Development of a laser-driven shock compression platform at the ID09 beamline of the ESRF-EBS

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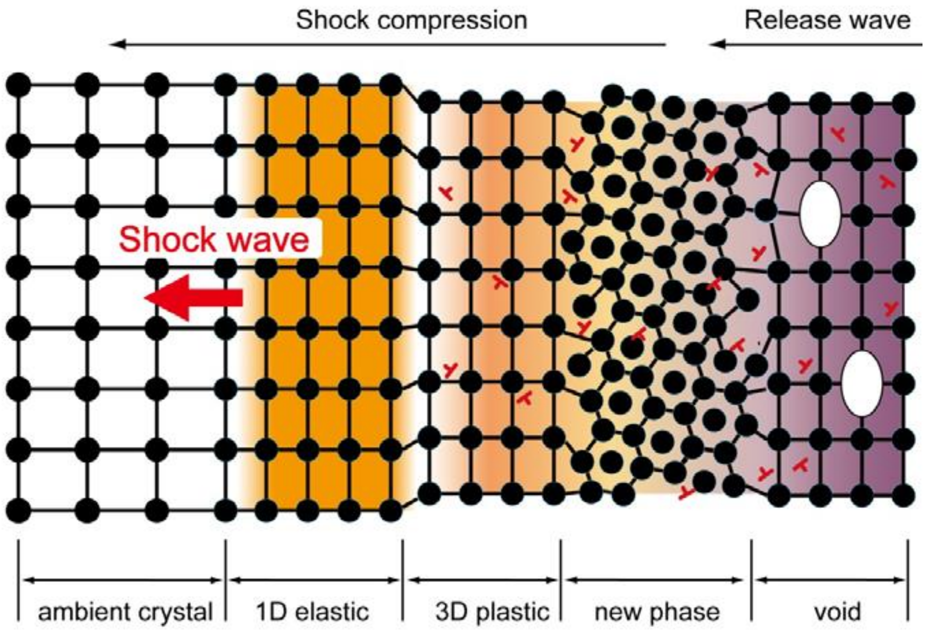
OUTLINE

1. Introduction
2. Description of the laser shock platform
3. First experimental results
4. Conclusion

1. Introduction

An ongoing revolution in the field of HEDP

- Coupling of new dynamic compression platforms with large scale X-ray facilities
  - Can probe matter *in situ* under extreme conditions of pressure and temperature
  - Temporal and spatial scales commensurate with those of microscopic simulations



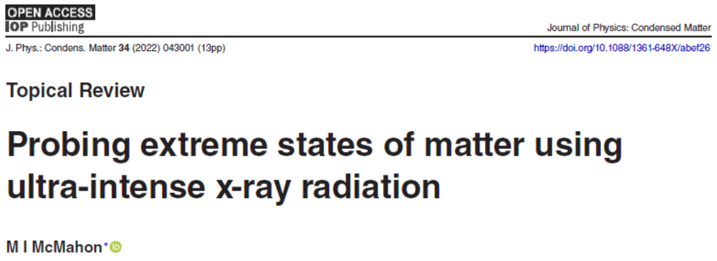
- Different X-ray techniques allowing to probe various physical phenomena
  - XRD, XAS, XES, PCI, …


nature reviews methods primers https://doi.org/10.1038/s43586-023-00264-5

Primer Check for updates

Materials under extreme conditions using large X-ray facilities

Sakura Pascarelli[1], Malcolm McMahon[2], Charles Pépin[3], Olivier Mathon[4], Raymond F. Smith[5], Wendy L. Mao[6], Hanns-Peter Liermann[7] & Paul Loubeyre[3]

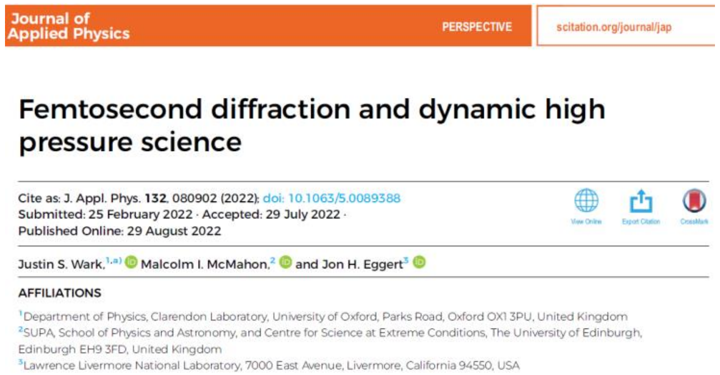

OPEN ACCESS
IOP Publishing
Journal of Physics: Condensed Matter

J. Phys.: Condens. Matter **34** (2022) 043001 (13pp) https://doi.org/10.1088/1361-648X/abef26

Topical Review

Probing extreme states of matter using ultra-intense x-ray radiation

M I McMahon*


Journal of Applied Physics PERSPECTIVE scitation.org/journal/jap

Femtosecond diffraction and dynamic high pressure science

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Justin S. Wark,[1,a)] Malcolm I. McMahon,[2] and Jon H. Eggert[3]

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An ongoing revolution in the field of HEDP

- Implementation of dynamic compression platforms @ all the major large scale X-ray facilities

REVIEW OF SCIENTIFIC INSTRUMENTS 88, 105113 (2017)

Shock drive capabilities of a 30-Joule laser at the matter in extreme conditions hutch of the Linac Coherent Light Source

Shaughnessy Brennan Brown,[1,2,a)] Akel Hashim,[2] Arianna Gleason,[3] Eric Galtier,[2] Inhyuk Nam,[2] Zhou Xing,[2] Alan Fry,[2] Andy MacKinnon,[2] Bob Nagler,[2] Eduardo Granados,[2] and Hae Ja Lee[2]
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[3]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Review of Scientific Instruments | ARTICLE | scitation.org/journal/rsi

The Dynamic Compression Sector laser: A 100-J UV laser for dynamic compression research

Cite as: Rev. Sci. Instrum. 90, 053001 (2019); doi: 10.1063/1.5088049
Submitted: 7 January 2019 • Accepted: 12 April 2019 •
Published Online: 10 May 2019

D. Broege,[1,a)] S. Fochs,[1] G. Brent,[1] J. Bromage,[1] C. Dorrer,[1] R. F. Earley,[1] M. J. Guardalben,[1] J. A. Marozas,[1] R. G. Roides,[1] J. Sethian,[2] X. Wang,[2] D. Weiner,[1] J. Zweiback,[3,b)] and J. D. Zuegel[1]

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[2]Dynamic Compression Sector (DCS), Institute for Shock Physics, Washington State University, Argonne, Illinois 60439, USA
[3]Logos Technologies, Fairfax, Virginia 22031, USA

Review of Scientific Instruments | ARTICLE | scitation.org/journal/rsi

The laser shock station in the dynamic compression sector. I

Cite as: Rev. Sci. Instrum. 90, 053901 (2019); doi: 10.1063/1.5088367
Submitted: 9 January 2019 • Accepted: 12 April 2019 •
Published Online: 10 May 2019

Xiaoming Wang,[1] Paulo Rigg,[1] John Sethian,[1] Nicholas Sinclair,[1] Nicholas Weir,[1] Brendan Williams,[1] Jun Zhang,[1] James Hawreliak,[2] Yoshimasa Toyoda,[2] Yogendra Gupta,[2,a)] Yuelin Li,[1,3] Douglas Broege,[4] Jake Bromage,[4] Robert Earley,[4] Dale Guy,[4] and Jonathan Zuegel[4]

High Power Laser Science and Engineering, (2018), Vol. 6, e65, 10 pages.

doi:10.1017/hpl.2018.56

Development of a 100 J, 10 Hz laser for compression experiments at the High Energy Density instrument at the European XFEL

Paul Mason[1], Saumyabrata Banerjee[1], Jodie Smith[1], Thomas Butcher[1], Jonathan Phillips[1], Hauke Höppner[2], Dominik Möller[2], Klaus Ertel[1], Mariastefania De Vido[1], Ian Hollingham[1], Andrew Norton[1], Stephanie Tomlinson[1], Tinesimba Zata[1], Jorge Suarez Merchan[1], Chris Hooker[1], Mike Tyldesley[1], Toma Toncian[2], Cristina Hernandez-Gomez[1], Chris Edwards[1], and John Collier[1]
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[2]Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf e.V., D-01328 Dresden, Germany

applied sciences | MDPI

Article

Development of an Experimental Platform for Combinative Use of an XFEL and a High-Power Nanosecond Laser

Yuichi Inubushi [1,2,*], Toshinori Yabuuchi [1,2], Tadashi Togashi [1,2], Keiichi Sueda [2], Kohei Miyanishi [2], Yoshinori Tange [1], Norimasa Ozaki [3,4], Takeshi Matsuoka [3], Ryosuke Kodama [3,4], Taito Osaka [2], Satoshi Matsuyama [3], Kazuto Yamauchi [3], Hirokatsu Yumoto [1,2], Takahisa Koyama [1,2], Haruhiko Ohashi [1,2], Kensuke Tono [1,2] and Makina Yabashi [1,2]

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An experimental platform using high-power, high-intensity optical lasers with the hard X-ray free-electron laser at SACLA[1]

Toshinori Yabuuchi,[a*] Akira Kon,[a,b] Yuichi Inubushi,[a,b] Tadashi Togahi,[a,b] Keiichi Sueda,[a] Toshiro Itoga,[a,b] Kyo Nakajima,[a] Hideaki Habara,[c] Ryosuke Kodama,[c,d] Hiromitsu Tomizawa[a,b] and Makina Yabashi[a,b]

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Development of shock-dynamics study with synchrotron-based time-resolved X-ray diffraction using an Nd:glass laser system

Sota Takagi,[a,b*] Kouhei Ichiyanagi,[c,b] Atsushi Kyono,[a] Shunsuke Nozawa,[b] Nobuaki Kawai,[d] Ryo Fukaya,[b] Nobumasa Funamori[b] and Shin-ichi Adachi[b]

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The High Power Laser Facility @ ID24-ED

- HPLF-I = 100 J laser + XAS + line VISAR
  - Fully operational

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‡ Now at European XFEL, Schenefeld, Germany.

Towards a dynamic compression facility at the ESRF

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- HPLF-II = Laser upgrade to 200 J IR / 140 J Green + extend to XRD, XRI, XES
  - Foreseen in the future

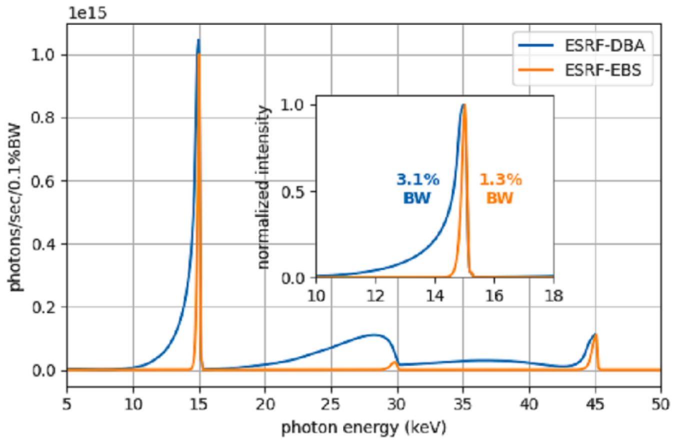
LTP HC-4528 submitted on ID09 in 2021 to pave the way for HPLF-II

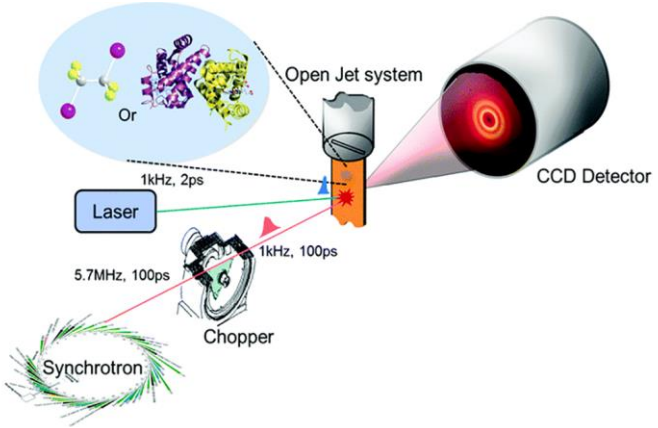
A few words about the ID09 beamline

- Beamline fully dedicated to time-resolved X-ray scattering/diffraction experiments
  - Part of the Complex System and Biomedical Sciences (CBS) group at ESRF
  - Custom advanced system of fast choppers and shutters → phenomena can be tracked as a function of time with 100 ps resolution up to seconds (or more)
  - Phenomena investigated = chemical or biological reactions, light-induced phase transitions in solid-state samples, laser-induced structural changes in colloidal systems

- ID09 has greatly benefited from the EBS upgrade (enhanced spectral purity of the beam)
  - Significant reduction of the second harmonic contamination
  - Bandwidth reduction (~ 1.5%)
  - Higher symmetry of the peak shape

Ultrafast pump–probe experiments, can now be performed with a 5-fold higher flux without employing any multilayer monochromator





Past solid state XRD experiments on ID09

- Already used to study phase transitions in solids at moderate pressure
  - Experiments on Sn and Bi

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Observation of the shock-induced β-Sn to b.c.t.-Sn transition using time-resolved X-ray diffraction

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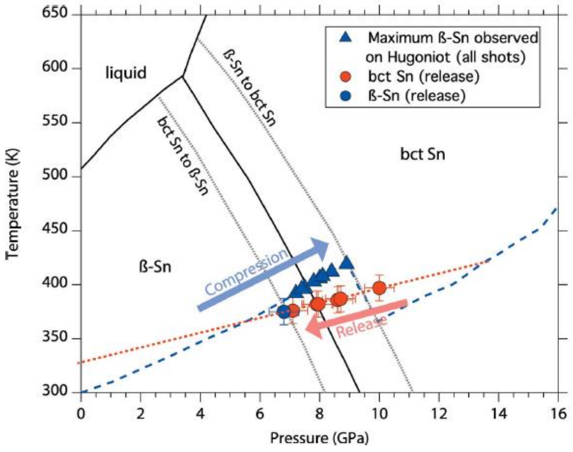

PHYSICAL REVIEW B **100**, 060101(R) (2019)
Rapid Communications

Kinetics and structural changes in dynamically compressed bismuth

Charles M. Pépin,[1,*] Arnaud Sollier,[1] Adrien Marizy,[1] Florent Occelli,[1] Mathias Sander,[2] Raffaella Torchio,[2] and Paul Loubeyre[1]
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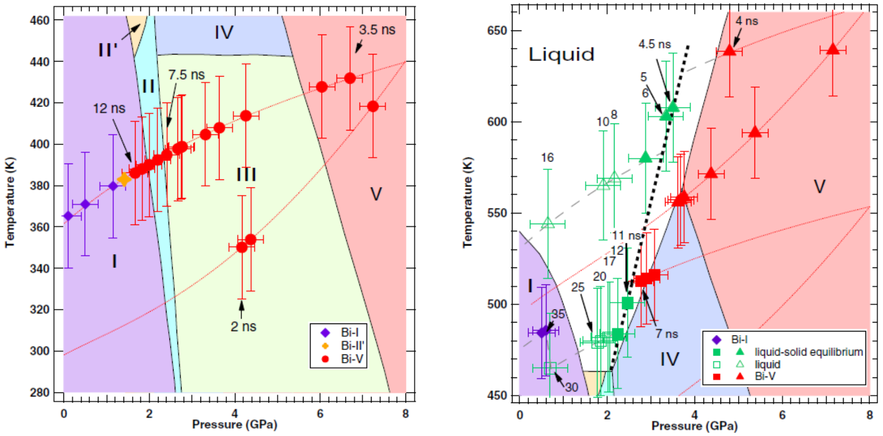
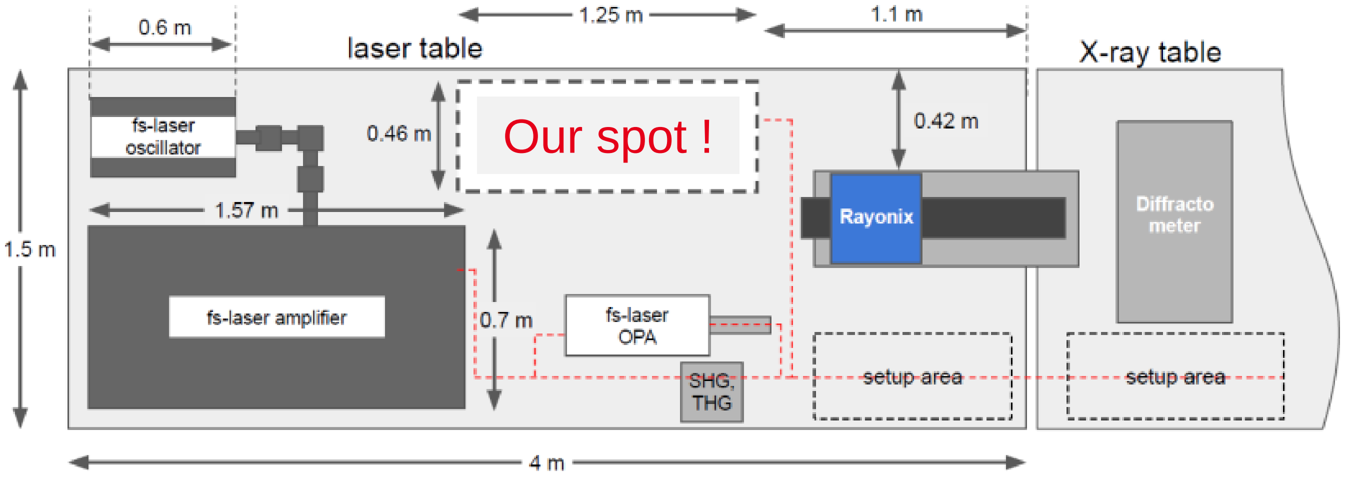


- But maximum pressure limited by the absence of vacuum chamber
  - Confined interaction scheme → P_{max} ≤ 15 GPa

2. The laser shock compression platform

The laser shock compression platform project @ ID09

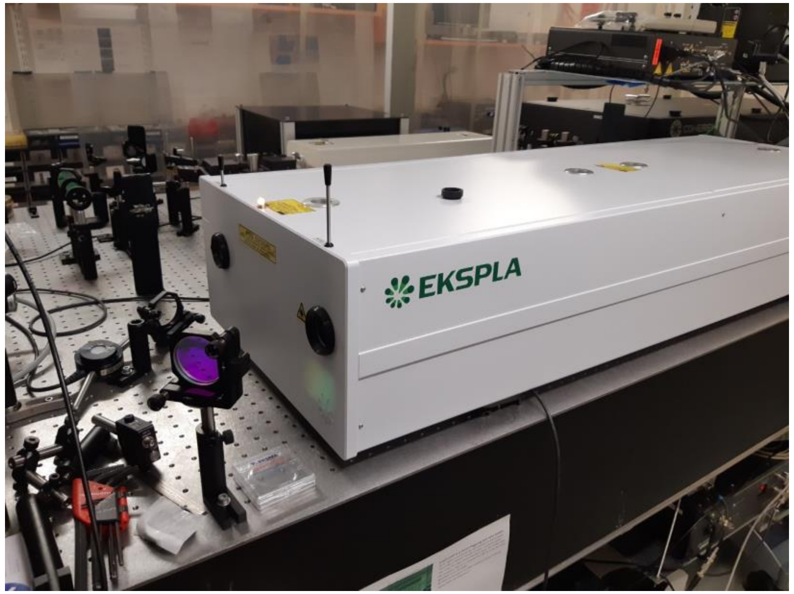
- A lot of compromises
  - Space constraint in ID09
    - ➢ Fit inside ID09's hutch without removing anything !
    - ➢ Use the existing laser beam path → beam diameter < 25 mm
  - Financial constraint → budget allocated ~ 400 k€
  - Time constraint → start as soon as possible to fit with the initial schedule for HPLF-II

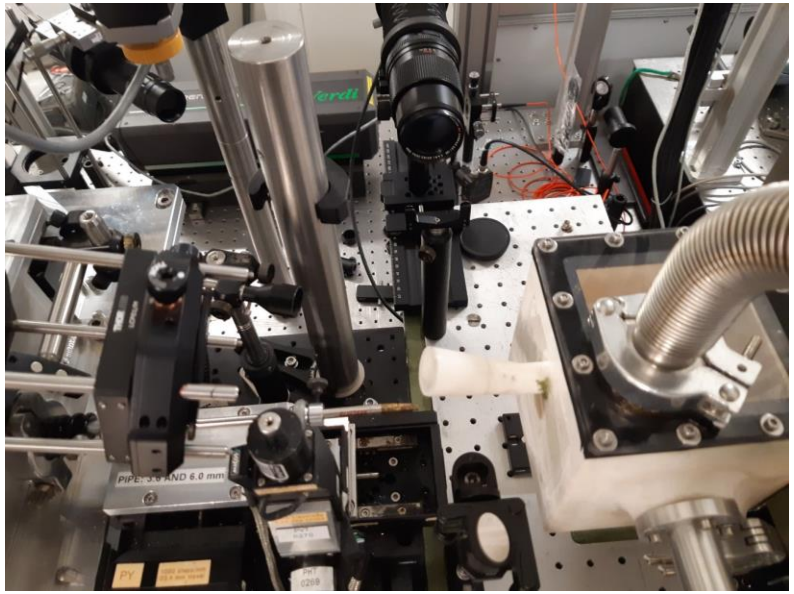
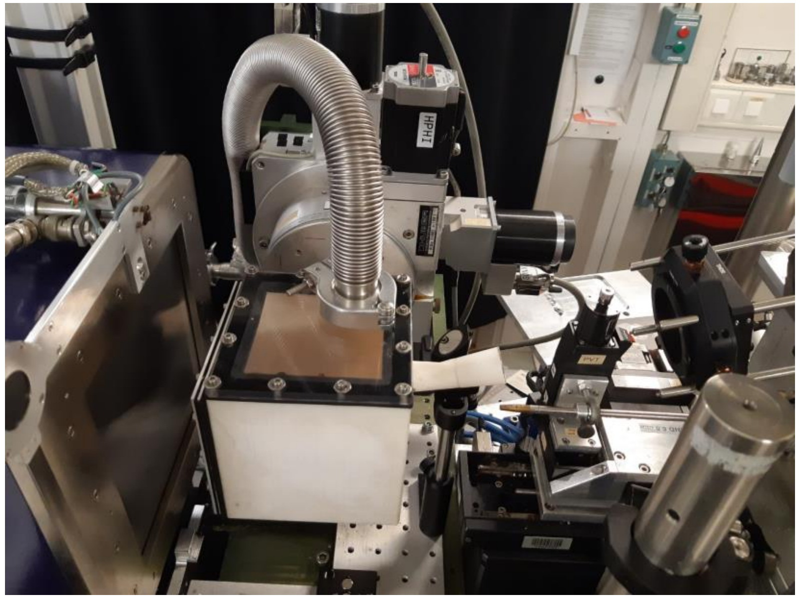


Industrial on the shelf laser coupled with a point VISAR/PDV system

Overview of the new laser-shock platform

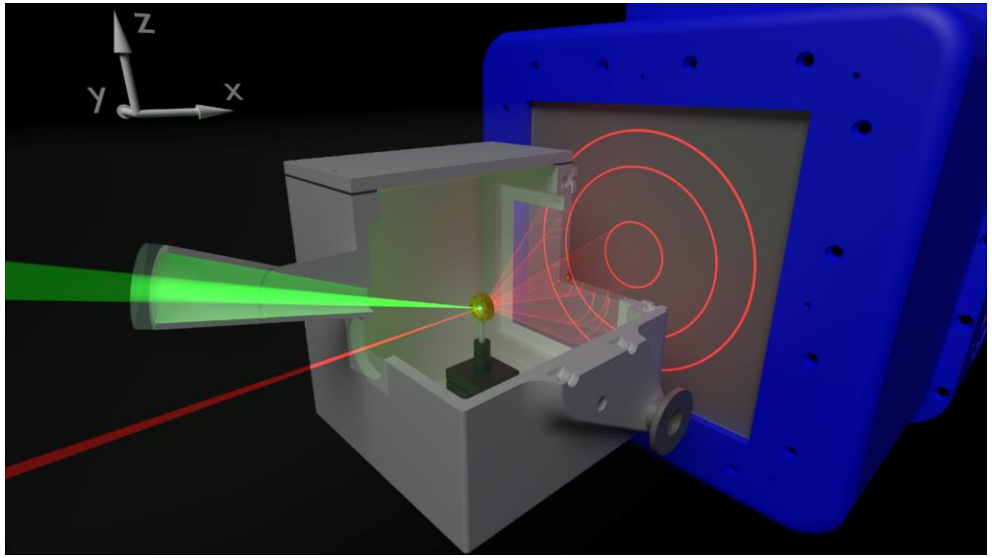
- Main components
  - Custom EKSPLA - ANL5kSS-SH laser system
    - > 5 J @ 1064 nm, 3,5 J @ 532 nm, 6.3 ns Gaussian pulse, near-field super Gaussian spatial profile
  - Custom 3D printed vacuum chamber developed by ESRF’s Sample Environment Support team
  - Rayonix MX170-HS CCD detector
  - Custom portable point Valyn VISAR system

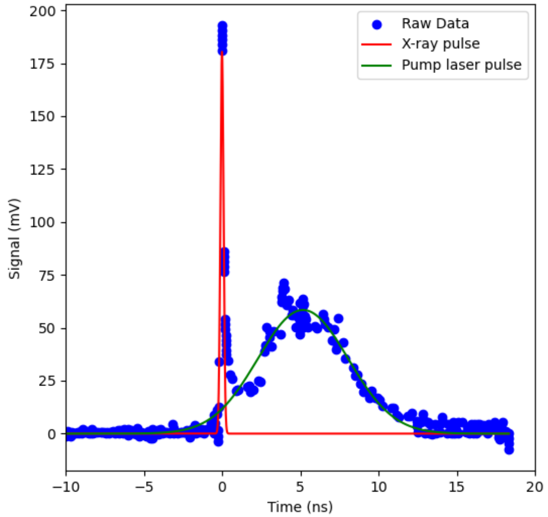


Overview of the new laser-shock platform

- A few details
  - 18° angle between laser and X-rays
  - Adjustable delay between laser and X-rays
    - Up to seconds by steps of 10 ps (controlled by CITY board)
    - Measured by an ultra-fast Hamamatsu S2383 photodiode coupled with a Picosecond Pulselabs 5531 High Voltage Bias Tee
    - t=0 corresponds to X-rays located at the left foot of the laser pulse
  - Adjustable focal spot
    - Silios DOE components (250 µm to 1 mm)
  - 1 cm diameter samples
    - Glued with low viscosity epoxy
    - Brass holder
    - Between 5 and 9 shots on each sample

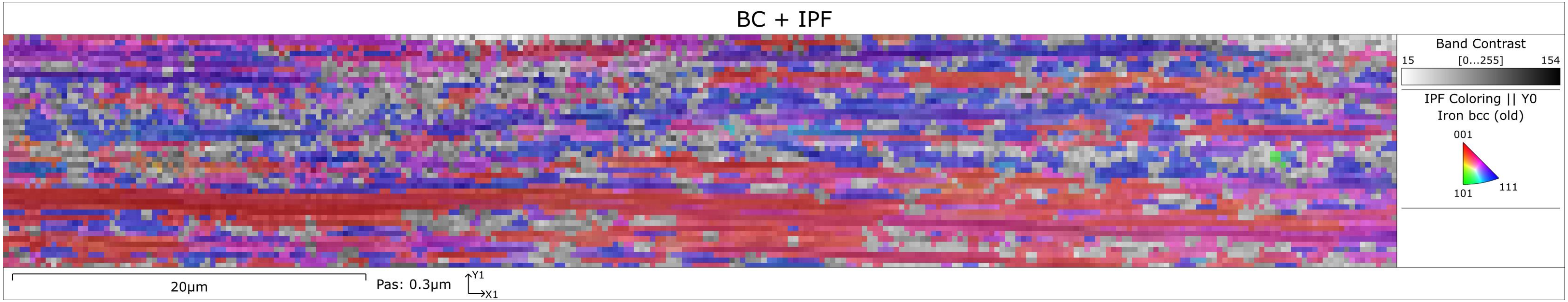




3. Preliminary results on Fe and Tin

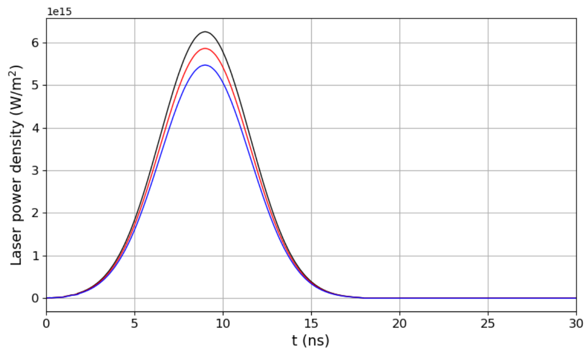
First experiment on Fe

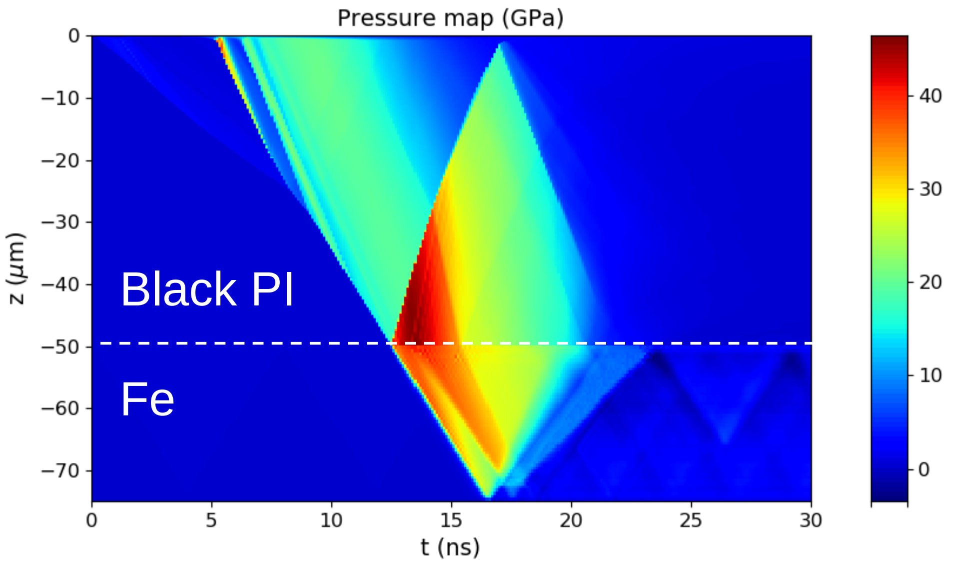
- Fe samples = 50 μm Black Kapton + 25 μm Fe + (500 μm LiF)
  - 25 μm thick high purity rolled foils purchased from GoodFellow
  - SEM + EBSD observations
    - ➢ Elongated grains and strong texturing typical of a rolling microstructure

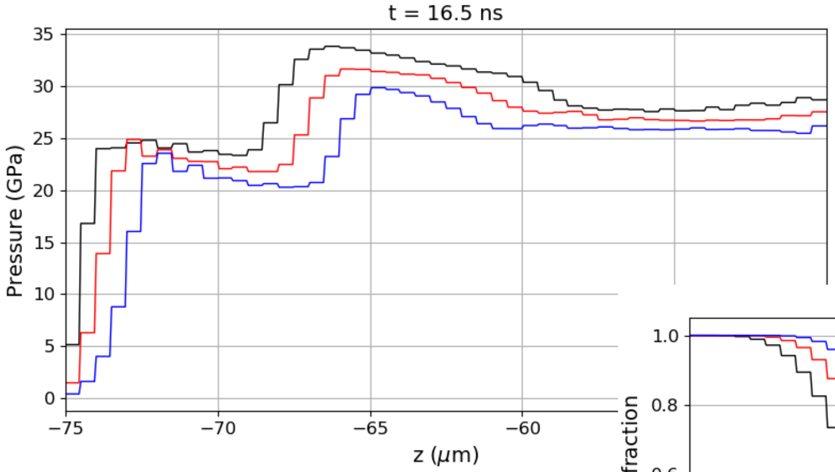


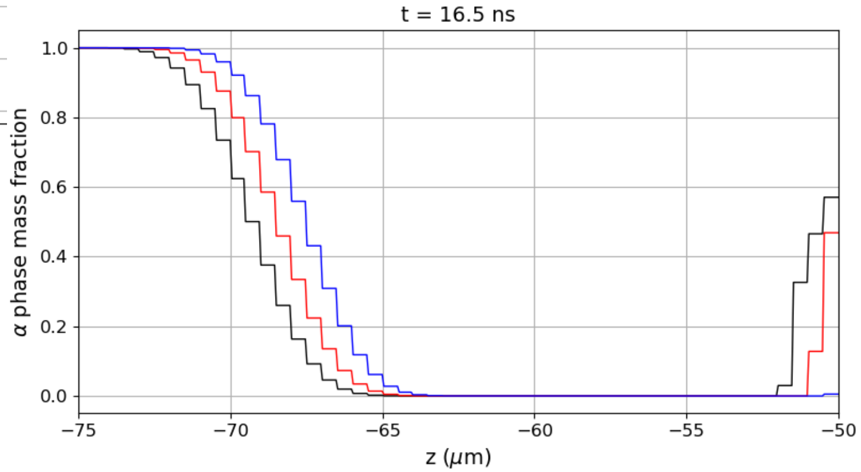
Fe ESTHER simulations

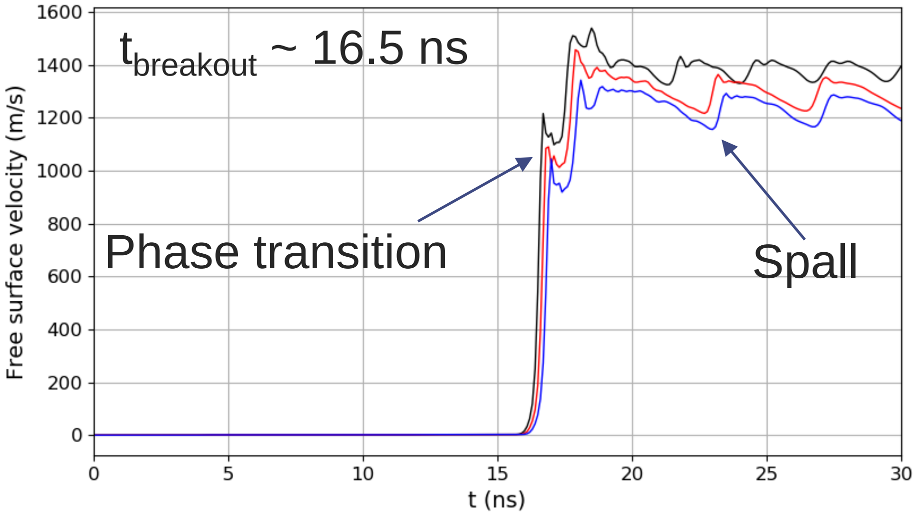
- 1D simulation
  - 2 phases EOS with JMAK kinetics



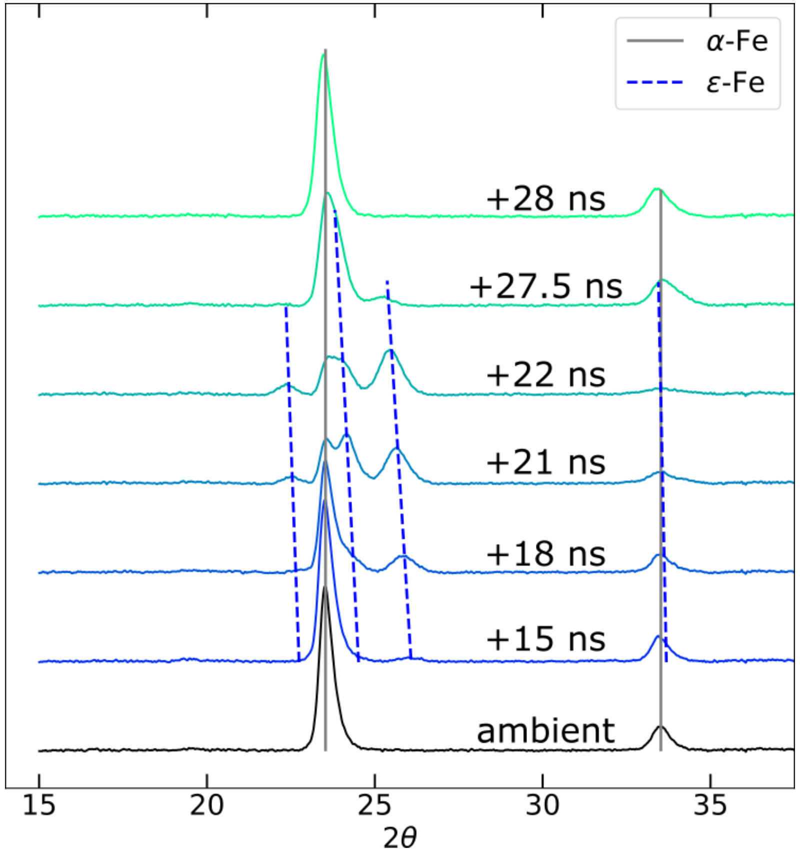


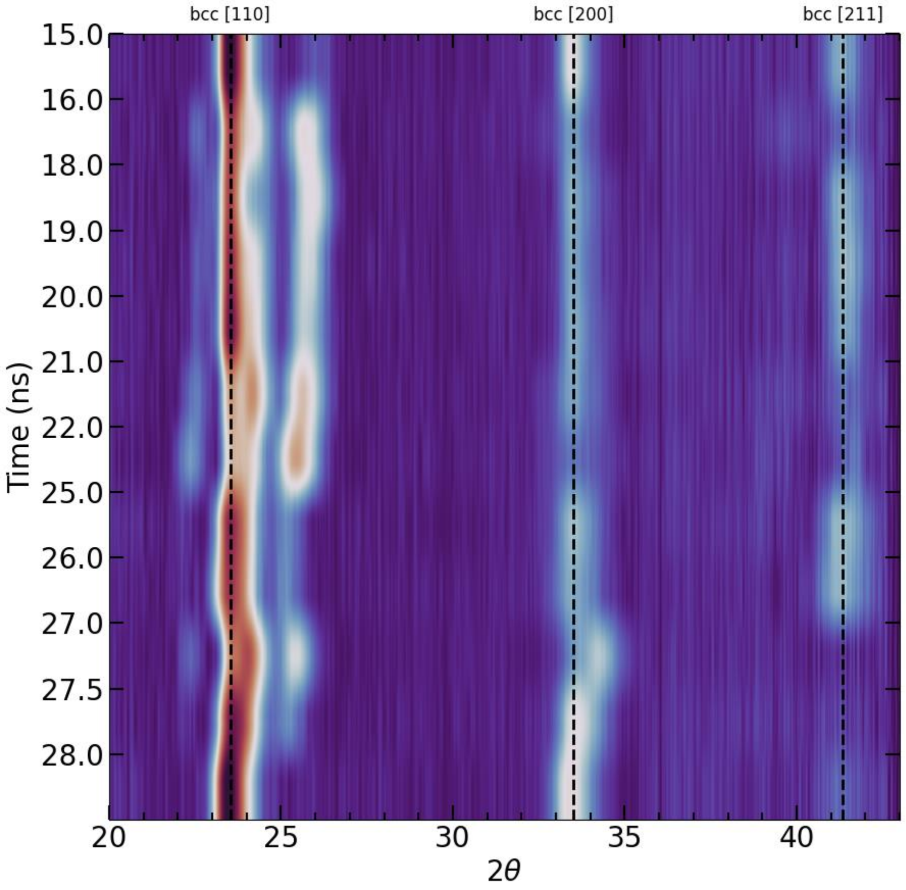






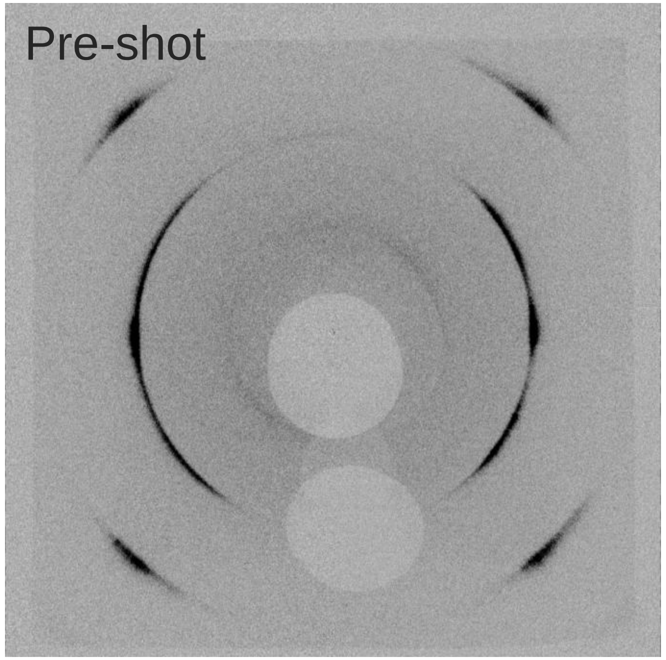
Fe XRD data

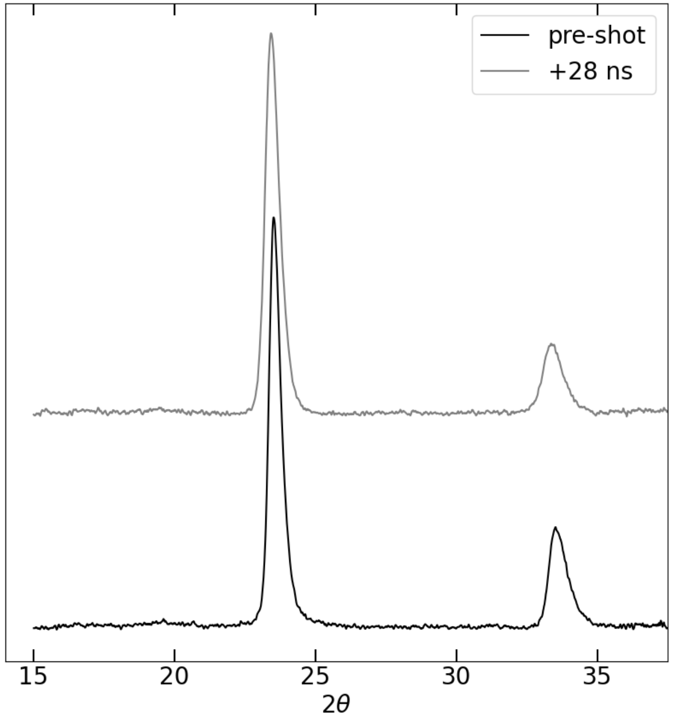


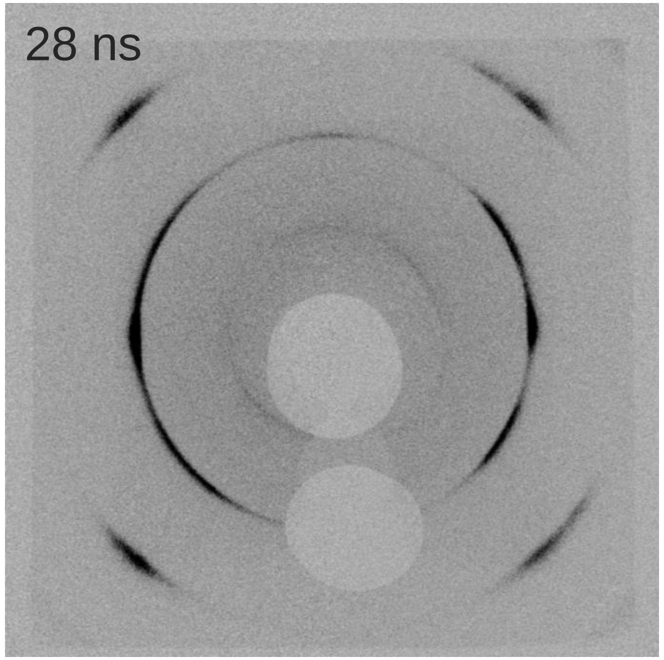


We do not observe a full transition to the ε *hcp* high pressure phase and always have some residual α *bcc* phase

Fe XRD data





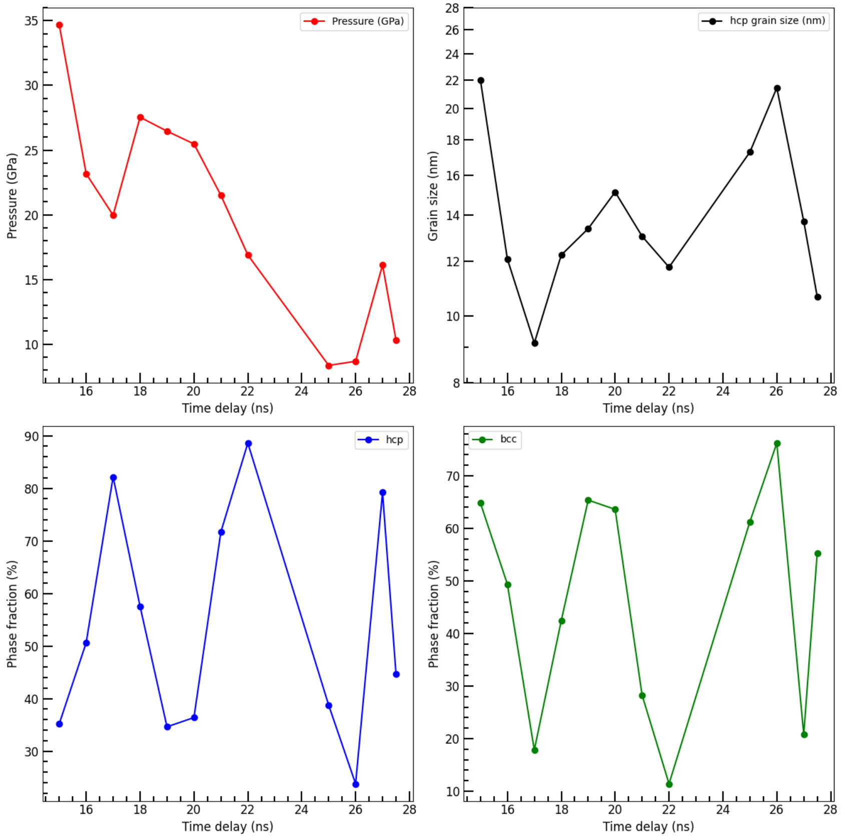


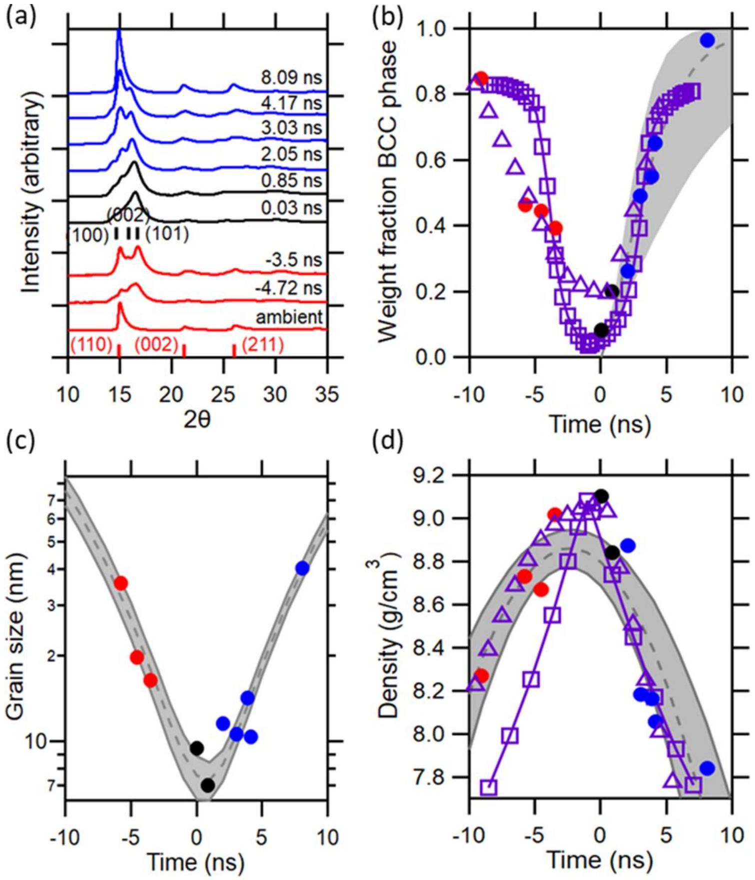
Significant memory effect

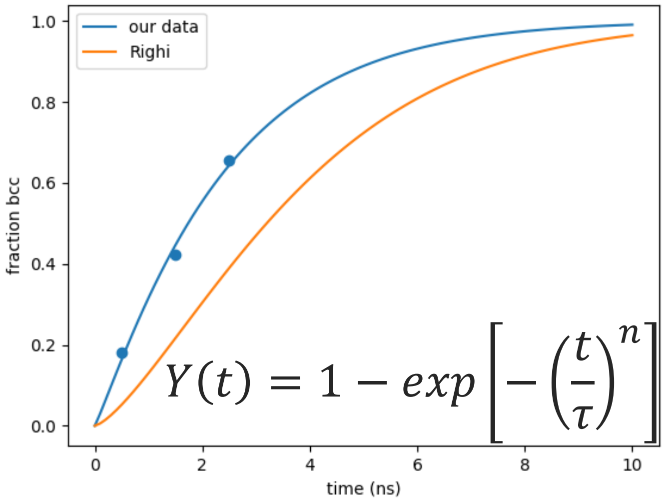
Comparison with Righi *et al.*

Righi *et al.*, Acta Mat. 257, 119148 (2023)

- Strong texturation → Pawley and Le Bail refinements instead of Rietveld refinement





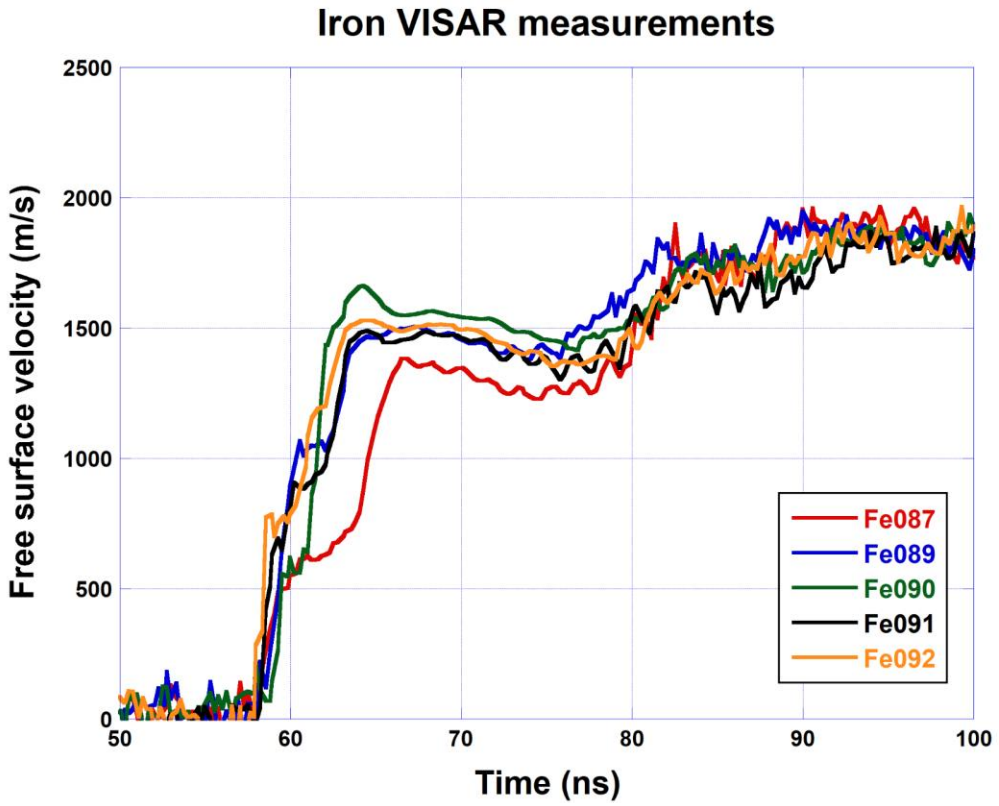


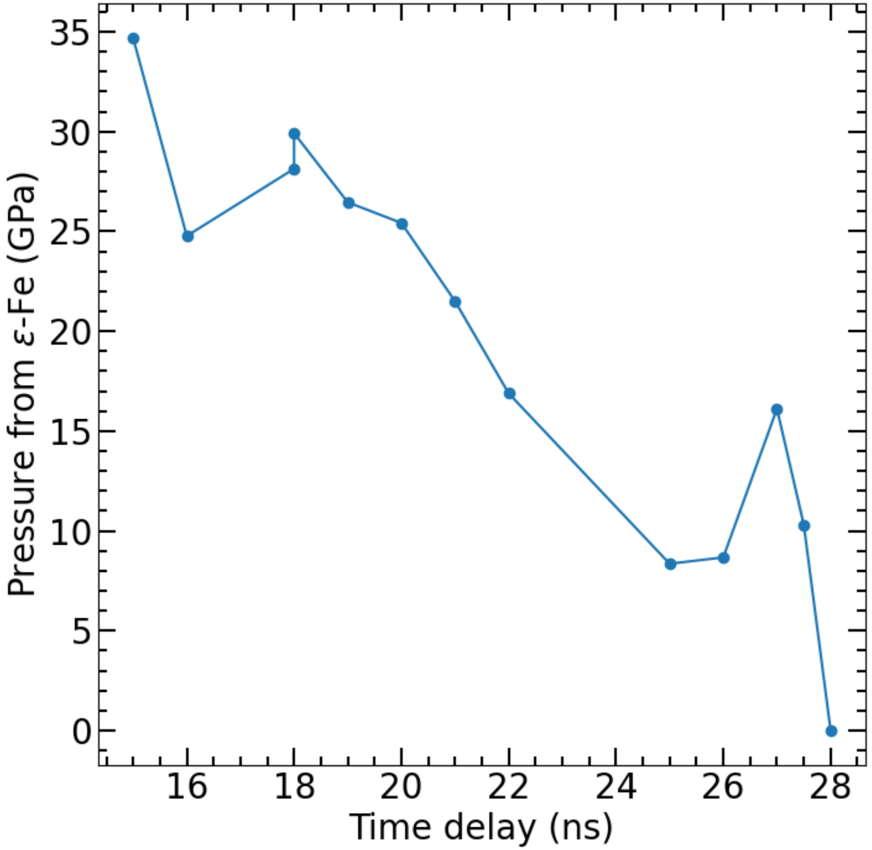
$$Y(t) = 1 - exp\left[-\left(\frac{t}{\tau}\right)^n\right]$$

Our work: τ = 2,43 ns ; n = 1,09

Righi *et al.*: τ = 4,17 ns ; n = 1,38

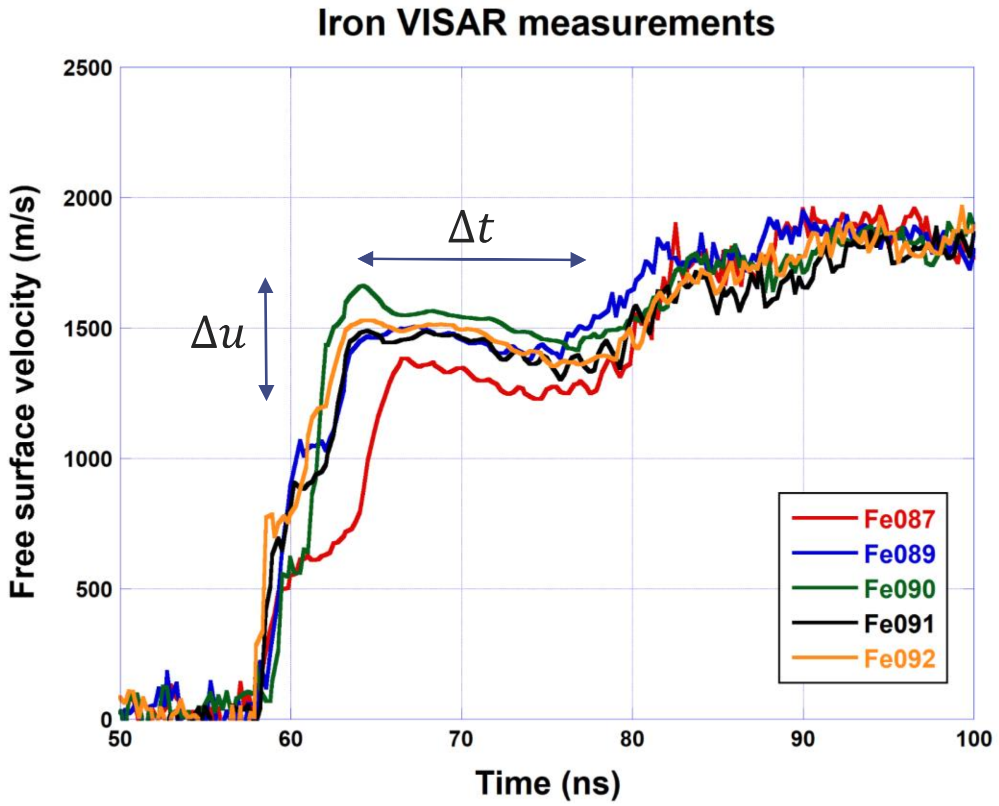
Fe VISAR data



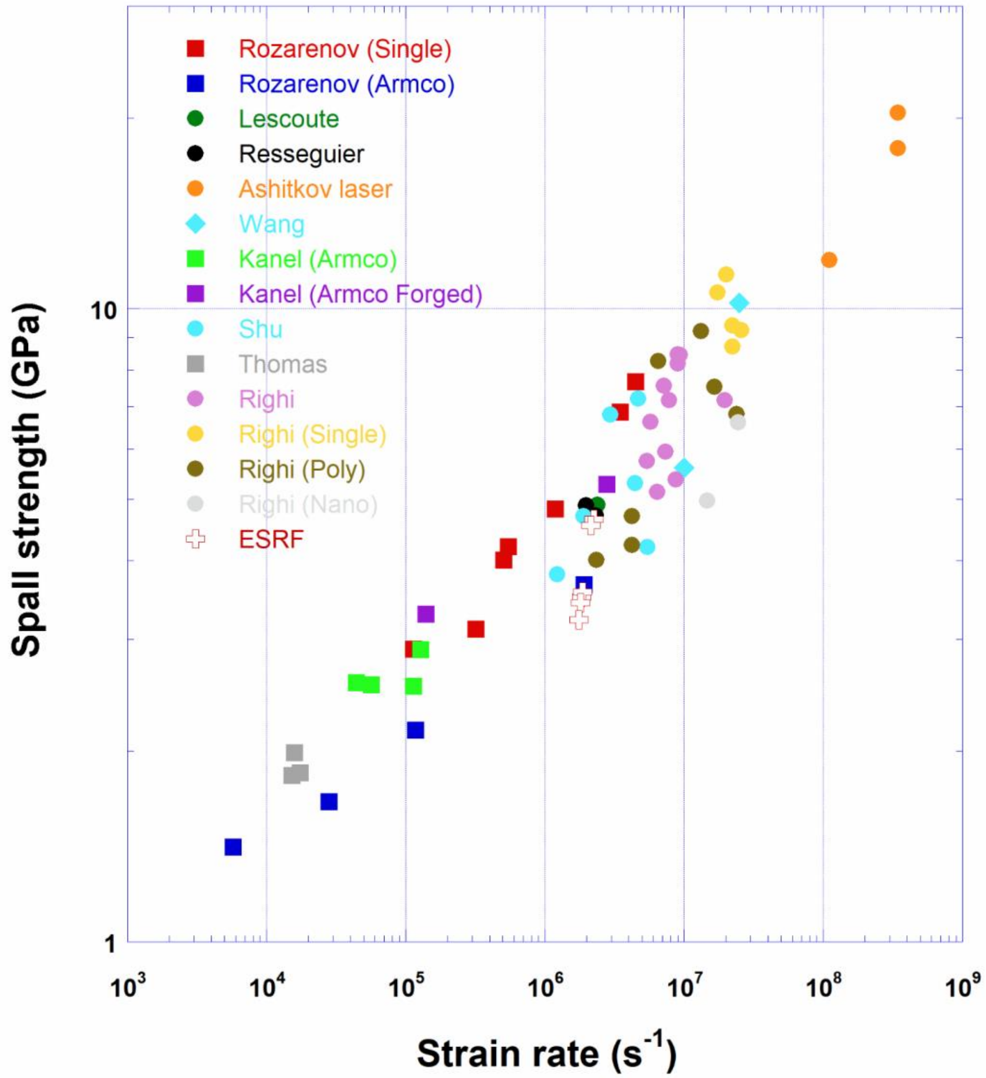


P_{fs} = 30,5 ± 1,6 GPa

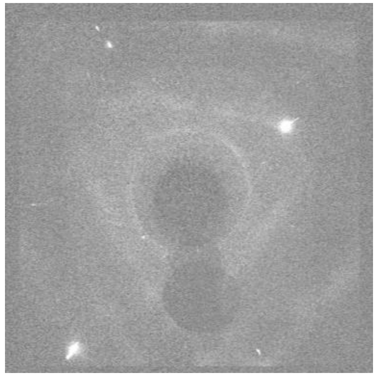
Fe results: VISAR data



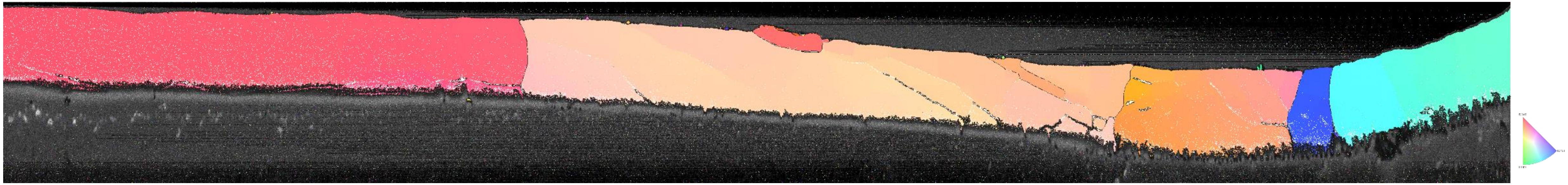
$$\sigma_{spall} = \frac{1}{2}\rho_0 C_b \Delta u \qquad \dot{\varepsilon} = \frac{1}{2C_b}\frac{\Delta u}{\Delta t} \qquad C_b = 4640\ m/s$$



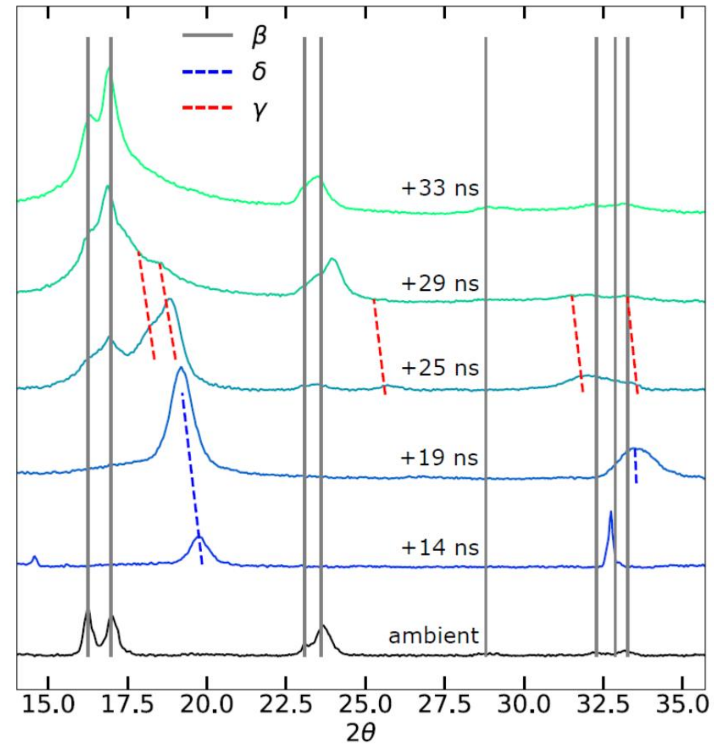
Experiment on tin

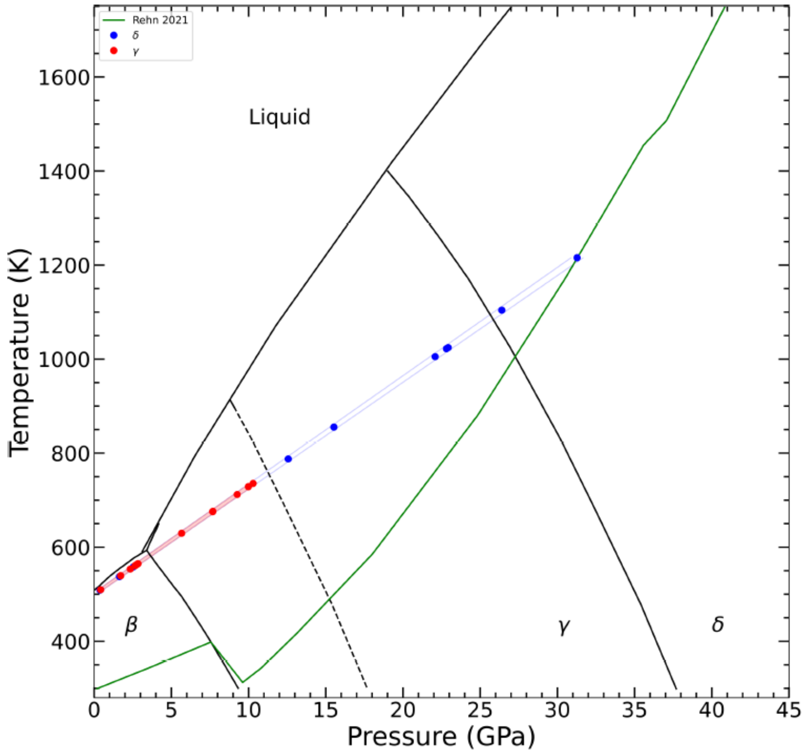


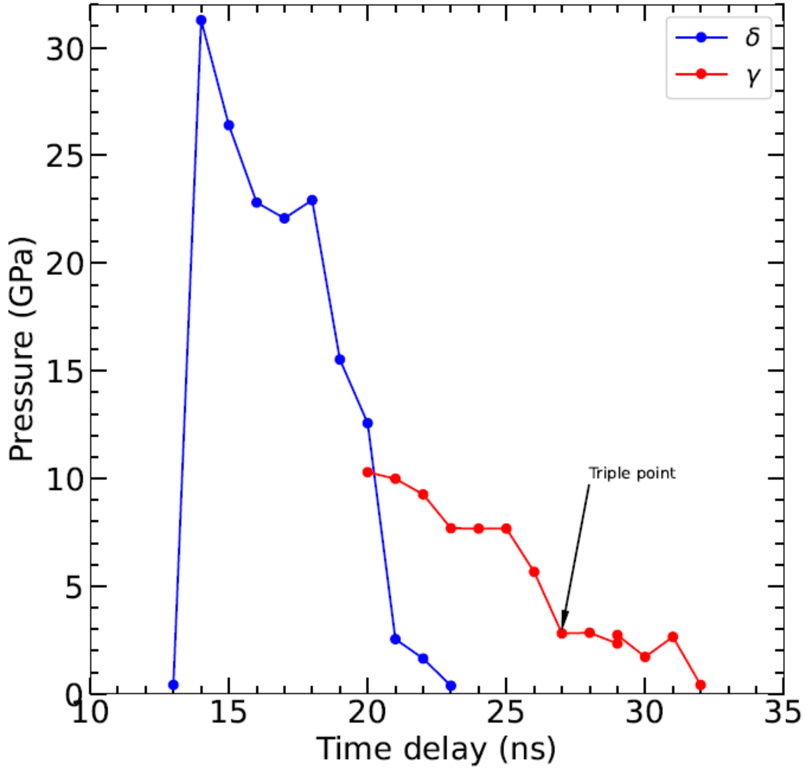
- Tin samples = 50 μm Black Kapton + 25 μm Sn + (500 μm LiF)
  - 25 μm high purity Sn foils purchased from GoodFellow
  - SEM + EBSD observations
    - ➢ Large grains (> 100 μm)
    - ➢ Grain boundaries perpendicular to the surface → quasi-columnar structure → no XRD peaks !



Tin results

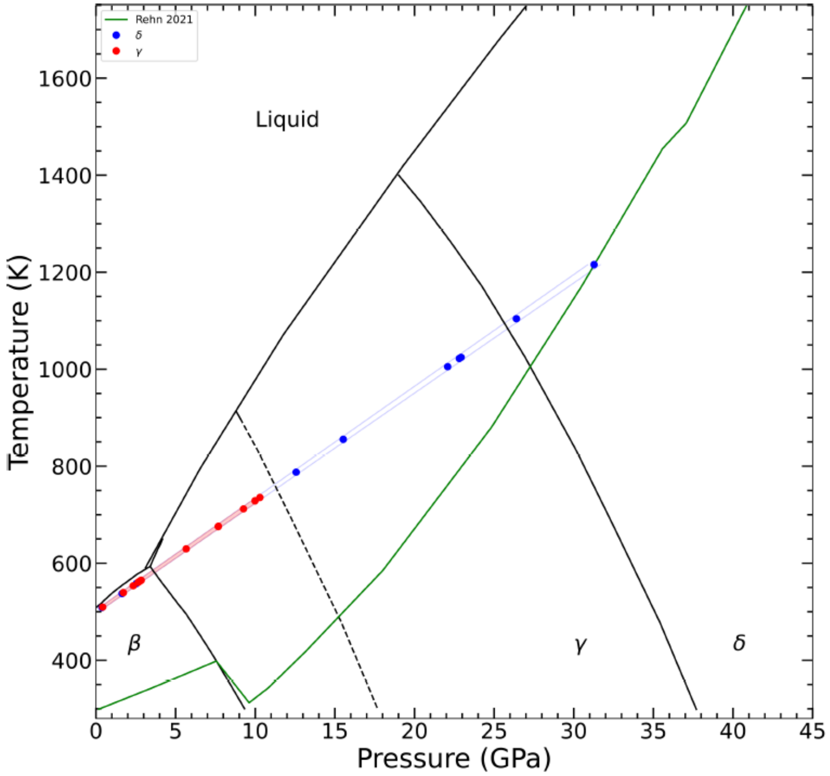




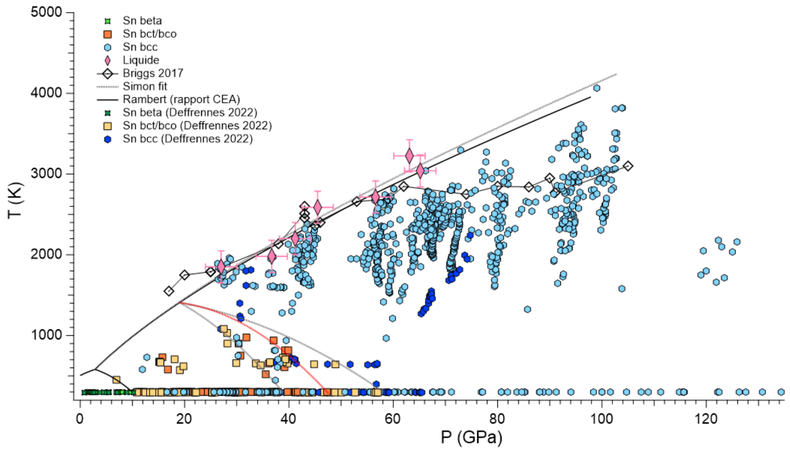


Full transition to the high pressure δ phase under shock, followed by a release in the γ and β phases passing through the triple point

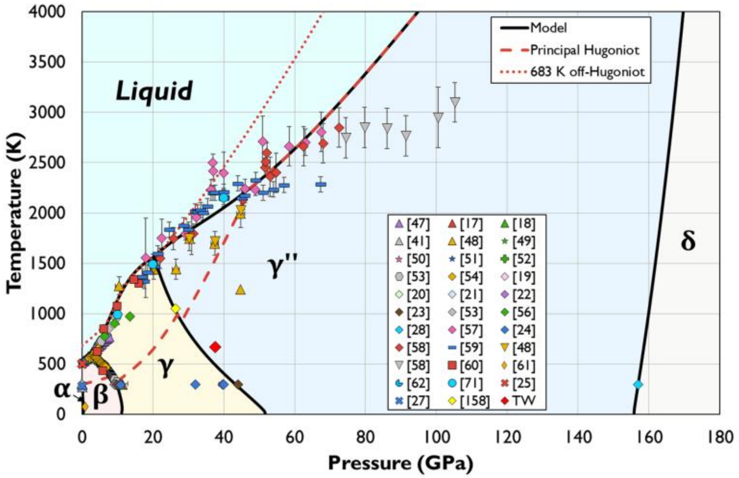
Tin results



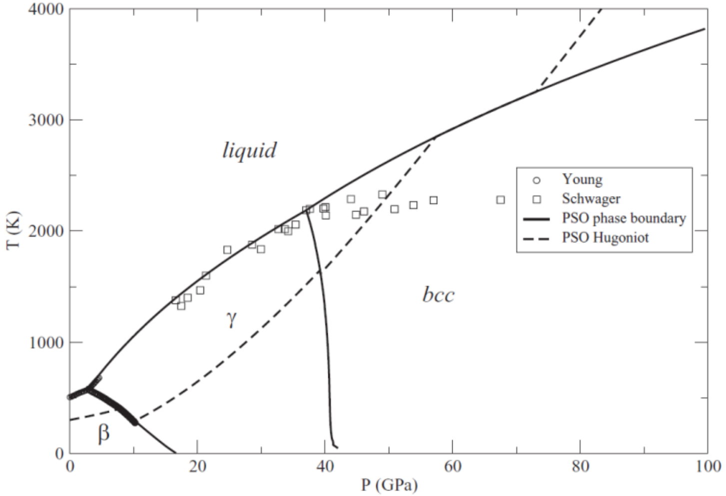
Fréville *et al.*, PRB (2024)



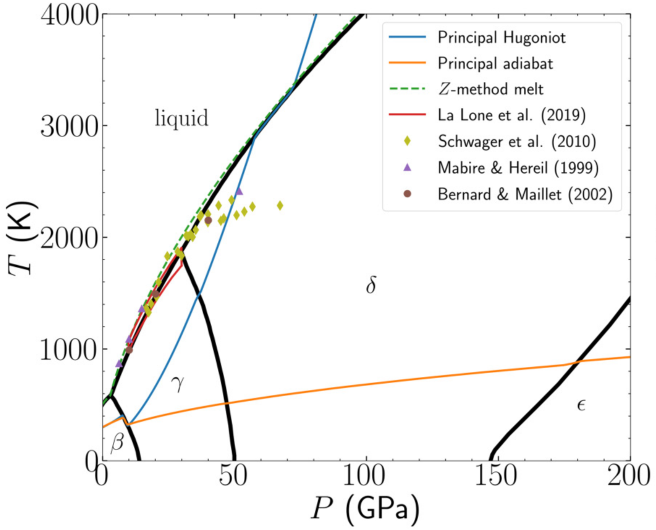
Deffrennes *et al.*, JAC 919, 165675 (2022)



Cox *et al.*, J. Phys.: Condens. Matter 27, 405201 (2015)



Rehn *et al.*, PRB 103, 184102 (2021)



CONCLUSION

- LTP HC-4528 launched in 2021, really started in 2023
  - The laser shock compression platform is now operational
  - First successful experiments on Fe, Sn, Zr and Ti

- Work plan for 2024
  - 2 new experiments
    - Other materials, different pressures, …
    - Reach higher pressures and probe liquid in Pb, Sn, or Bi
  - Evolutions of the setup
    - Couple our resistive heating system (up to 900 K) with the vacuum chamber
    - New fibered triature PDV system → on the fly velocity measurements
    - On the fly laser diagnostics
    - New DOEs

- Opening to collaboration planned in 2025
  - Think about it …

ID09 beamline visit
Mikhail Kozhaev's poster

Thank you for your attention

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