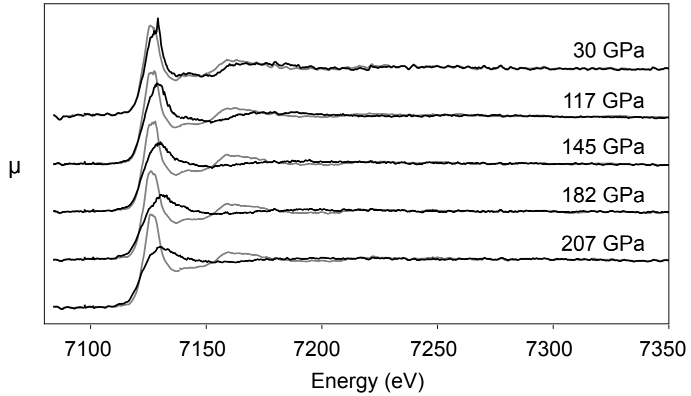


Status and first results from the High Power Laser Facility at the ESRF

J.-A. Hernandez[1], N. Sevelin-Radiguet[1], R. Torchio[1], S. Balugani[1], G. Berruyer[1], S. Chazalette1, C. Clavel[1], D. Bugnazet[1], D. Lorphèvre[1], F. Perrin[1], S. Pasternak[1], F.Villar[1], O. Mathon[1]

[1]European Synchrotron Radiation Facility, Grenoble, France

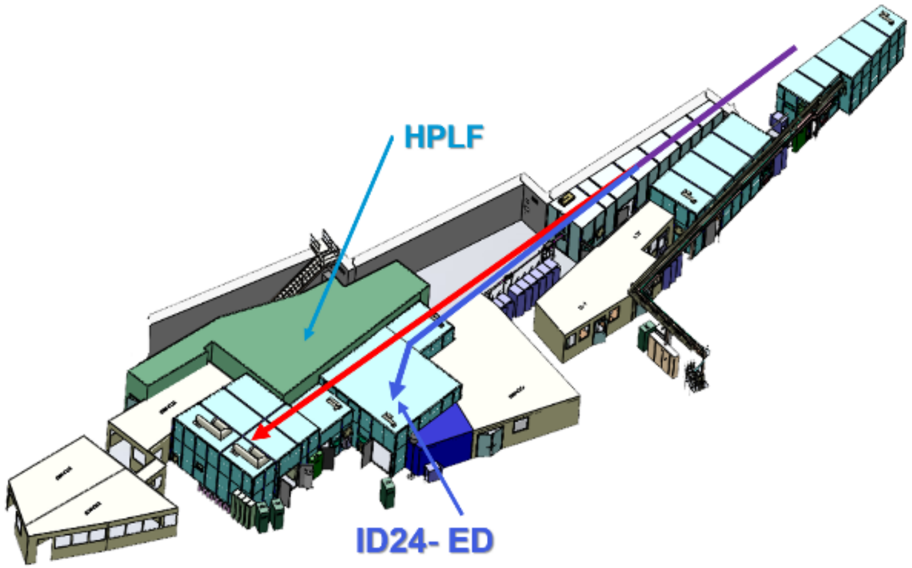
jean-alexis.hernandez@esrf.fr

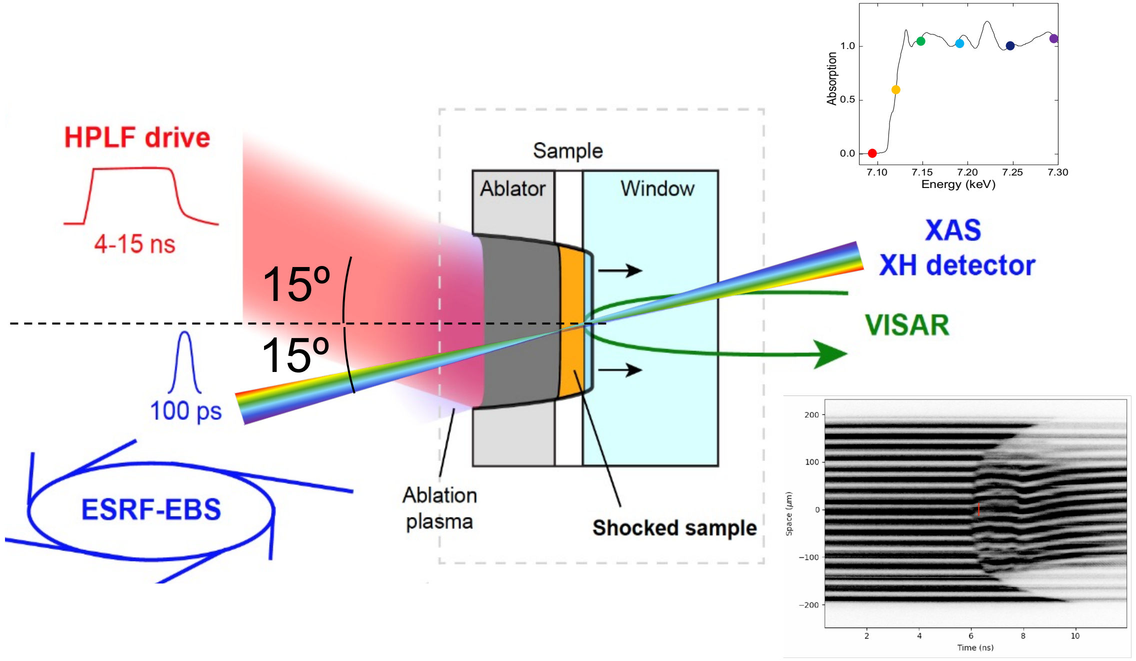
DyCoMaX ESRF-EBS EBS Science Workshop STREAMLINE Amplitude

HPLF on ID24-ED

→ **A platform for laser-driven dynamic compression experiments coupled to time-resolved XAS**

ID24 High-brillance XAS beamline



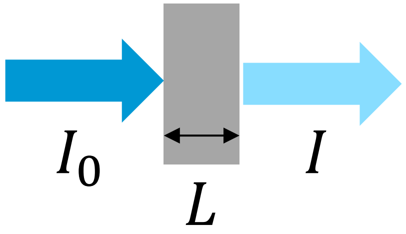


ID24-ED: energy-dispersive branch
Fast measurements down to single-bunch XAS

X-ray absorption spectroscopy

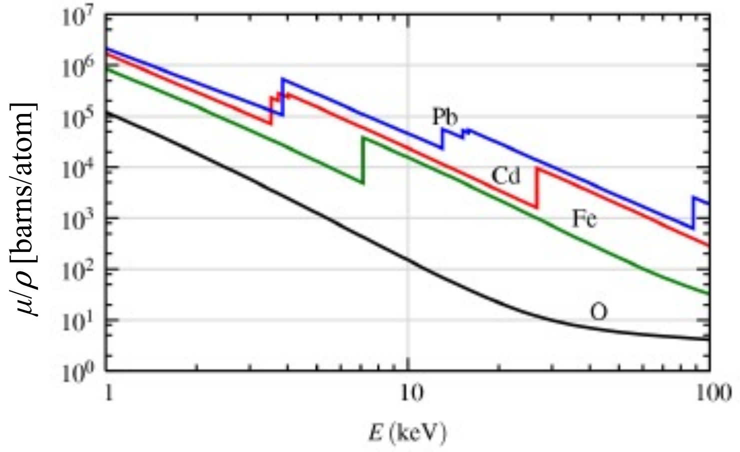
→ X-ray Absorption Spectroscopy

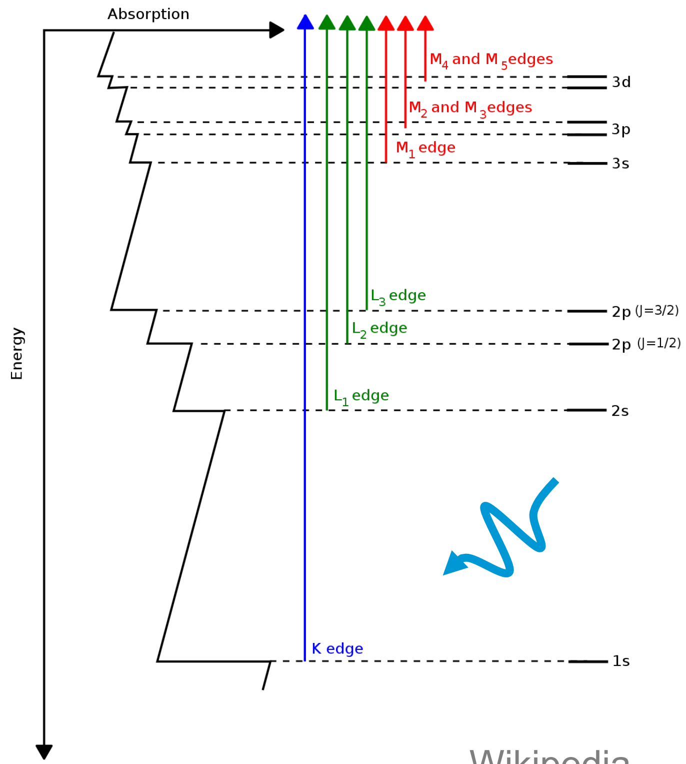
- Absorption edge energies specific to each elements



$$I = I_0 e^{-\mu L}$$

μ: absorption coefficent





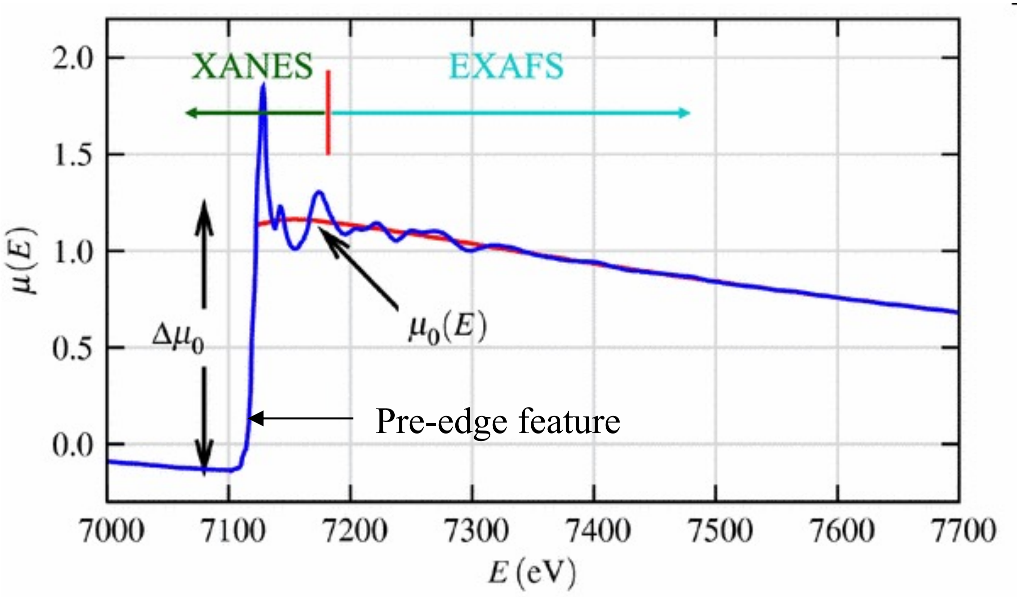
Wikipedia

- Absorption of X-ray photon by a core-level electron by photo-electric effect
- Transition of the photo-electron from core-levels to unoccupied states

X-ray absorption spectroscopy

→ X-ray Absorption Fine Structure (XAFS)

Ex. of Fe *K*-edge spectrum



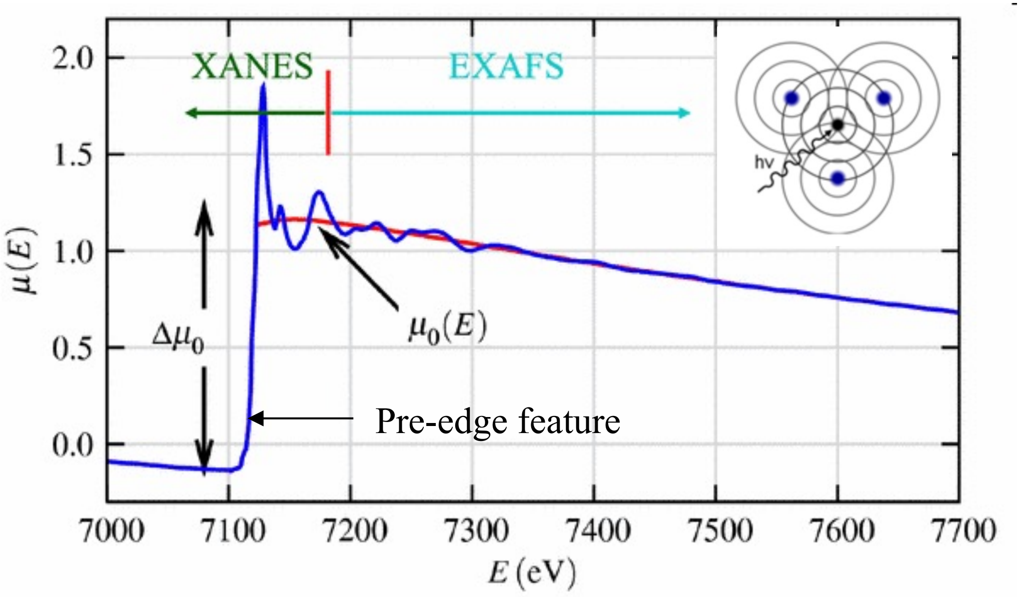
XANES: X-ray Absorption Near-Edge Structure

- Core to quasi-bounded state transitions
- **Coordination chemistry**, **oxidation state**, …
- Molecular orbitals (p-d hybridization, CFT, …)
- Band structure
- Multiple-scattering
- **Sensitive to the electronic structure**

X-ray absorption spectroscopy

→ **X-ray Absorption Fine Structure (XAFS)**

Ex. of Fe *K*-edge spectrum



XANES: X-ray Absorption Near-Edge Structure

- Core to quasi-bounded state transitions
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- Band structure
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- **Sensitive to the electronic structure**

EXAFS: Extended X-ray Absorption Fine Structure

- Core to continuum
- Interferences between forward and backward scattering to and from neighboring atoms
- **Sensitive to local ionic structure (distances, number of atoms, disorder)**

→ **XAS is element specific, local, and adapted to both ordered and disordered phases**

→ **Complementary to XRD (long-range order) and other X-ray techniques**

World-wide context

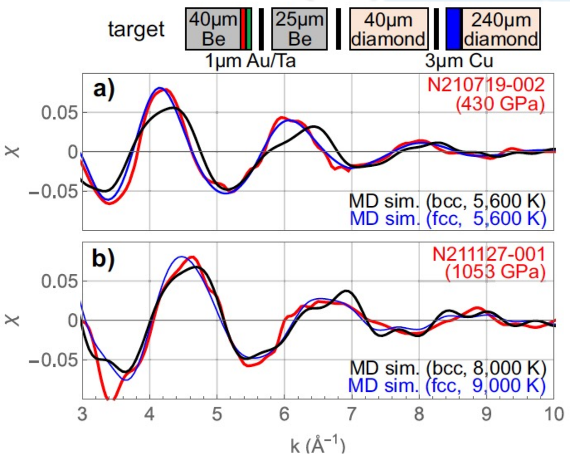
→ **HPLF is one of the 5 high-power lasers coupled to large X-ray facilities (3 on XFELs, 2 on synchrotrons)**

World-wide context

→ **HPLF is one of the 5 high-power lasers coupled to large X-ray facilities (3 on XFELs, 2 on synchrotrons)**

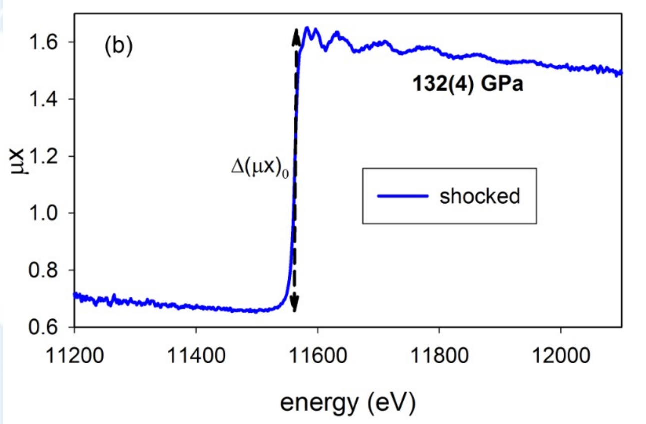
Omega
LULI2000
EuXFEL
LMJ
NIF

NIF / Omega



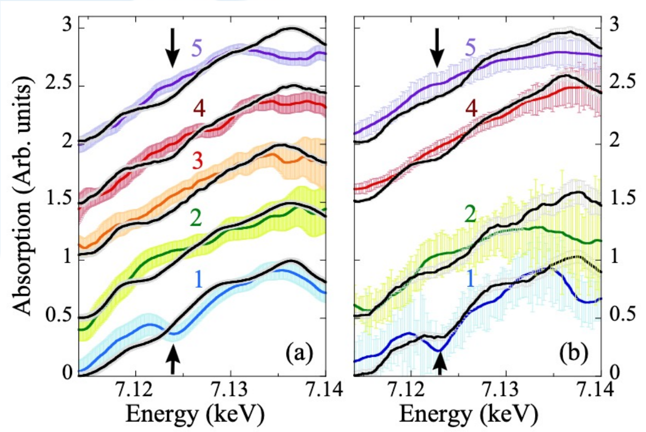
Krygier *et al.*, Nat. Com. (2023)

APS DCS



Turneaure and Das, PRB (2023)

LCLS



Harmand *et al.*, PRB (2015)

→ **HPLF is the only one dedicated to high-resolution XAS**

Evolution of HPLF since last DyCoMax

2021

Installation of clean room, drive laser, and beam transport structure

First laser + X-ray shot

Temporary shock diagnostic setup (1 line-VISAR and loaned probe laser)

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2022

Beginning of user and in-house experiments (x6)
Drive laser at 45 J with 10 and 5 ns flat-top pulses
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2023

User and in-house experiments (x7)
Installation of new shock diagnostics (2 line-VISAR + custom probe laser)
Analysis and simulations tools for hydrodynamics
Drive laser at 55 J with 4-15 ns flat-top pulses

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Installation of clean room, drive laser, and beam transport structure
First laser + X-ray shot
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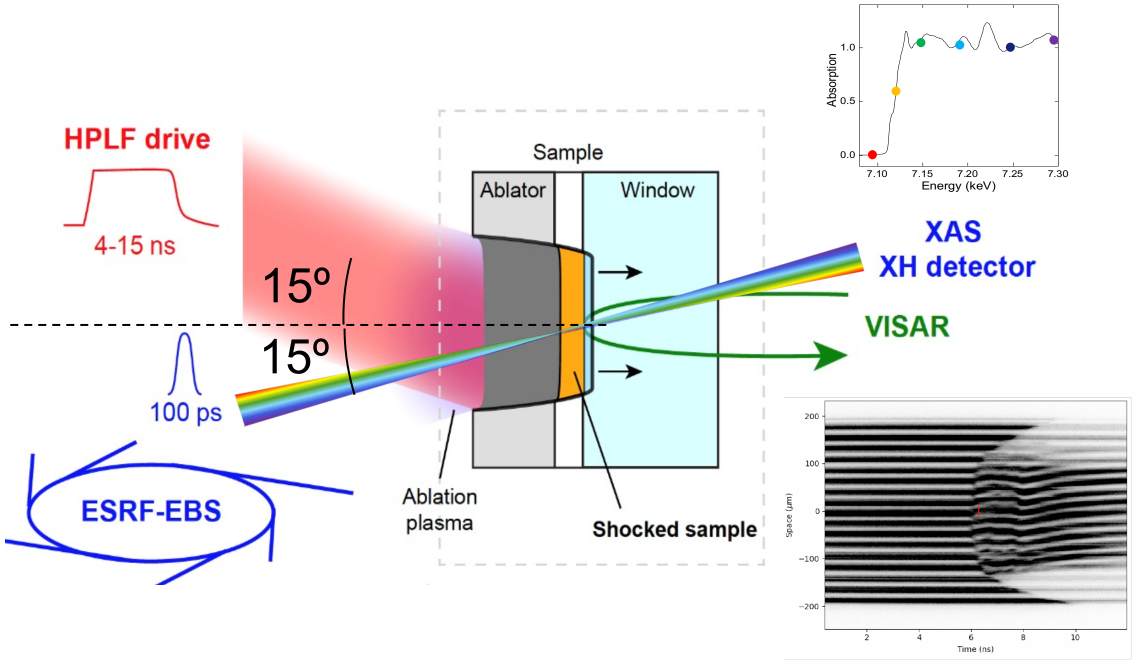
2023

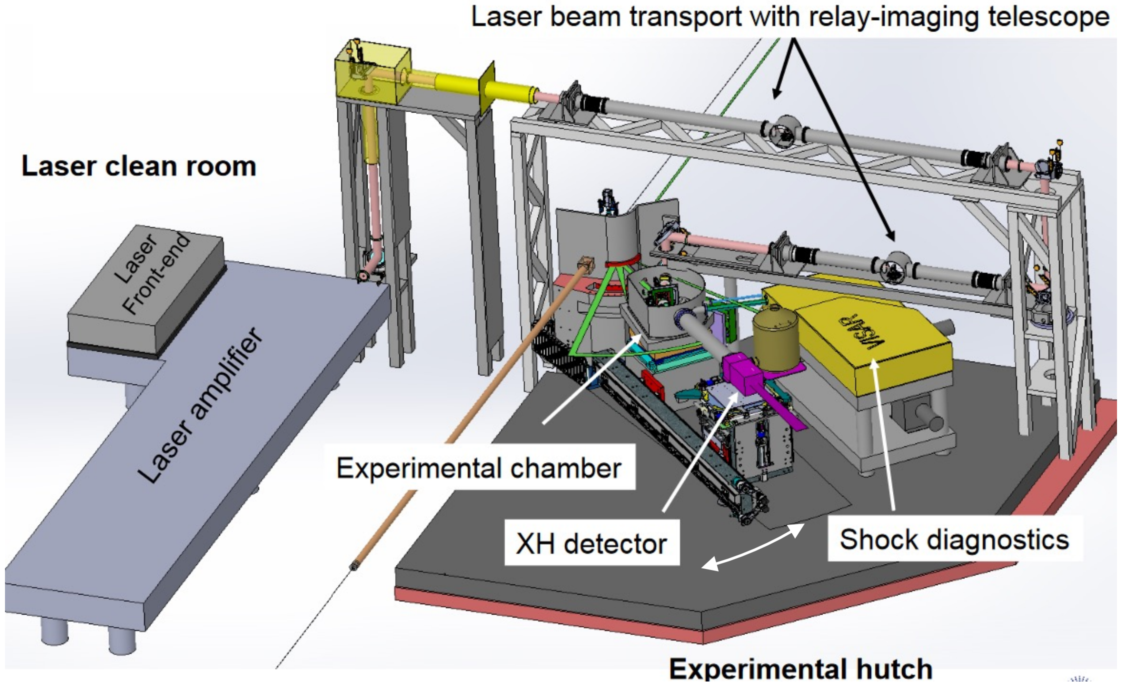
User and in-house experiments (x7)
Installation of new shock diagnostics (2 line-VISAR + custom probe laser)
Analysis and simulations tools for hydrodynamics
Drive laser at 55 J with 4-15 ns flat-top pulses

2024

User and in-house experiments
Installation of SOP
Design of optional 3rd line-VISAR (orthogonal FOV)
3rd steak camera received onsite

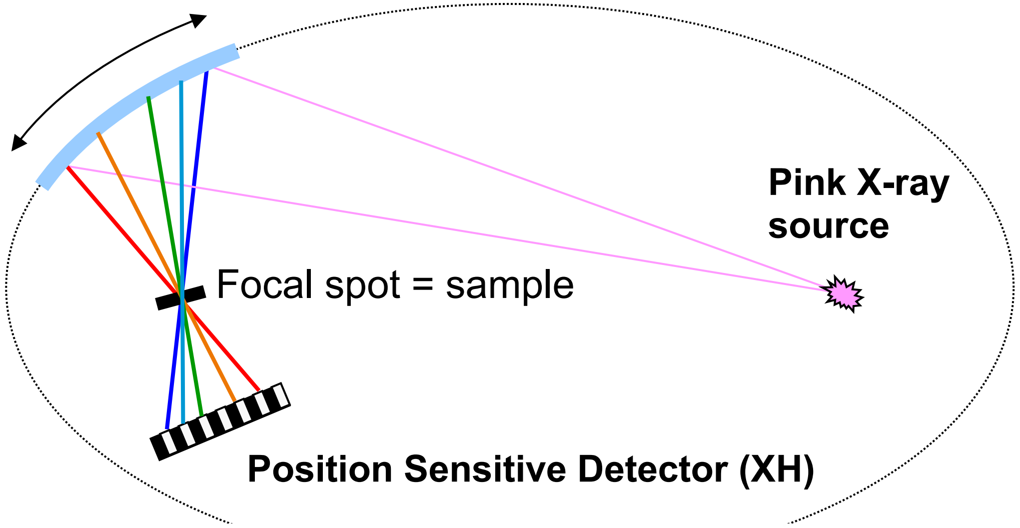
→ Experimental geometry

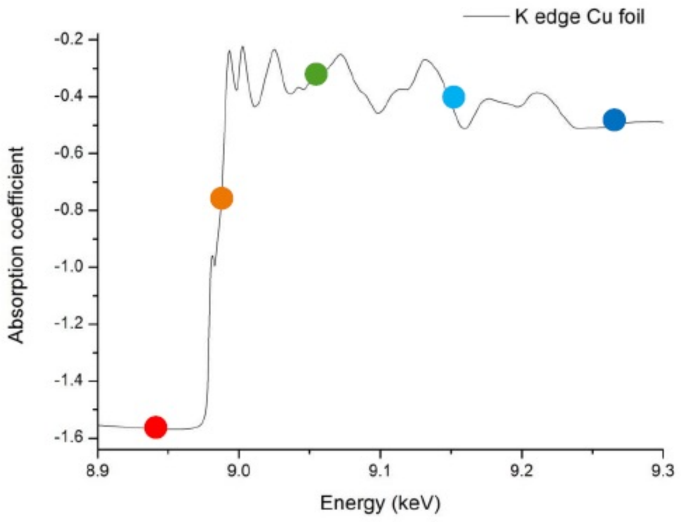


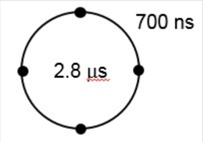
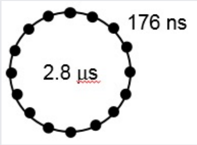
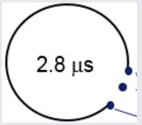


Single bunch XAFS on ID24-ED

Polychromator
Bent Si(111, 220, 311) crystal with elliptical shape





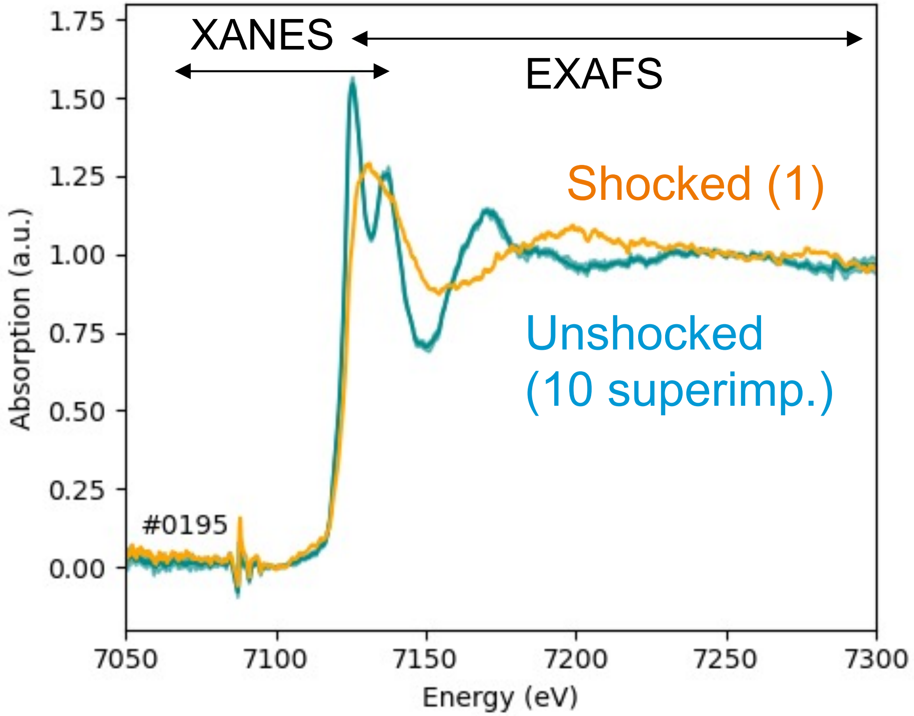
XAS on ID24-ED (HPLF-I)			
Pulse duration	**100 ps (up to 10^{14} ph/s)**		
Energy	**5 - 28 keV** **K-edges between V (Z=23) and Cd (Z=48)** **L3-edges between Cs (Z=55) and U (Z=92)**		
XAS energy range	**150 eV - 2500 eV (E-dpt)**		
Focusing	Hor. 5-50 µm (E-dpt) Vert. 5-50 µm		
Detector	XH, Ge strip		
Integration time	≥ 100 ns		
Readout time / rep.rate	2 µs / 2.8 µs		
Timing modes	**4-bunch** 	**16-bunch** 	**7/8+1** 

Borri M. *et al.*, NIMPR-A, 988 (2021)

Sévelin-Radiguet, N., Torchio R. *et al.* JSR 29 (2022)

Single bunch XAFS on ID24-ED

Single-bunch XAS of Fe K-edge in $(Mg,Fe)CO_3$ with 0.7 eV experimental resolution



XAS on ID24-ED (HPLF-I)			
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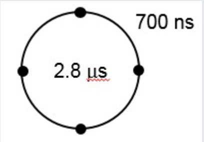
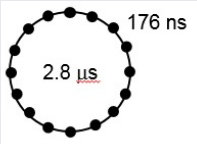
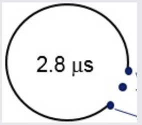
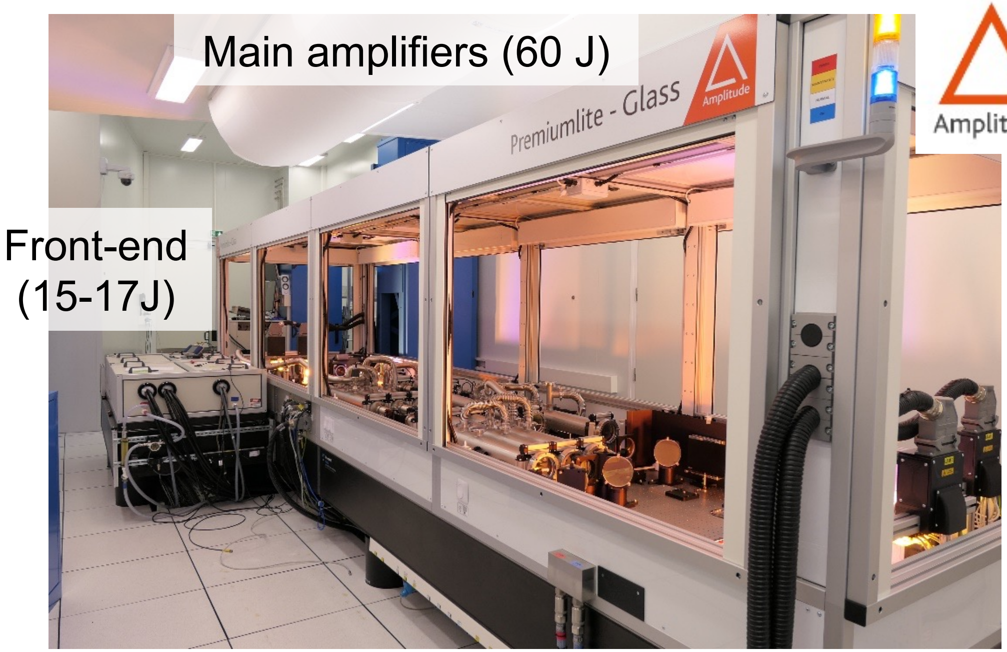
Readout time / rep.rate	2 µs / 2.8 µs		
Timing modes	**4-bunch** 	**16-bunch** 	**7/8+1** 

Borri M. *et al.*, NIMPR-A, 988 (2021)

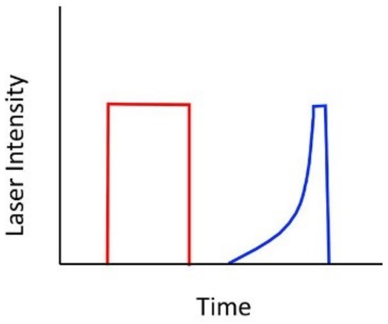
Sévelin-Radiguet, N., Torchio R. *et al.* JSR 29 (2022)

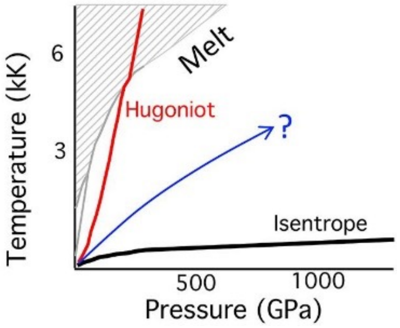
HPLF drive laser

Drive laser	Premiumlite – Glass prototype from Amplitude
Wavelength	**1053 nm**
Energy	**1-55 J on target**
Pulse temporal shape	**Flat-top, tunable on request**, 0.25 ns rise and 0.125 ns control step
Pulse duration	**4-15 ns on request**
Phase plates	500, 250, 100 µm, SSD
Rep. rate	1 shot / 7-20 min (limited by target alignment and sequence duration)



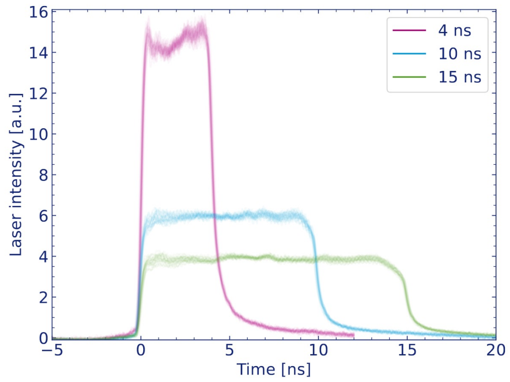
Pulse shaping capabilities to generate different P-T



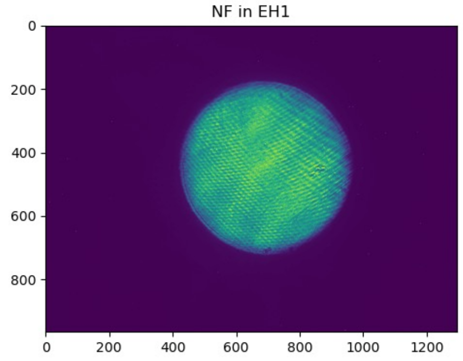


Duffy and Smith, Front. Earth Sci. (2019)

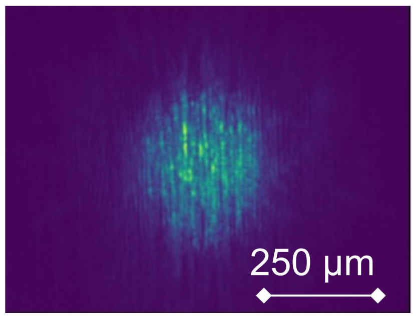
On-shot monitoring at different positions along laser path



Temporal profile and energy



NF

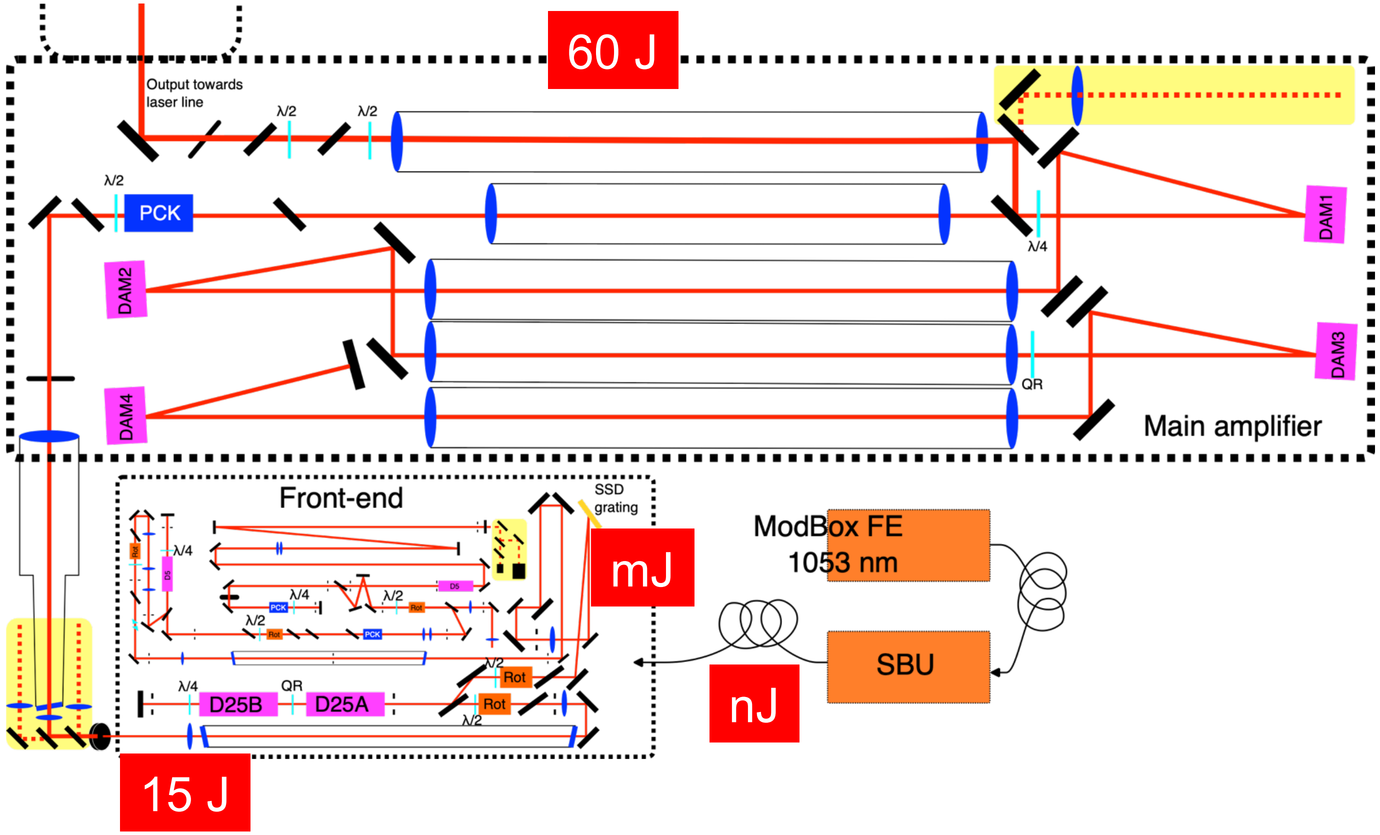


Focal spot on target

HPLF drive laser

→ Premiumlite – Glass prototype from Amplitude

- Fibered front-end (ModBox) with pulse-shaping (CW, AOM, 2 EOM with AWG)
- Spectral Broadening Unit for 1D-SSD
- Intrepid front-end
  - free-space regenerative cavity with flash-pumped rod amplifiers (Nd:glass)
  - 5 mm diam. rod amplifiers + spatial shaping
  - SSD
  - 25 mm diam. rod amplifiers
- Main amplifier
  - Pseudo-Active Mirror Disk Amplifier Modules
  - Two attenuators (λ/2 + pol.)

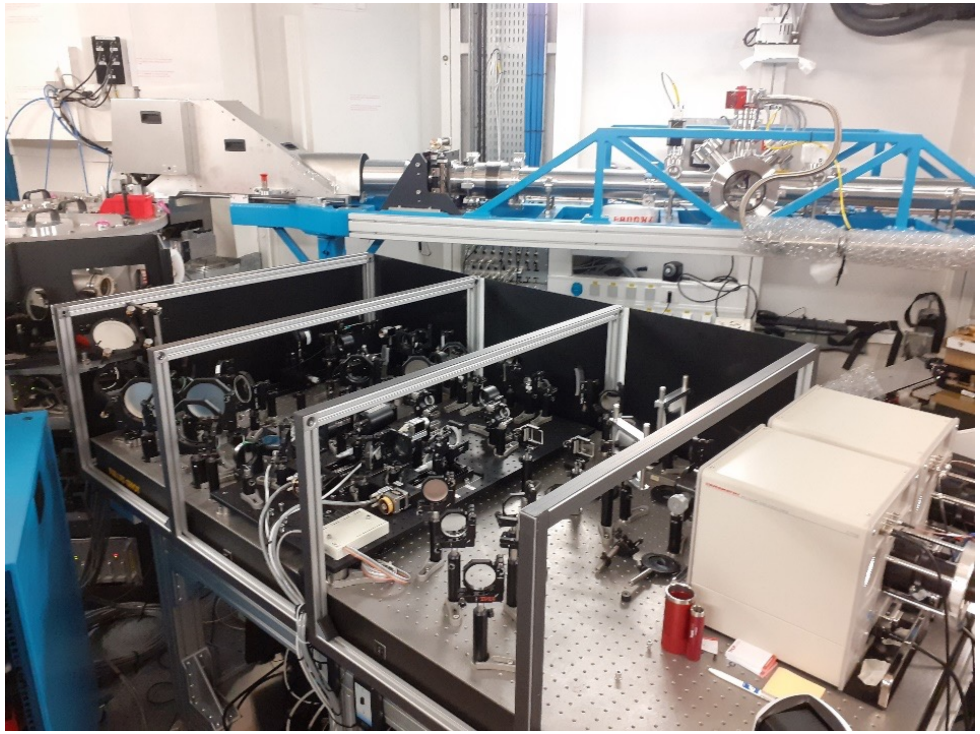


→ See talk of O. Zabiolle (Amplitude) at 17:20

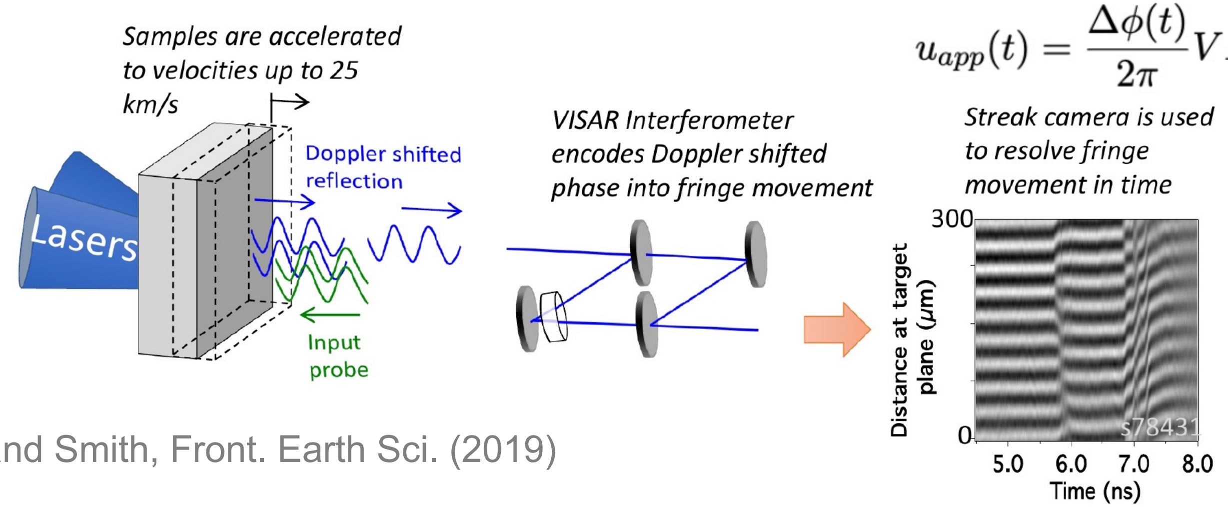
Optical diagnostics

Line-imaging VISAR (x2)

- Time-resolved velocity measurements
- Pressure determination
- Reflectivity measurement



$$u_{app}(t) = \frac{\Delta\phi(t)}{2\pi} VPF$$



Duffy and Smith, Front. Earth Sci. (2019)

HPLF line-imaging VISAR – Current setup	
Probe laser	**532 nm, 100 ns flat-top pulses**, custom laser from LULI SLM, ~100 kW/pulse
VISAR (x2)	**VPF from <1 km/s/fr to 30 km/s/fr**
Magnification	Adjustable, x33-67 (**FOV ~480-240 µm on target**),
Streak cameras (x2)	High dyn. range Hamamatsu with S20 photocat., from HZDR 10, 20 and 50 ns time windows commonly used
Other characteristics	Good WL imaging, allows to assess target quality before shot, and alignment with X-rays and drive laser Compact and potentially transferable to other beamlines

Optical diagnostics

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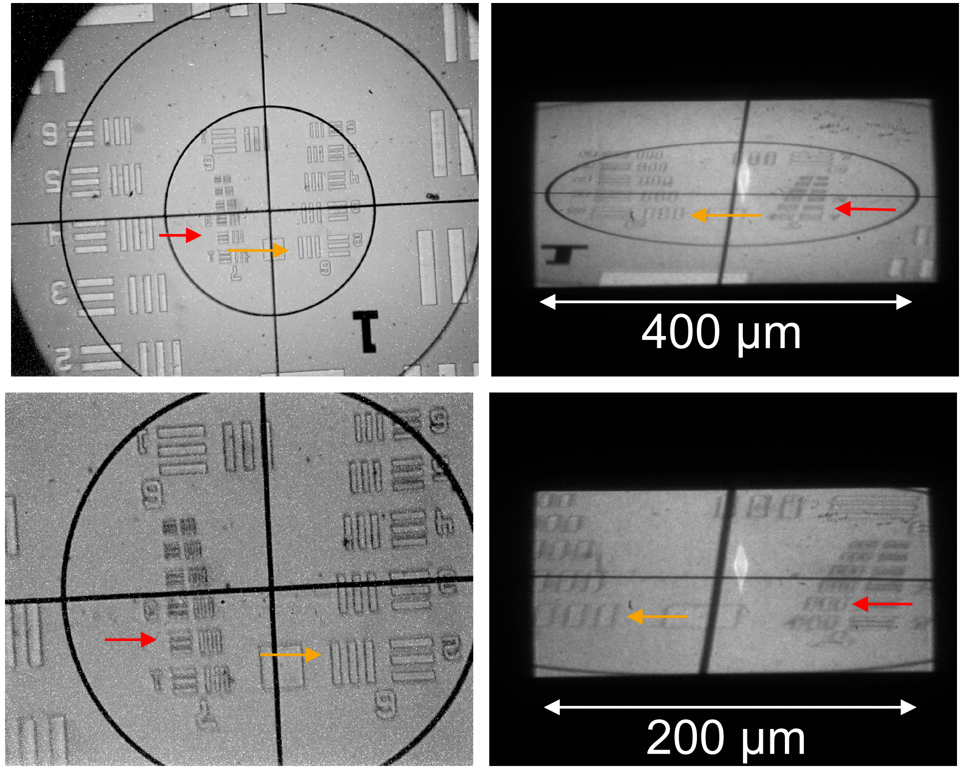
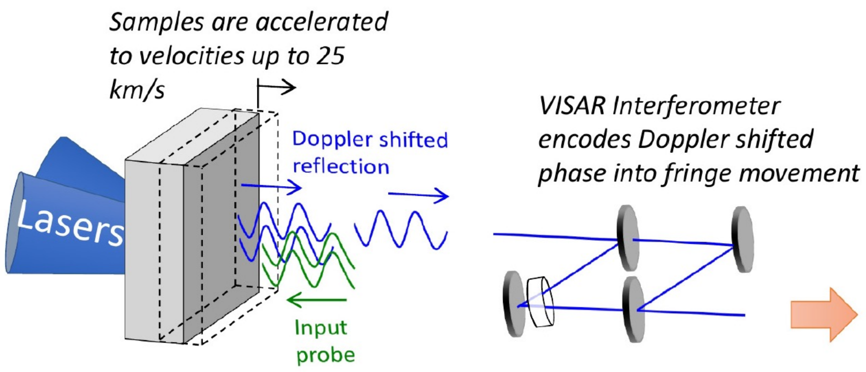


Line widths: 6.96 µm, 3.48 µm



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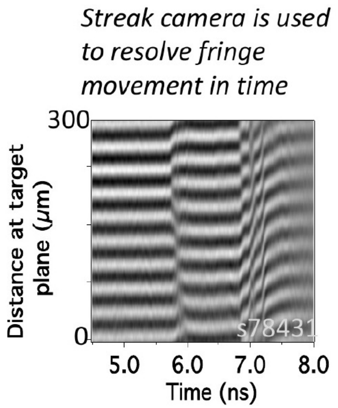

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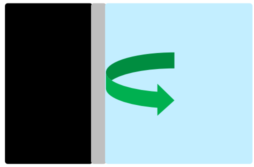
Optical diagnostics

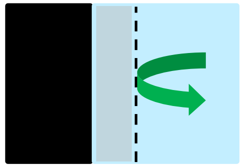
Line-imaging VISAR: Different cases

Breakout

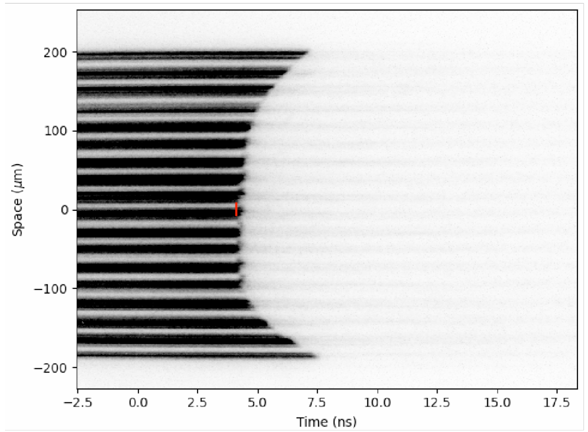
Free surface

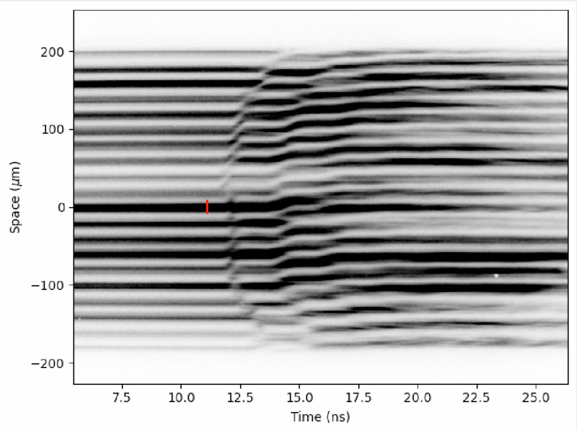


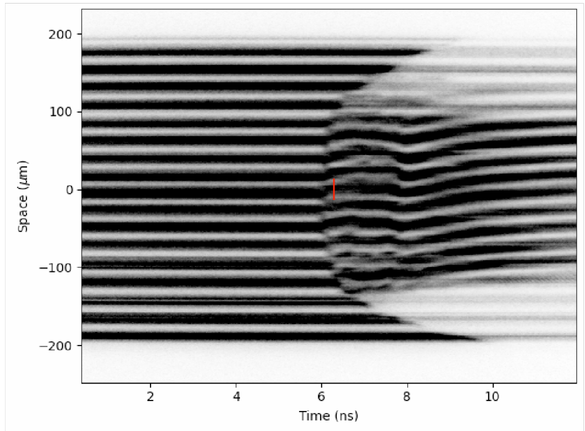
Interface with window

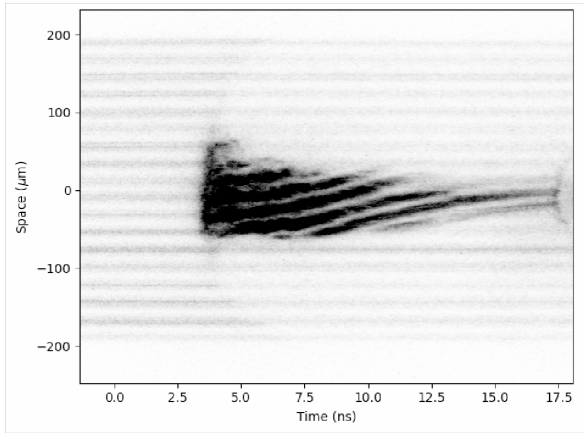


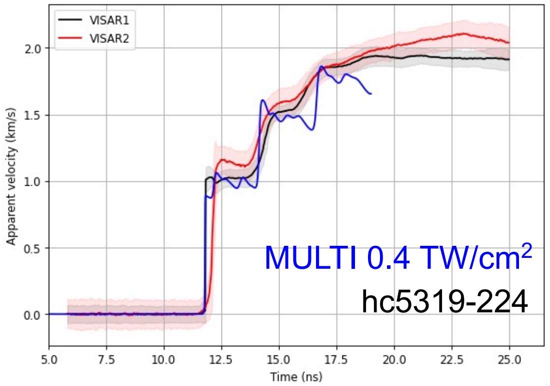
Shock front

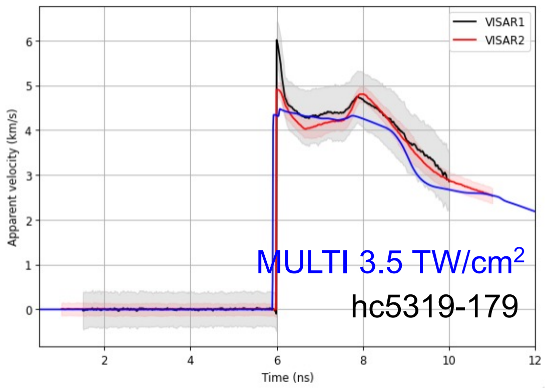


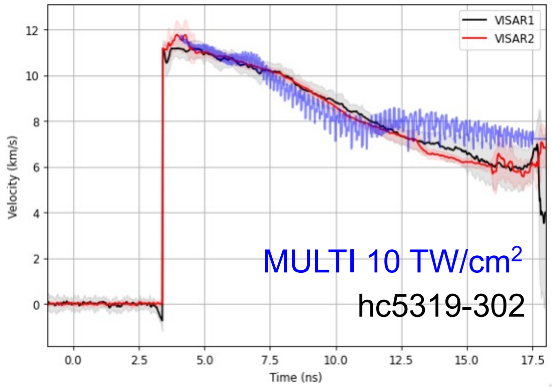






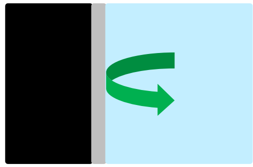




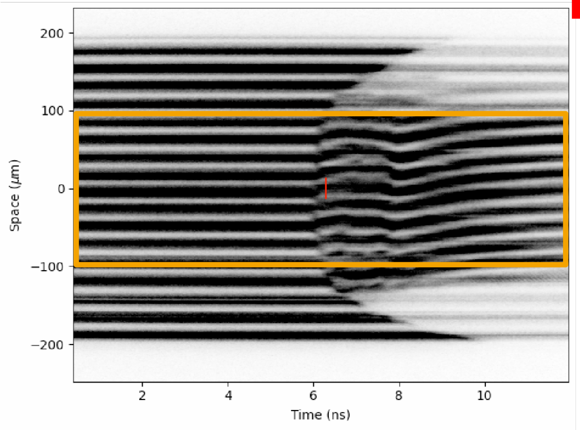


Support for analysis and hydrodynamic simulations

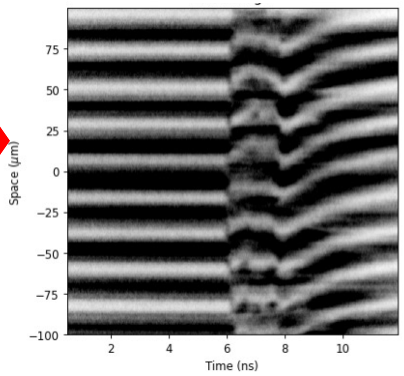
→ **Development of tool to analyse VISAR images and determine pressure**



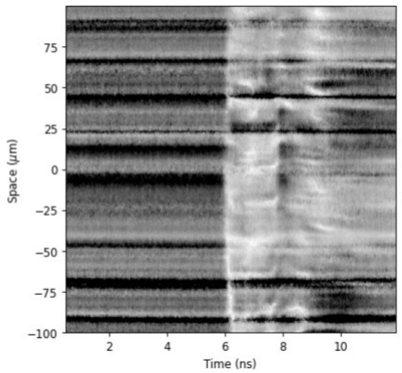
Interface with window



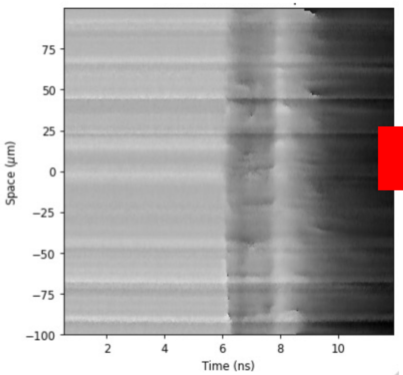
ROI



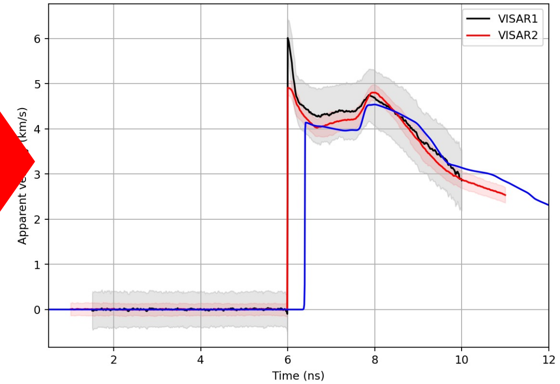
Reflectivity

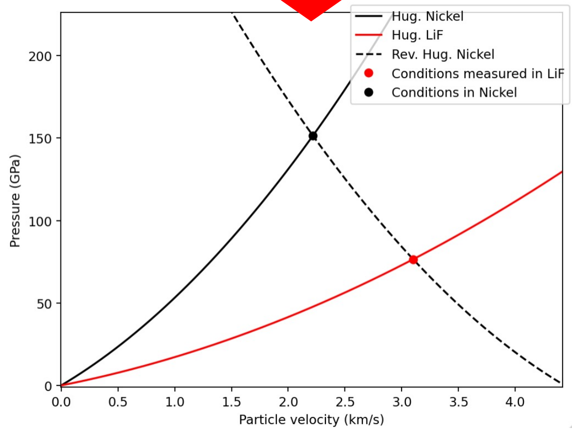


Velocity



Velocity average on ROI

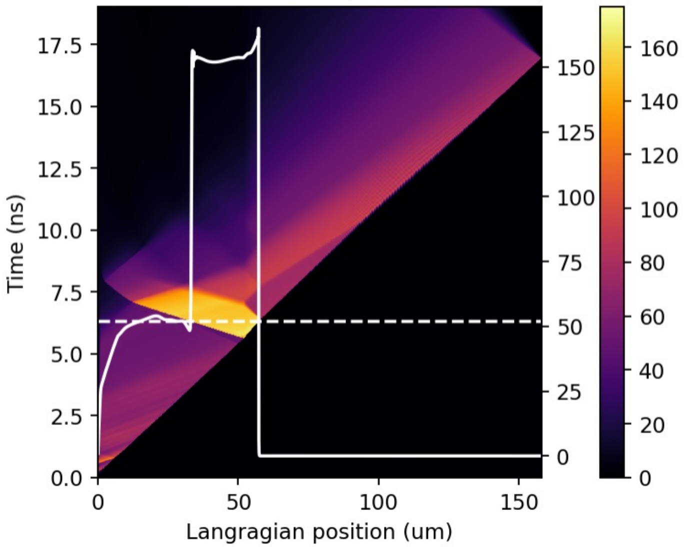




→ **Hydrodynamic simulations with MULTI and ESTHER codes**

- Experiment preparation, target design
- Analysis of shock hydrodynamics

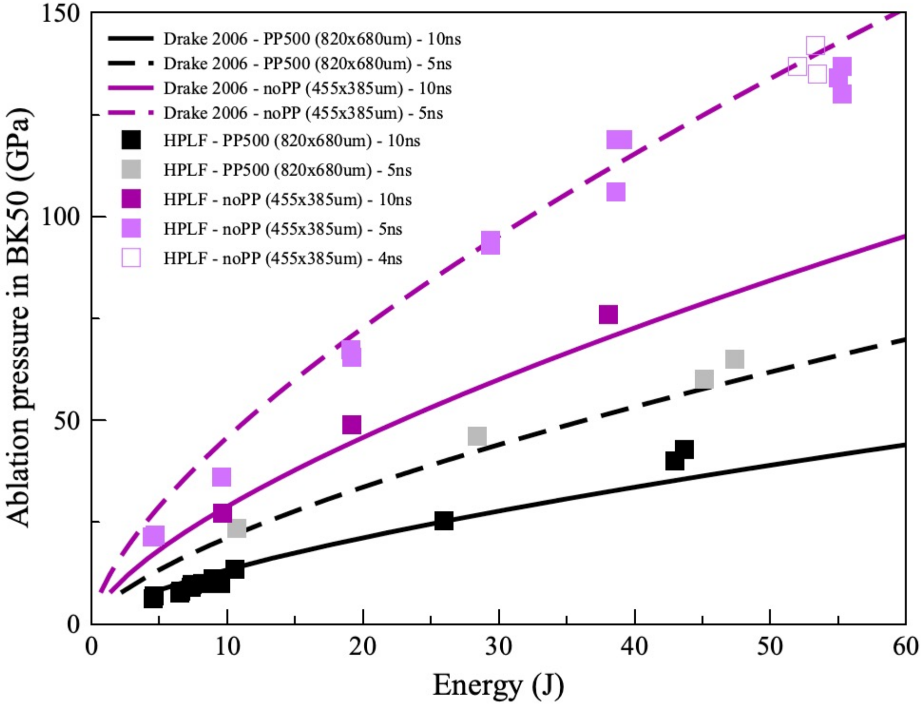
Pressure (GPa)



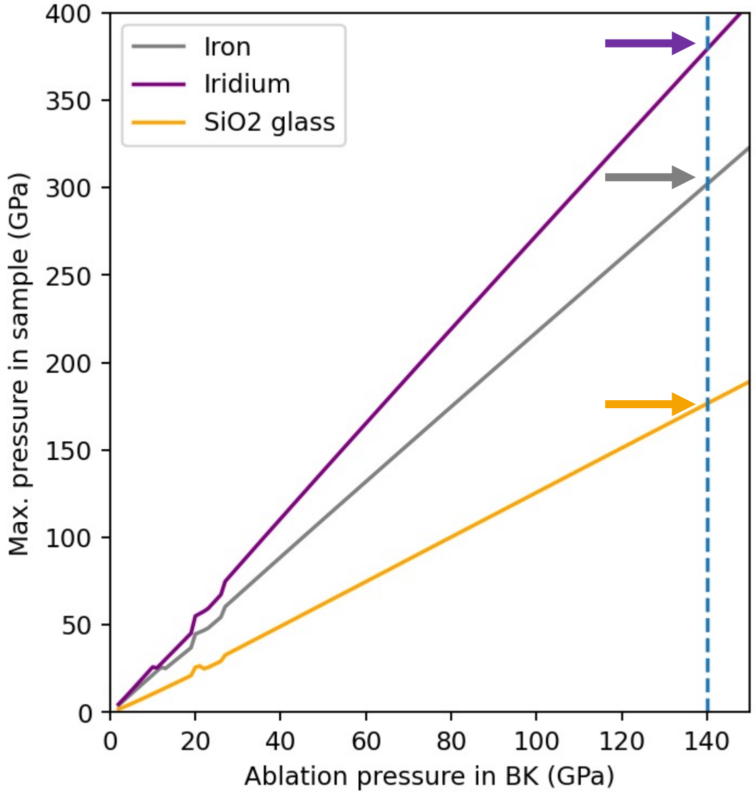
HPLF drive capabilities

→ **Ablation pressure measurements in Black Kapton (max. 140 GPa)**

Ablation pressures for different pulse durations and focal spot sizes



Corresponding shock pressure in a sample directly attached to black kapton



Consistent results with different targets (BK/LiF, BK/SiO_2 glass, BK/metal, BK alone)

Some science cases investigated in the last two years

Fundamental physics

Warm Dense Matter, Phase diagrams (Fe, Cu, Co)
S. Balugani et al. (ESRF, FLF, LULI, Oxford Uni.)

Shock induced metallization of GeO_2 A. Benuzzi et al. (LULI, CELIA, ESRF)

Shock of pre-compressed water in DAC A. Dwivedi et al. (EuXFEL, Milano Univ., ESRF, LULI, LLNL)

Material sciences

Ni, phase transitions
A. Sollier, C. Pépin et al. (CEA)

Bulk and Nanopourous Cu
A. Krygier, J. Eggert, et al. (LLNL)

CuZr based Metallic glasses
D. Loison (Uni. Rennes1, Warsaw Uni., LULI)

Phase transitions
Local ionic structure

T from EXAFS

Electronic structure

Planetary sciences

Fe-oxides
J. Pintor, M. Harmand et al. (IMPMC U. Rochester, EuXFEL, LULI, PIMM)

Fe-bearing silicate melts
JA Hernandez et al. (ESRF, IMPMC, LULI, Arizona Univ., Stanford Univ.)

Fe-alloys
G. Morard, J.-A. Hernandez, G. Garofalo et al. (ESRF, IMPMC, LULI, Arizona Univ., Stanford Univ.)

Reactivity of Fe and H
D. Kraus, C. McGuire et al. (Rostock Uni., HZDR, LULI, Stanford Uni., LLNL)

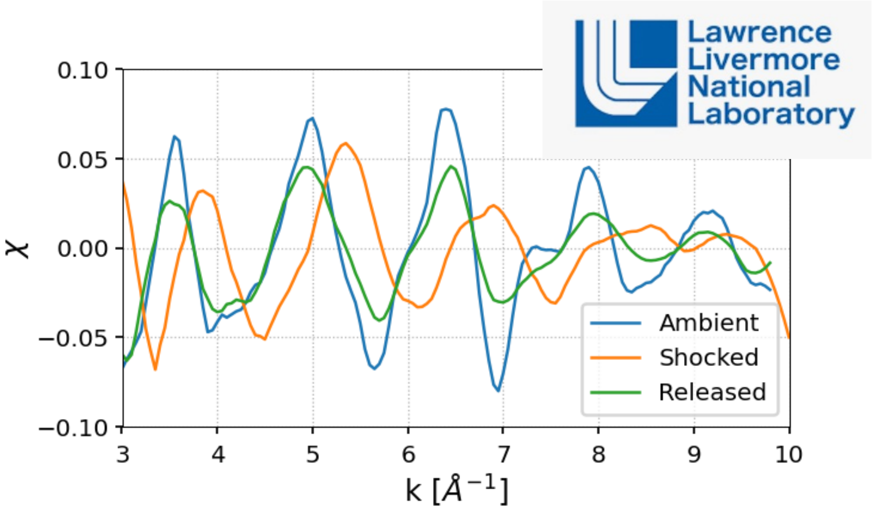
Fe-bearing carbonate
A. Diwedi et al. (EuXFEL, ENSTA, IMPMC, MNHM, PIMM, ESRF)

Investigation of 3d-metals structure and electronic properties

Copper

Focus on temperature determination from EXAFS in fcc phase

A. Krygier, J. Eggert, C. McGuire, C. Vennari, P. Hesselbach et al.



Courtesy of A. Krygier

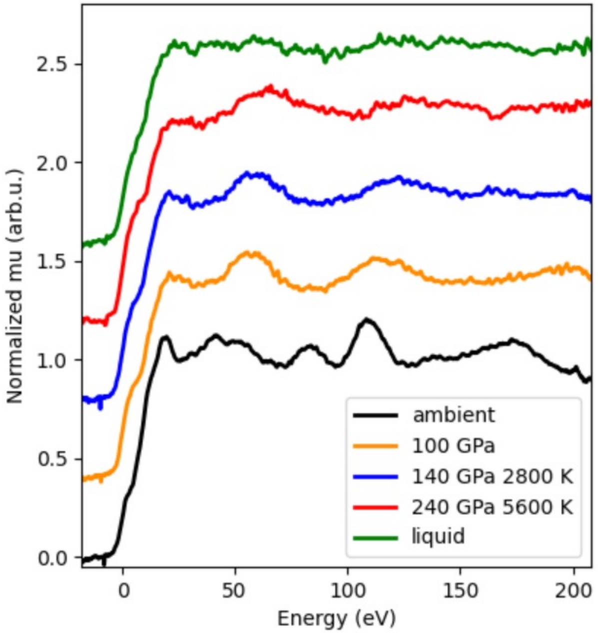
→ **See talk of A. Krygier (LLNL) on Wednesday at 8:30**

Iron

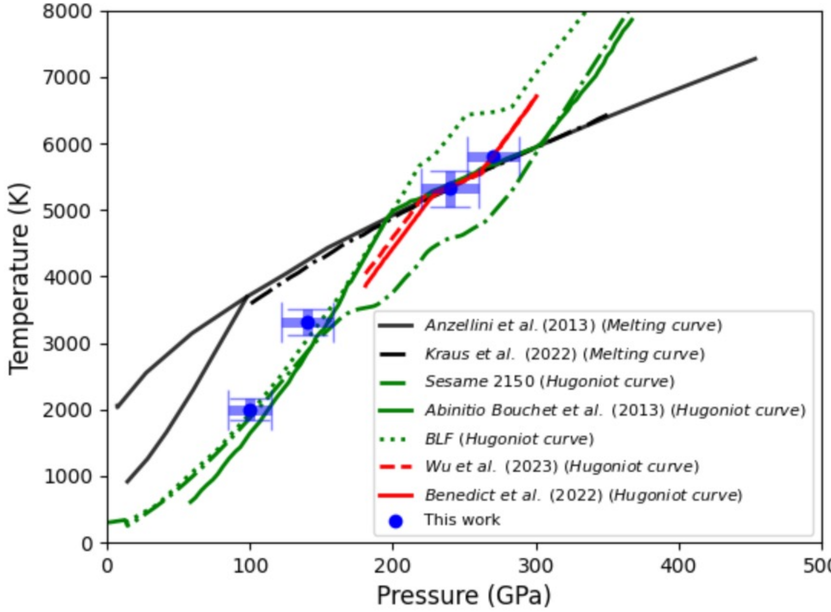
Focus on phase transitions and liquid in the warm dense state

S. Balugani, R. Torchio, et al.

On-Hugoniot states



T from EXAFS, agreement with DFT-MD based Hugoniot T



Balugani et al., in prep.

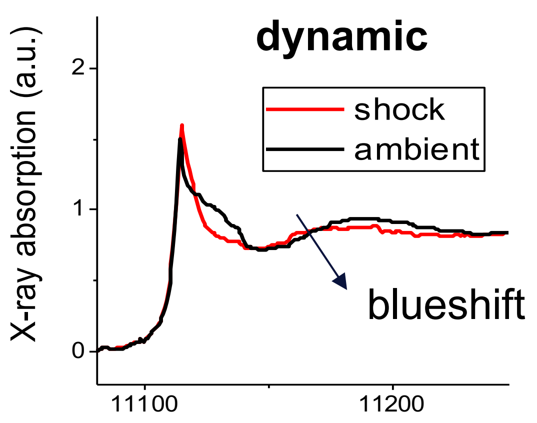
→ **See talk of S. Balugani (ESRF) on Wednesday at 9:00**

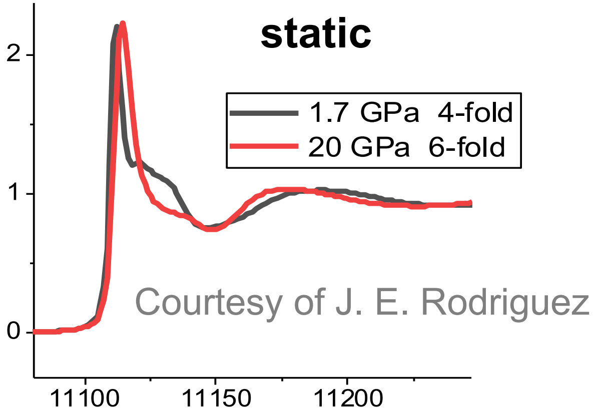
Structural transitions and metallization of glassy GeO_2

GeO_2 as analogue of SiO_2, key constituent of Earth and planets

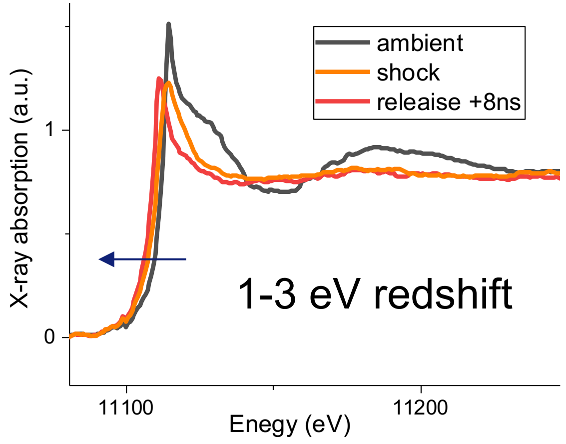
A. Benuzzi-Mounaix, R. Torchio et al.

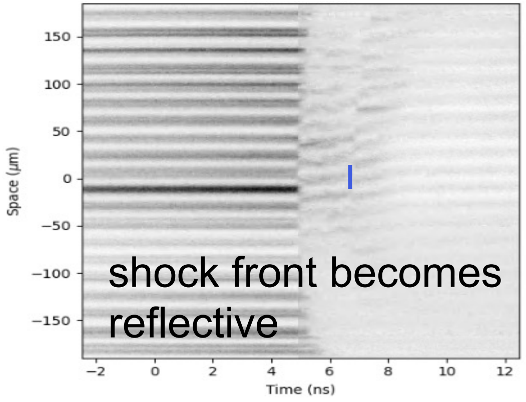
Densification to 6-fold rutile structure (P < 100 GPa)



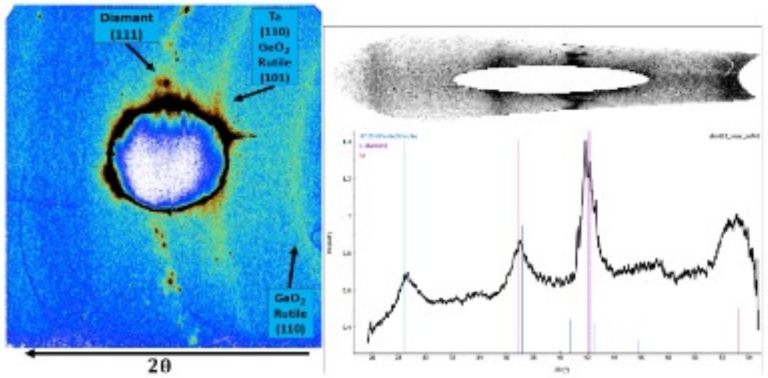


Metallization and band gap closure (P > 100 GPa)

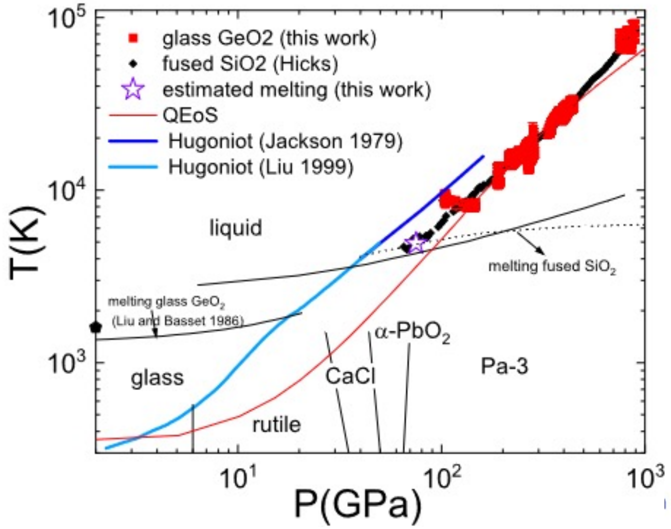




EOS and XRD done at LULI



XRD @ LULI,
Denoeud, Hernandez *et al*. RSI, 2021



→ **See talk of A. Benuzzi (LULI) on Thrusday at 11:10**

ESRF

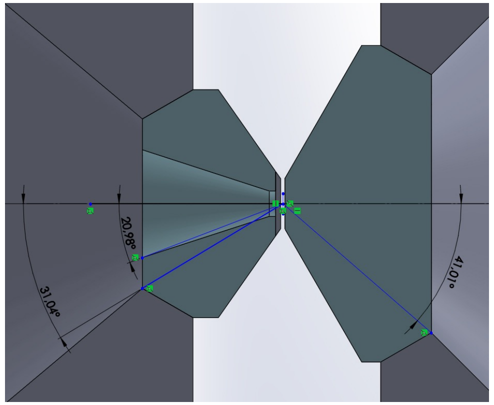
Exploring denser states by coupling static and dynamic compressions

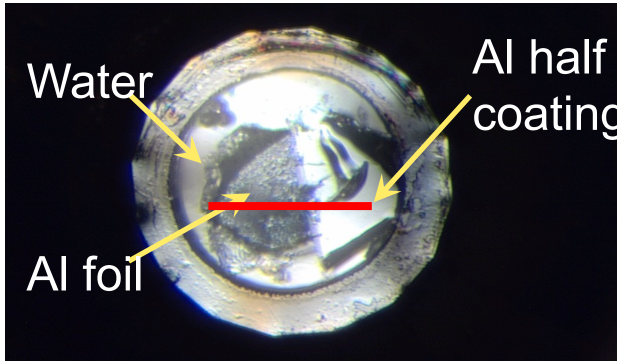
Laser-shock in DAC pre-compressed samples, adaptation for 100J-class lasers

A. Diwendi, V. Cerantola, J.-A. Hernandez, A. Ravasio, E. Brambrink, M. Millot, et al.

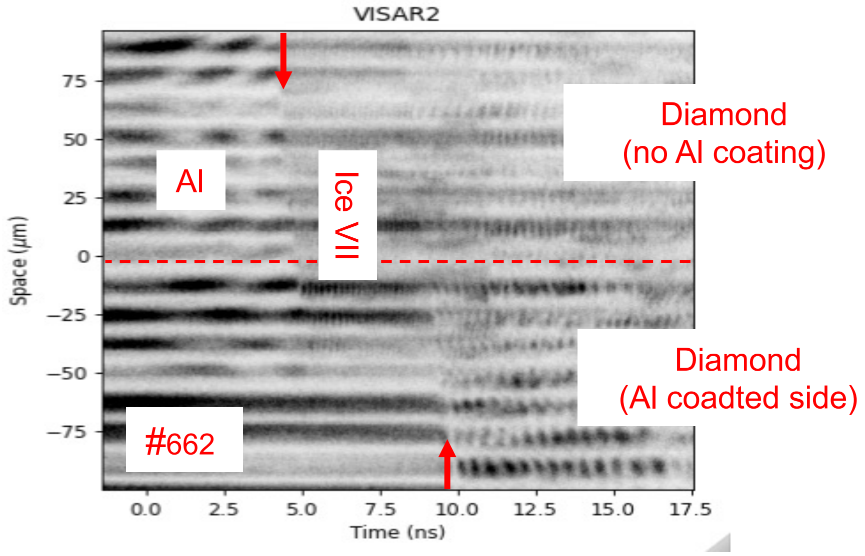
Pre-compression in DAC increases pre-shock density and allows to produce shock states with higher ρ and lower T (so far reserved to large laser facilities)

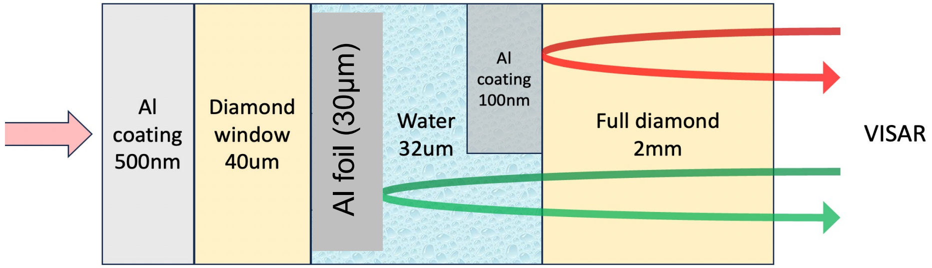
Adaptation to 100J-class lasers coupled with X-ray facilities using perforated diamond anvils?





Shock in ice VII pre-compressed at 5 GPa on HPLF
Pressure was about 40 GPa in H_2O





First laser-only tests and proof-of-principle done on HPLF

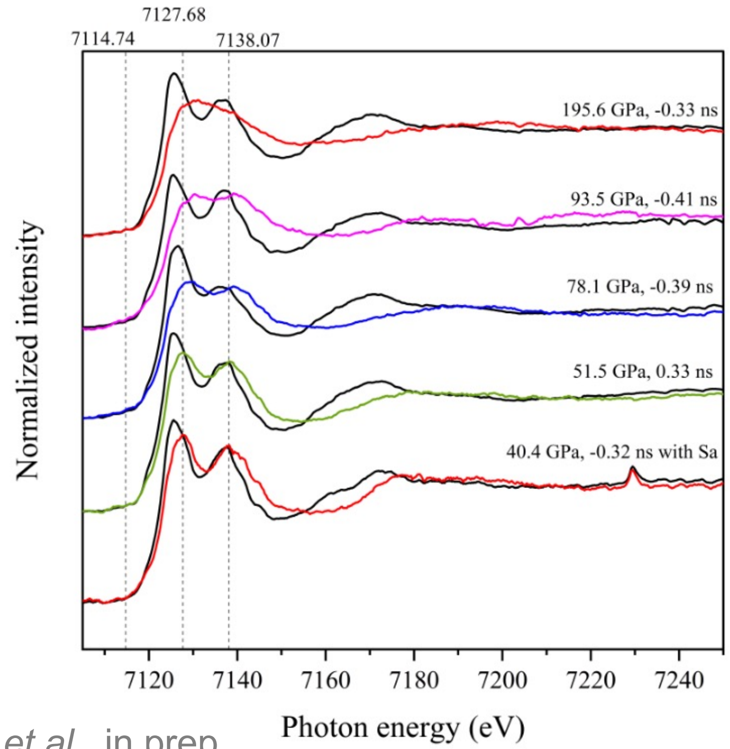
→ **See poster of A. Dwivedi (EuXFEL)**

Fe-bearing planetary compounds

Siderite (Mg,Fe)CO_3

A. Diwendi, V. Cerantola, F. Guyot, M. Harmand, T. de Resseguier et al.

Transformation mechanisms upon impact?
Fate of carbonates at lower mantle conditions?



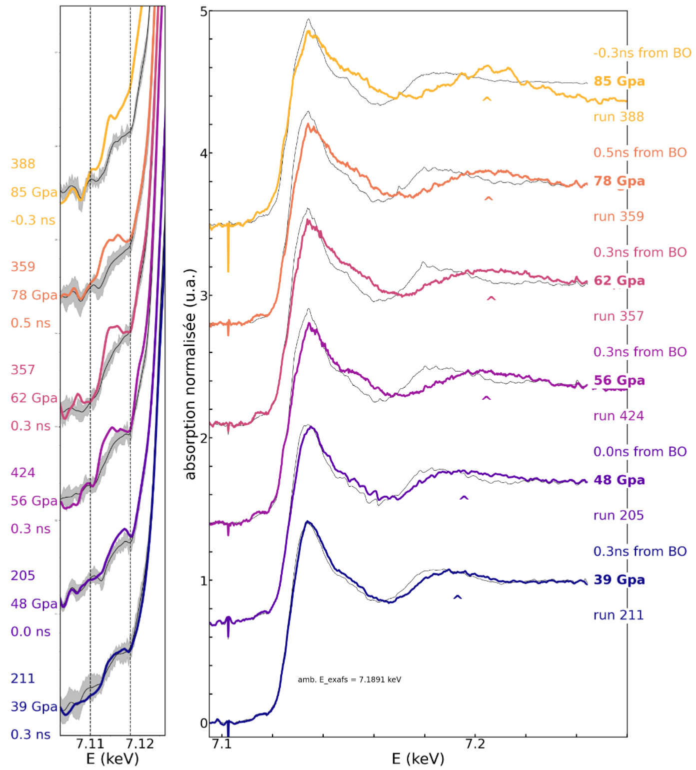
A. Diwendi *et al.*, in prep.

→ **See talk of A. Dwivedi (EuXFEL) on Wednesday at 11:50**

Hematite Fe_2O_3

J. Pintor, A. Amouretti, K. Appel, K. Buakor, M. Harmand et al.

Effect of strain rate and kinetics in Fe_2O_3 HP
Interplay between electronic and ionic structures?



J. Pintor *et al.*, in prep.

→ **See talk of J. Pintor (IMPMC) on Wednesday at 12:10**

ESRF

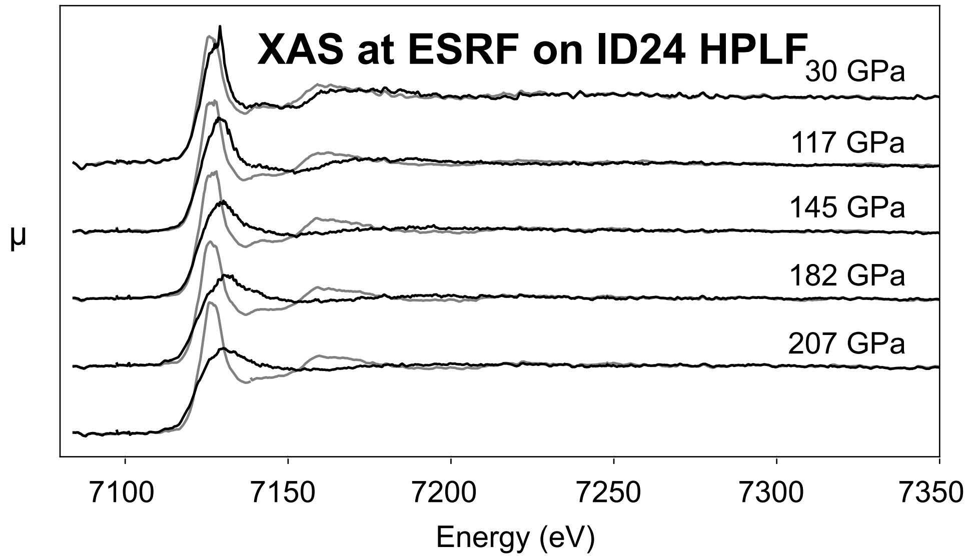
Fe-bearing planetary compounds

Investigation of dense Fe-bearing silicate melts: example of Almandine garnet $(Mg,Fe)_3Al_2Si_3O_{12}$

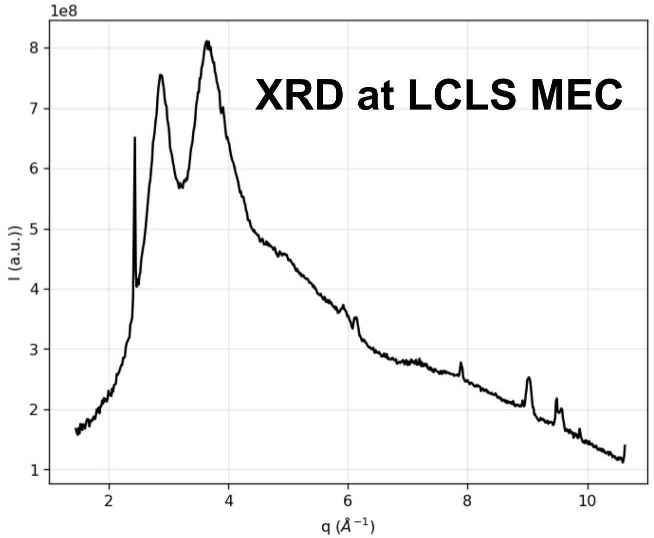
J.-A. Hernandez, L. Lebon, G. Morard, S. Pandolfi, A. Ravasio, S. H. Shim, X. Xong, A. Gleason, R. Alonso-Mori, H. J. Lee, W. Mao, C. Prescher, N. Sevelin-Radiguet, R. Torchio

Thermodynamics, structural and electronic properties of Fe-bearing dense silicate melts
Implications for deep magma oceans of terrestrial planets (composition, lifetime, conductivity)

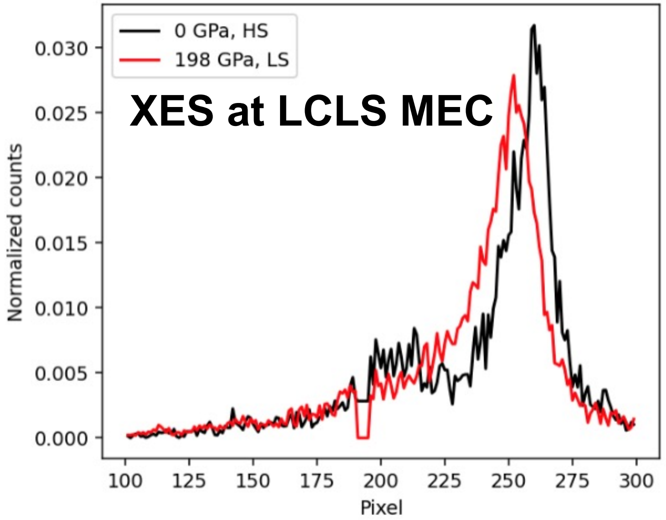
Local structure around Fe atoms and electronic transitions from XAS



Phase transitions and liquid structure from XRD



HS-LS transition evidenced by Kβ XES



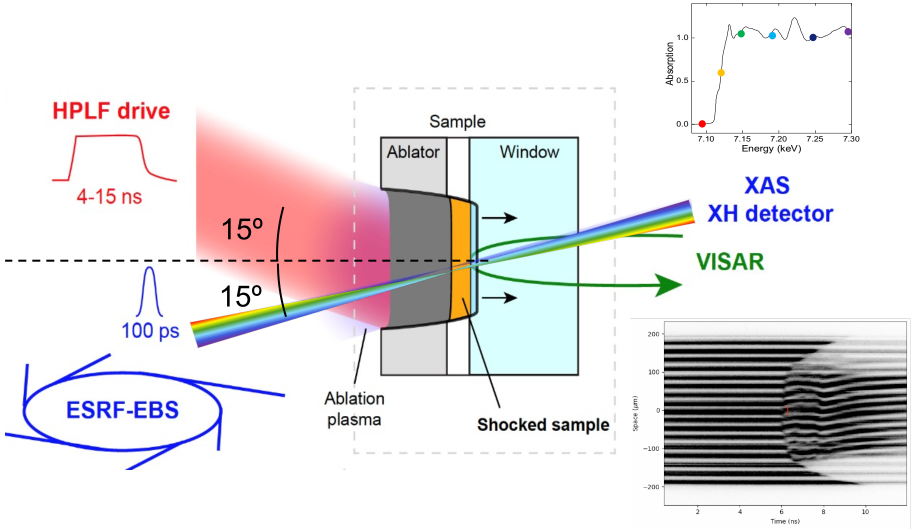
+ EOS at LULI

Summary and next steps

✓ **HPLF has been welcoming users since June 2022!**

✓ **Experimental configuration**

- Drive laser providing **55 J in 4-15 ns at 1053 nm**
- **Up to 140 GPa ablation pressure** in black kapton
- **High-resolution XAS for edges between 5 and 28 keV**
- **2 line-imaging VISAR**
- Support for analysis and experiment preparation



✓ **Good first science results**

- First manuscripts expected to be submitted in the coming weeks/months
- Most studies are at the stage of performing comparative atomistic simulations

→ **Streaked Optical Pyrometer** to be installed by mid-2024

→ **HPLF-II**: HPLF laser upgrade and coupling with other X-ray diag. (XRD, XRI, …)

→ **See round table session**

Université Grenoble Alpes

ESRF The European Synchrotron

Applying for beamtime on the High-Power Laser Facility on ID24-ED

Pratical information

Register to hplf@esrf.fr
(facility parameters, proposal deadlines, target testing sessions)

Proposal submission
2 calls per year (September and March)
Beamtime 1 year after acceptation

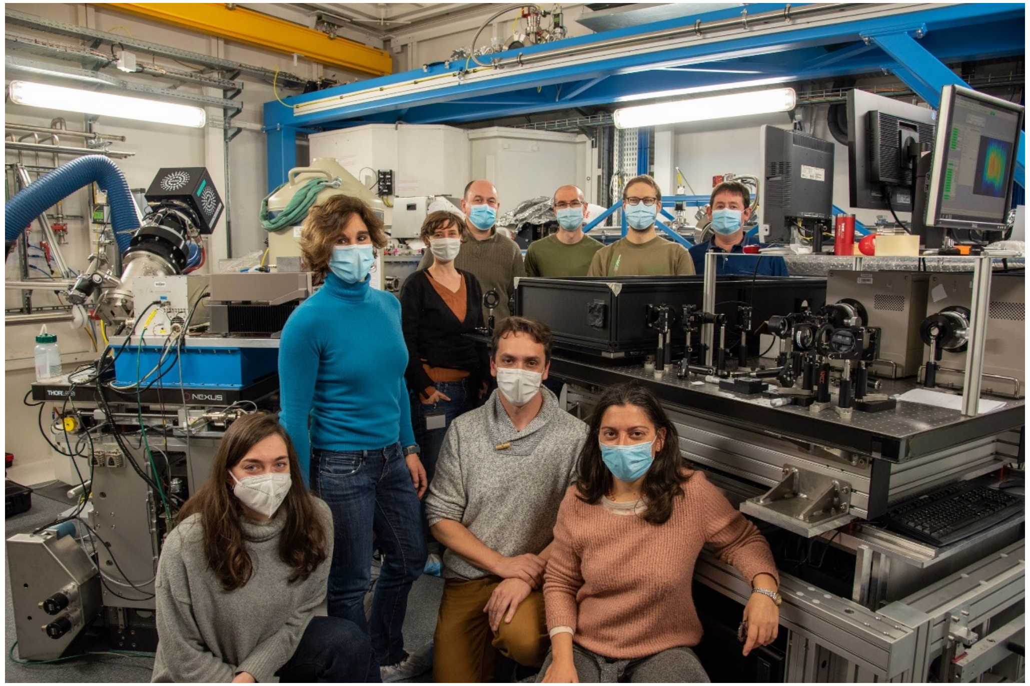
- **Help provided for experiment design if needed**
- **~100-150 samples needed per beamtime**
- **Samples should be tested in advance**

Contacts:
R. Torchio, raffaella.torchio@esrf.fr (Scientist in charge of ID24-ED and HPLF)
J.-A. Hernandez, jean-alexis.hernandez@esrf.fr (Scientist responsible of dynamic compression experiments)

Acknowledgments

→ ESRF, partners and staff for supporting this facility

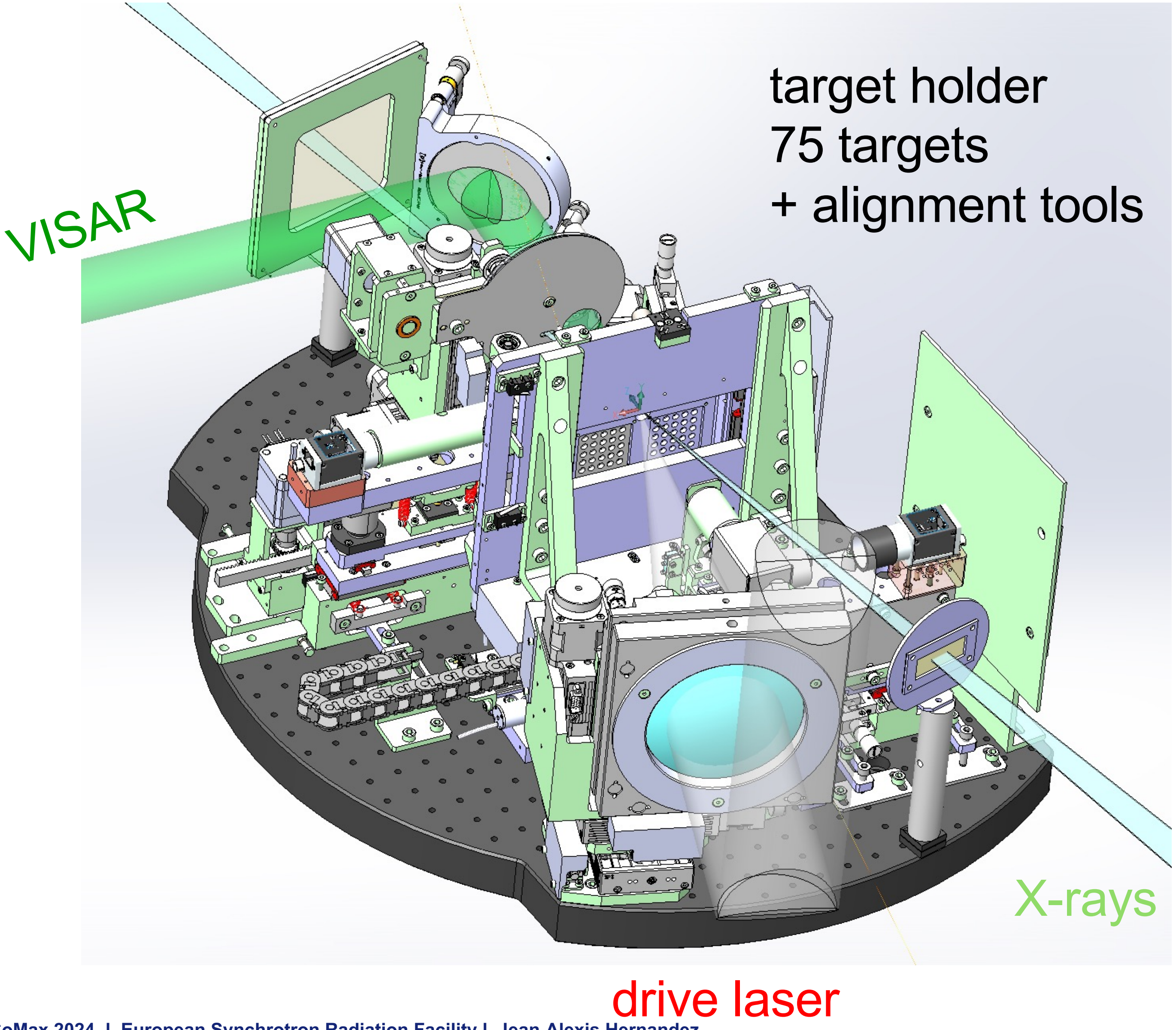
→ All people who provided help and advices from different institutes



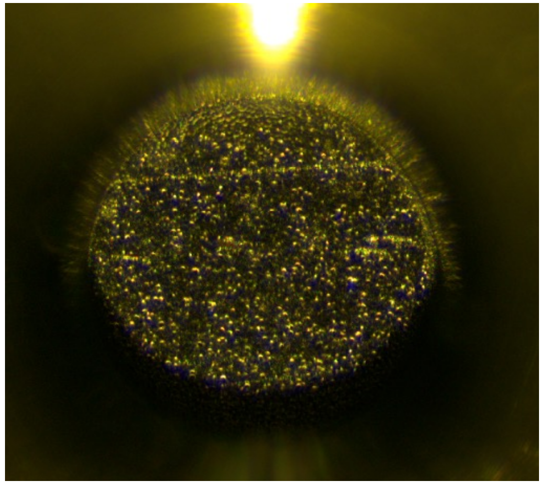
→ Users for their interest, feedback and for making leading science at ESRF!

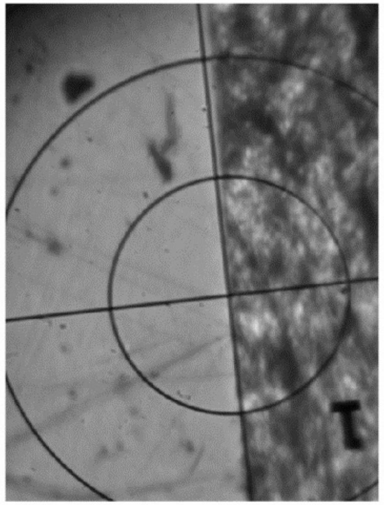
Thank you for your attention

Interaction chamber and target holder



Upstream µscope image

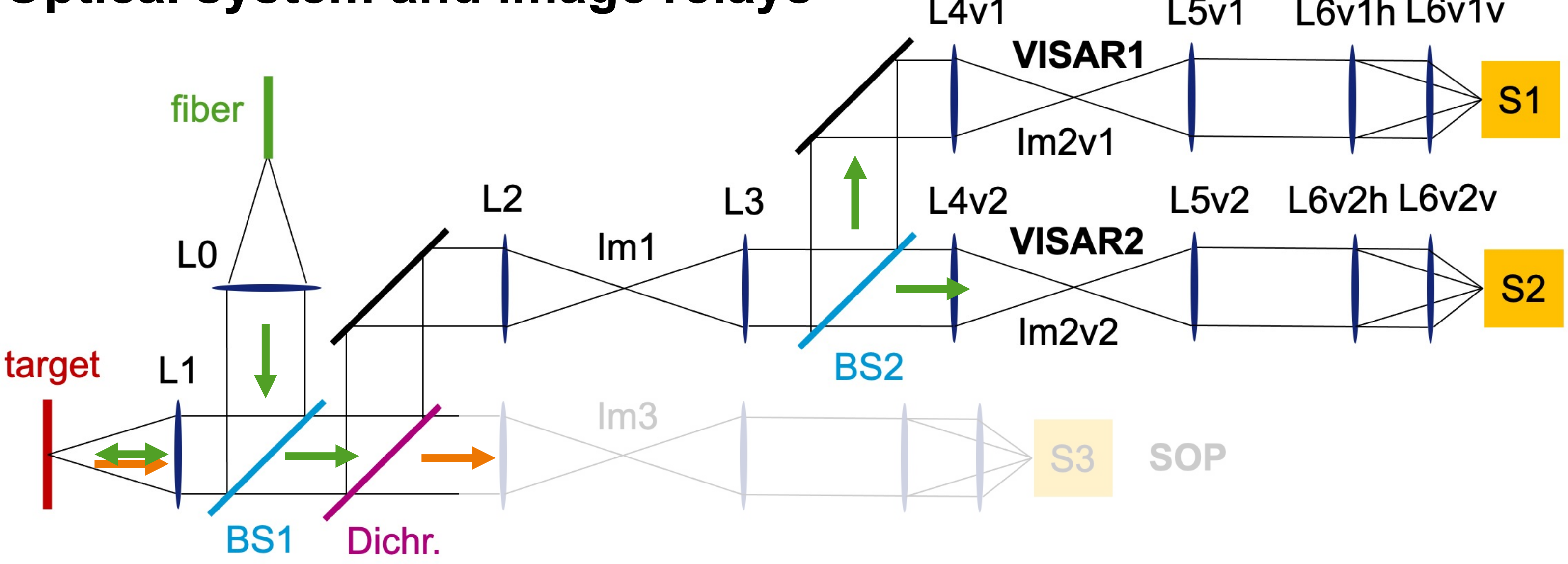




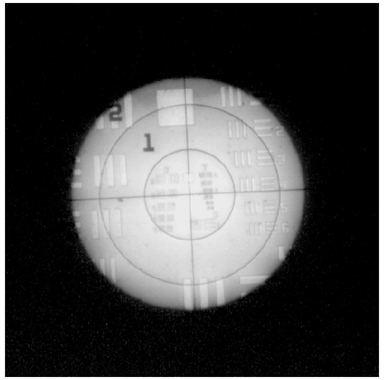
Downstream visar image

Optical diagnostics

Line-imaging VISAR: Optical system and image relays



Im1 (x2.7)



Im2 (x13.5)

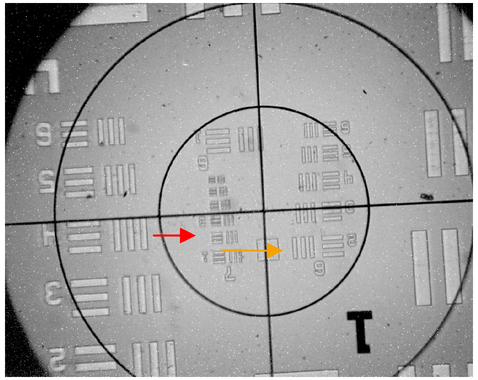
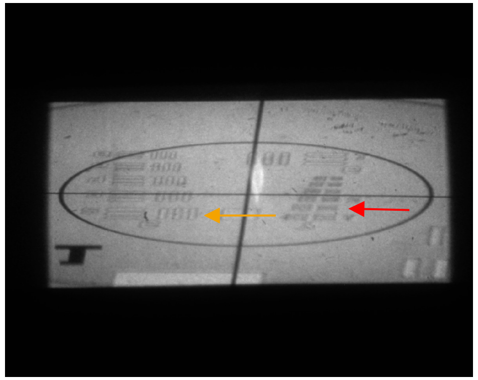


Image (x33) on streak slit



Im2 (x27)

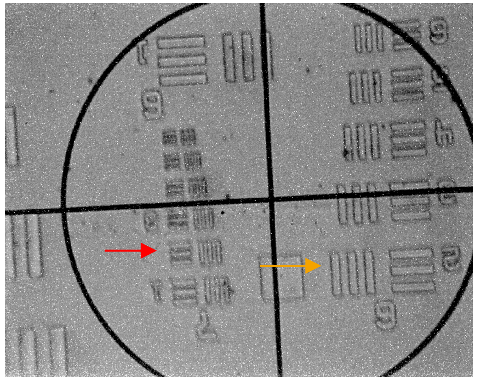
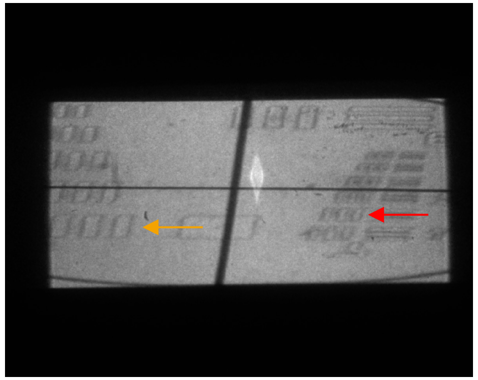


Image (x67) on streak slit



Line widths: 6.96 µm, 3.48 µm

Max. fov = 400 um usable

Min. fov = 200 um usable