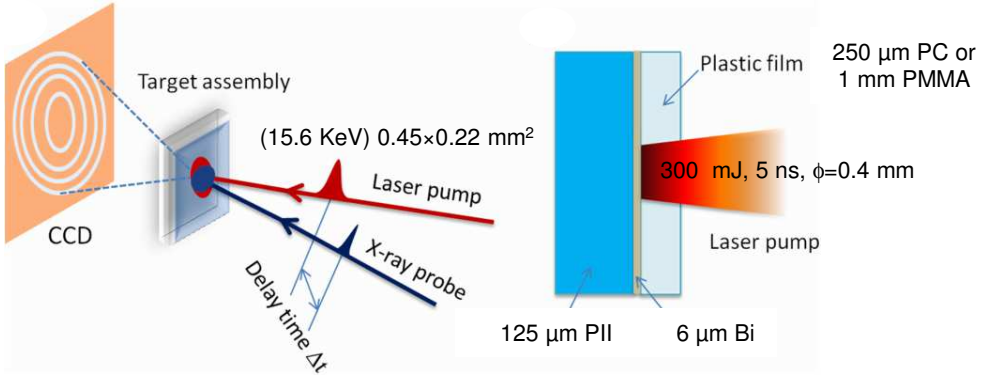
1D, scalable pressure, very reproducible

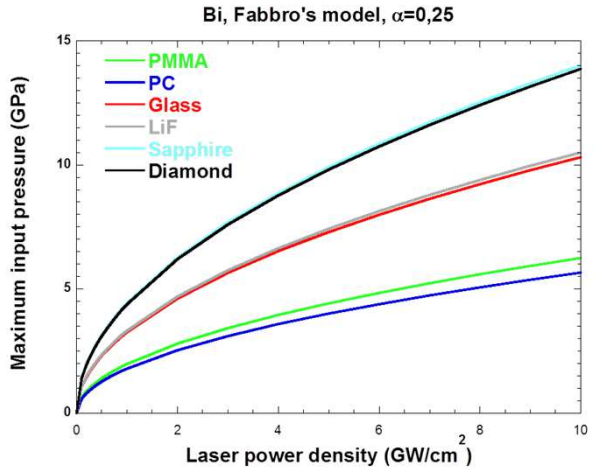
Bi laser shock compression on ID09

Experiment HC 2848 (Nov 2016)



Confined geometry setup with the inline EKSPLA ns laser system

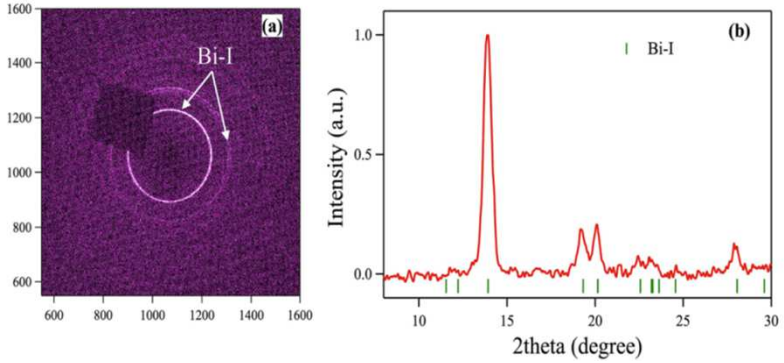


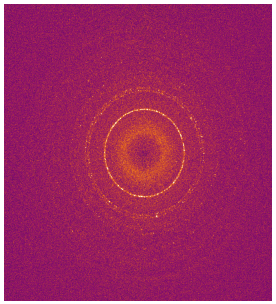


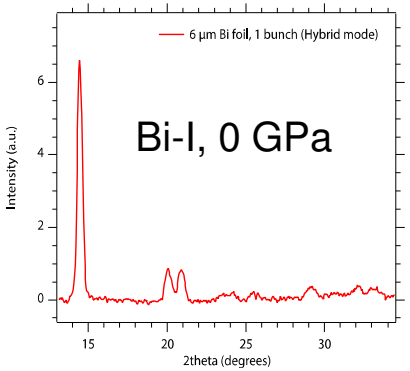
For each target (~ 12 x 12 mm), between 6 and 10 laser shots could be fired

Bi laser shock compression on ID09

Reference Bi-I pattern

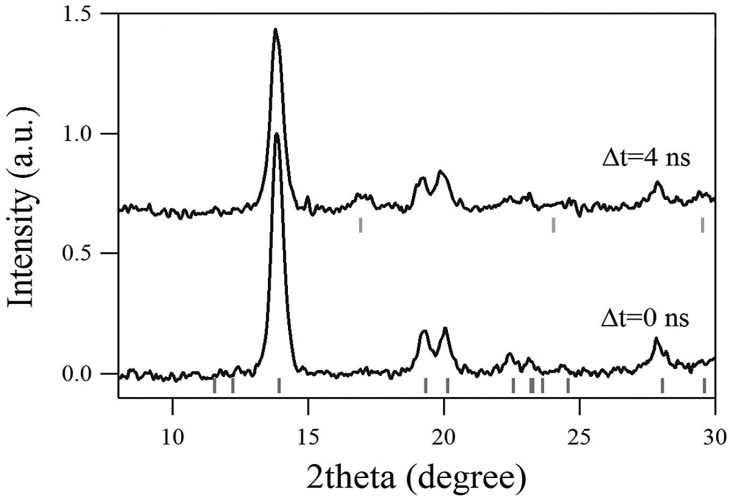




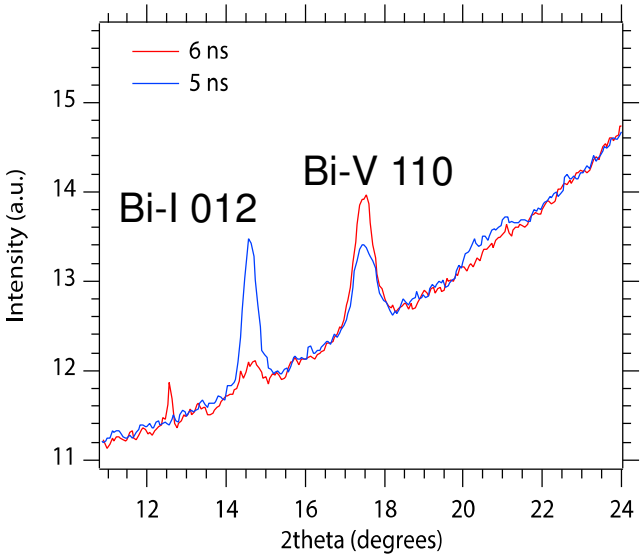


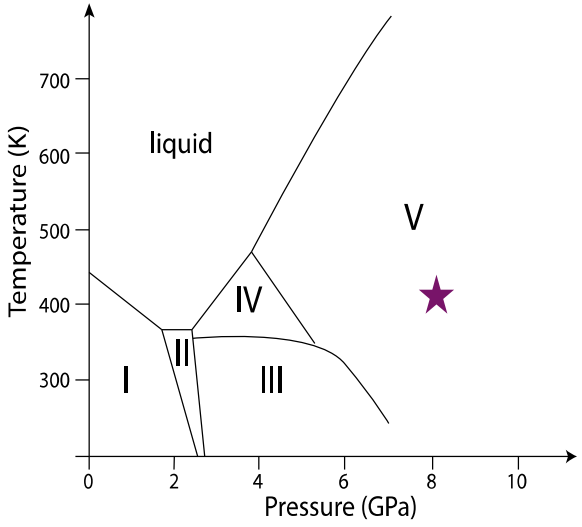
ID09, single bunch exposure

Shock compression @ P ~ 8 GPa



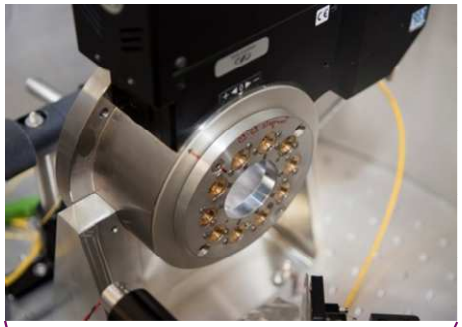
J. Hu et al., Complex structural dynamics of bismuth under laser-driven compression. Appl. Phys. Lett. **103**, 161904 (2013).



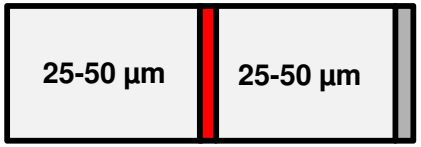


Bi-V (bcc) forms after 5 ns with a compression (V/V_0) corresponding to a pressure of 8 GPa.
At 6 ns, the majority of the 6 µm sample is compressed in the high pressure state.

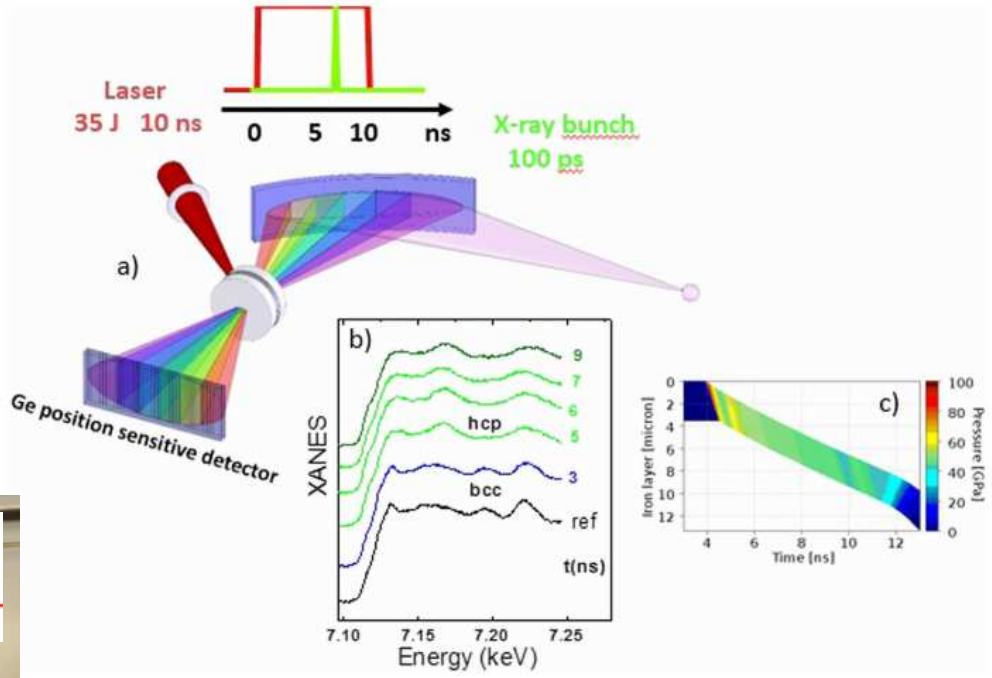
Fe laser shock compression on ID24

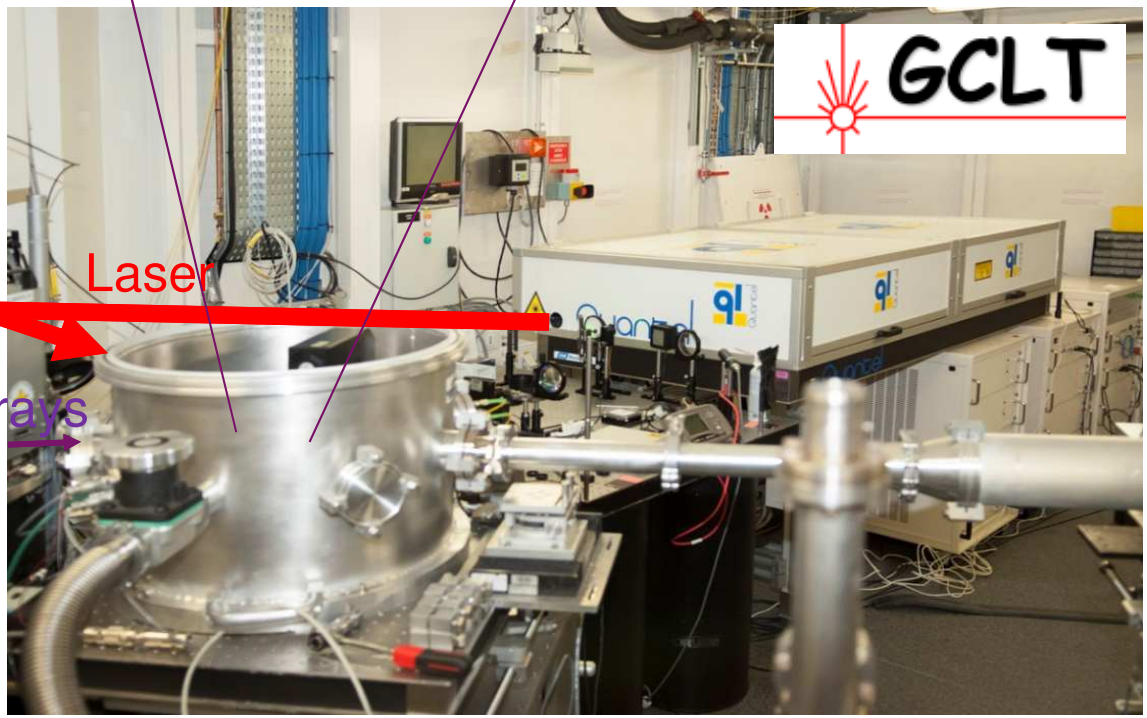


Diamond Diamond CH



Sample
A few µm





XH detector

Fe laser shock compression on ID24

SCIENTIFIC REPORTS

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Probing local and electronic structure in Warm Dense Matter: single pulse synchrotron x-ray absorption spectroscopy on shocked Fe

Raffaella Torchio[1,2], Florent Occelli[1], Olivier Mathon[2], Arnaud Sollier[1], Emilien Lescoute[1], Laurent Videau[1], Tommaso Vinci[3,4], Alessandra Benuzzi-Mounaix[3,4], Jon Headspith[5], William Helsby[5], Simon Bland[6], Daniel Eakins[5,6], David Chapman[6], Sakura Pascarelli[2] & Paul Loubeyre[1]

Laser parameters

E = 23 J, τ= 10 ns, ϕ ~380 µm (PZP)

I ~ 2 10^{12} W/cm^2

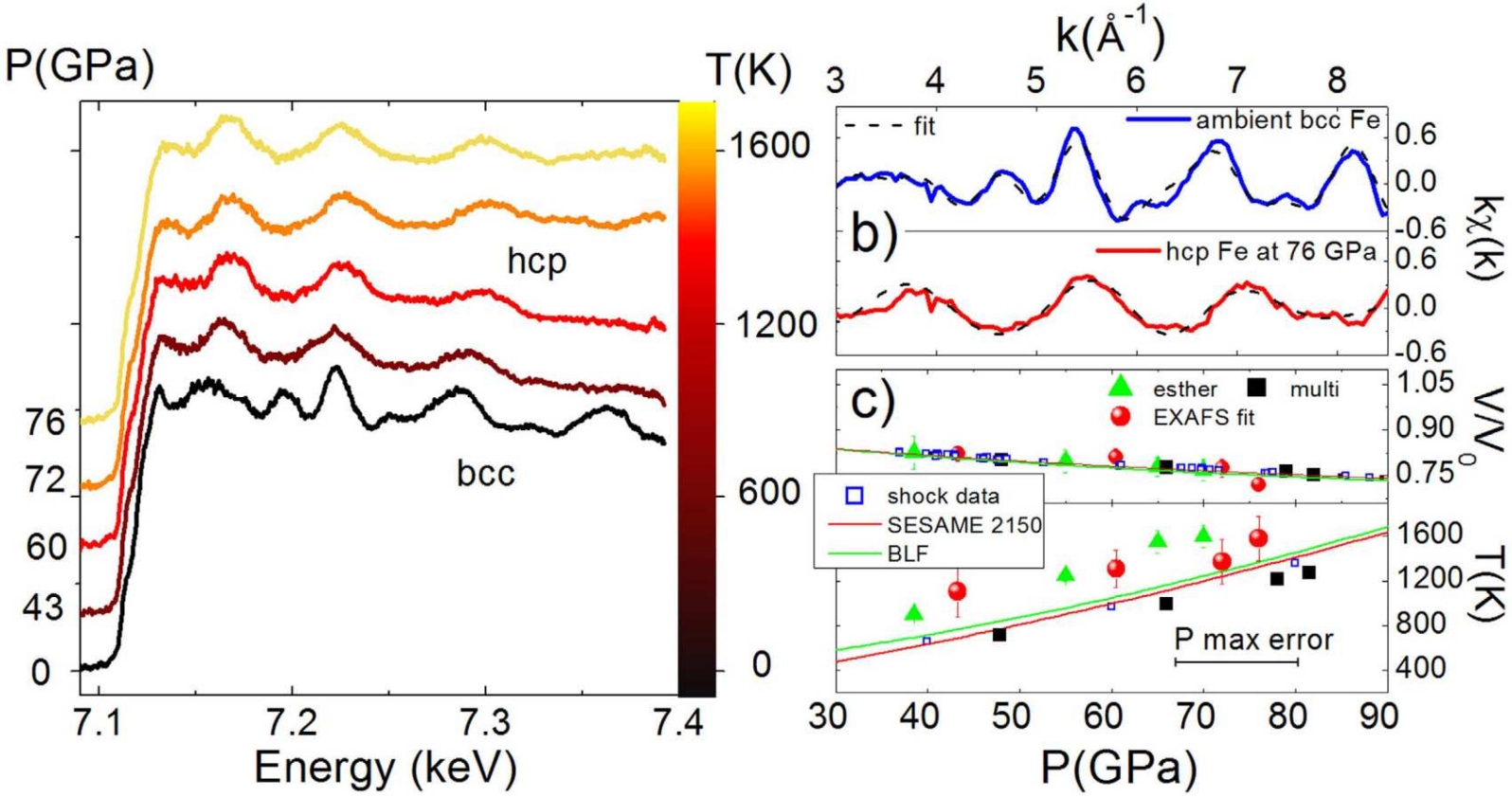
X-rays 5 x 90 µm

The bcc-hcp transition is clearly observed

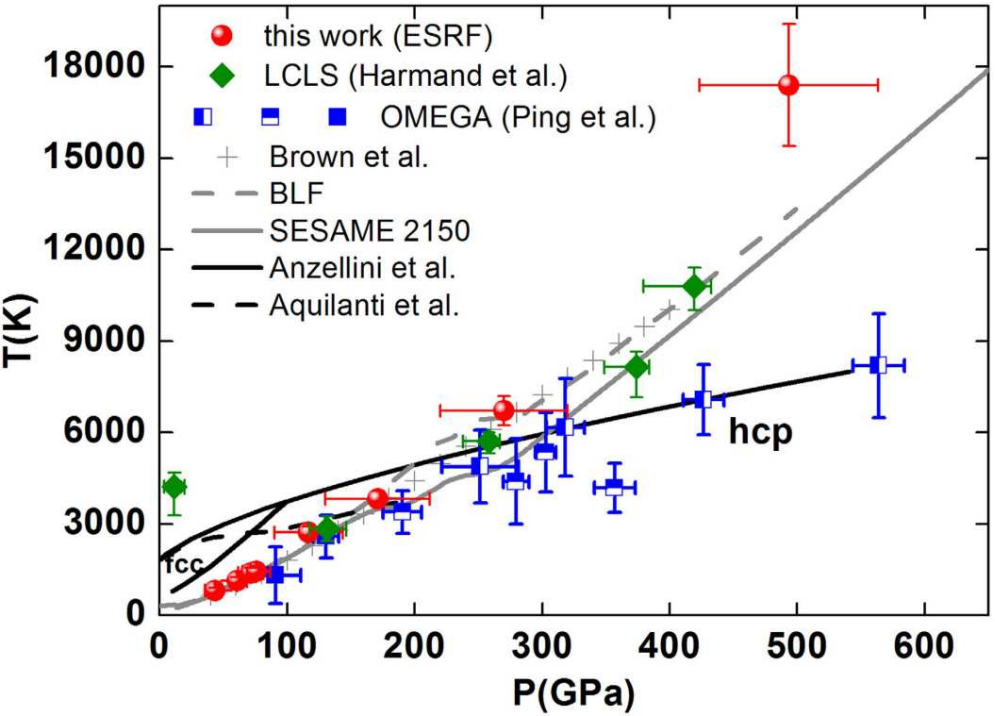
The reproducibility is good but not perfect

Low pressure data

Single pulse acquisitions



Fe laser shock compression on ID24



Laser parameters

E = 31 J, τ = 10 ns, ϕ~90µm

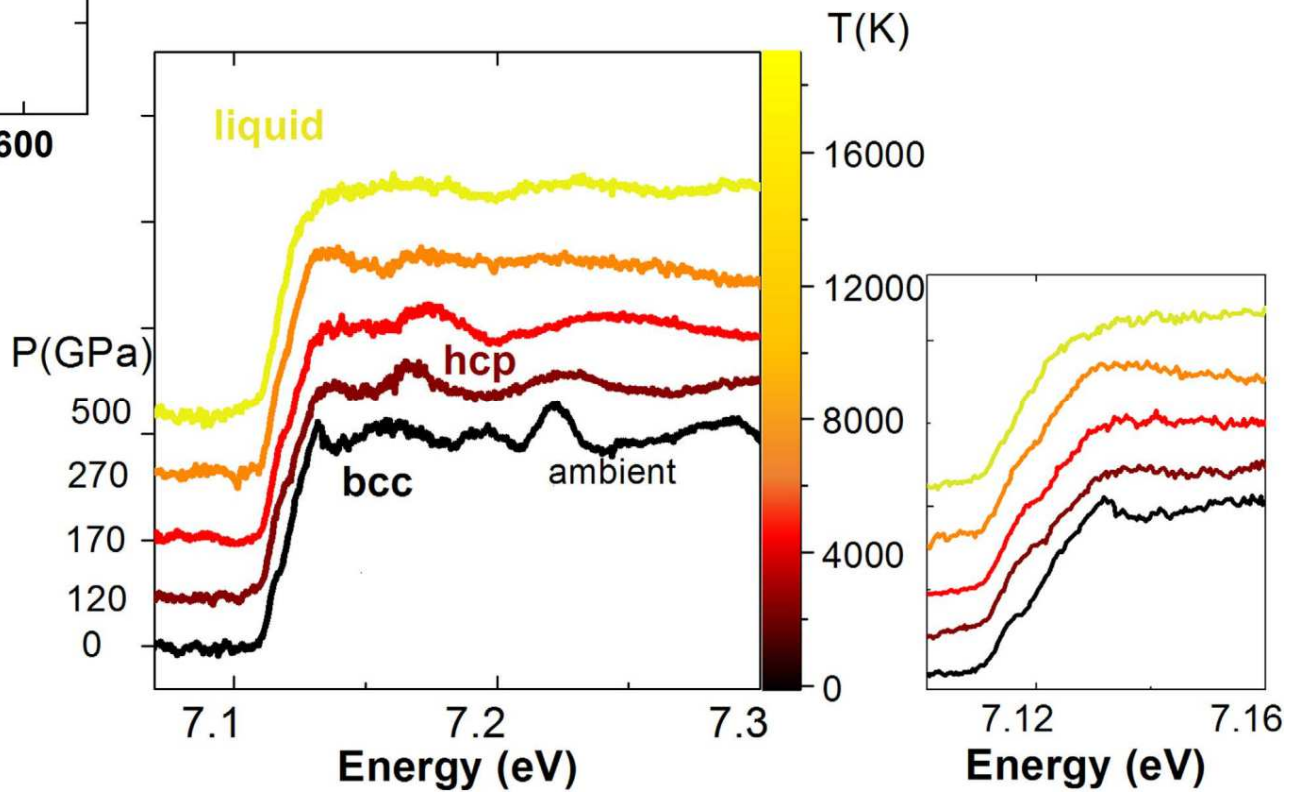
I_{max} ~ 5 10^{13} W/cm^2

X-rays 5 x 7 µm

High pressure data

Single pulse acquisitions

Lower quality because of X-ray focusing optics



Conclusion

- Various dynamic loading facilities available or in development at ESRF
  - Different loading paths
  - Different strain rates
- A unique opportunity to study various aspects of the dynamic behavior of materials in a large P/T range
- Collaborative work to go from proof of principle experiments to systematic fine microscopic measurements!
- But a lot of issues still need to be fixed
  - Integration into the beamlines
  - Adaptation of the existing beamlines to time-resolved conditions
  - New XR diagnostics (fast gate, high frame rate, high sensitivity)
  - New P/T diagnostics at all the relevant time scales

Strong collaboration required

You are all welcome …