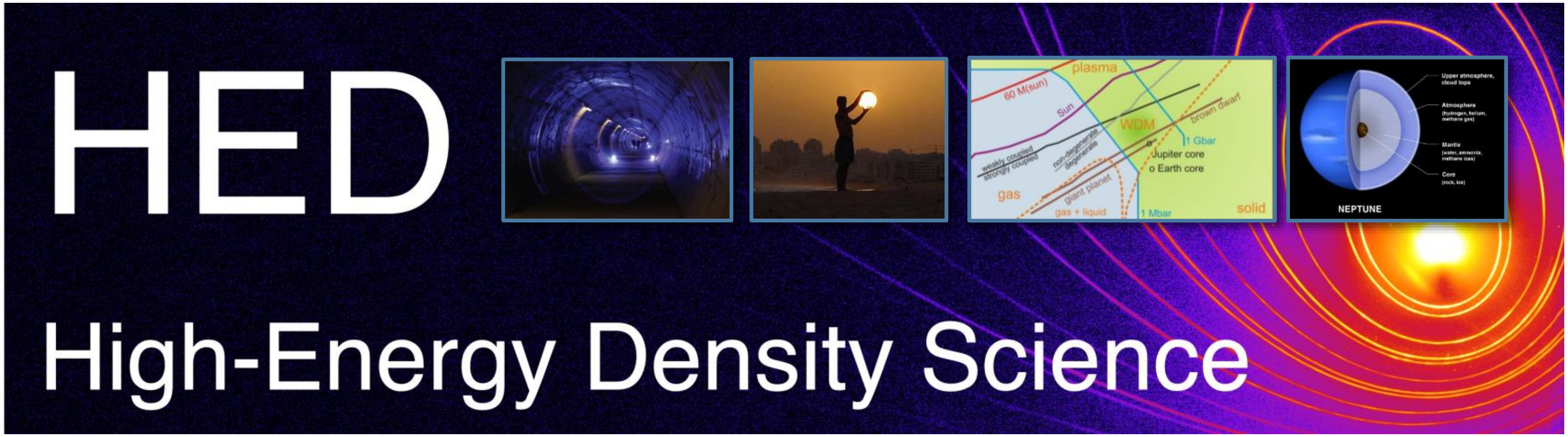
User’s meeting 2024 – Eurizon 2020+

Science at the HED-HIBEF instrument

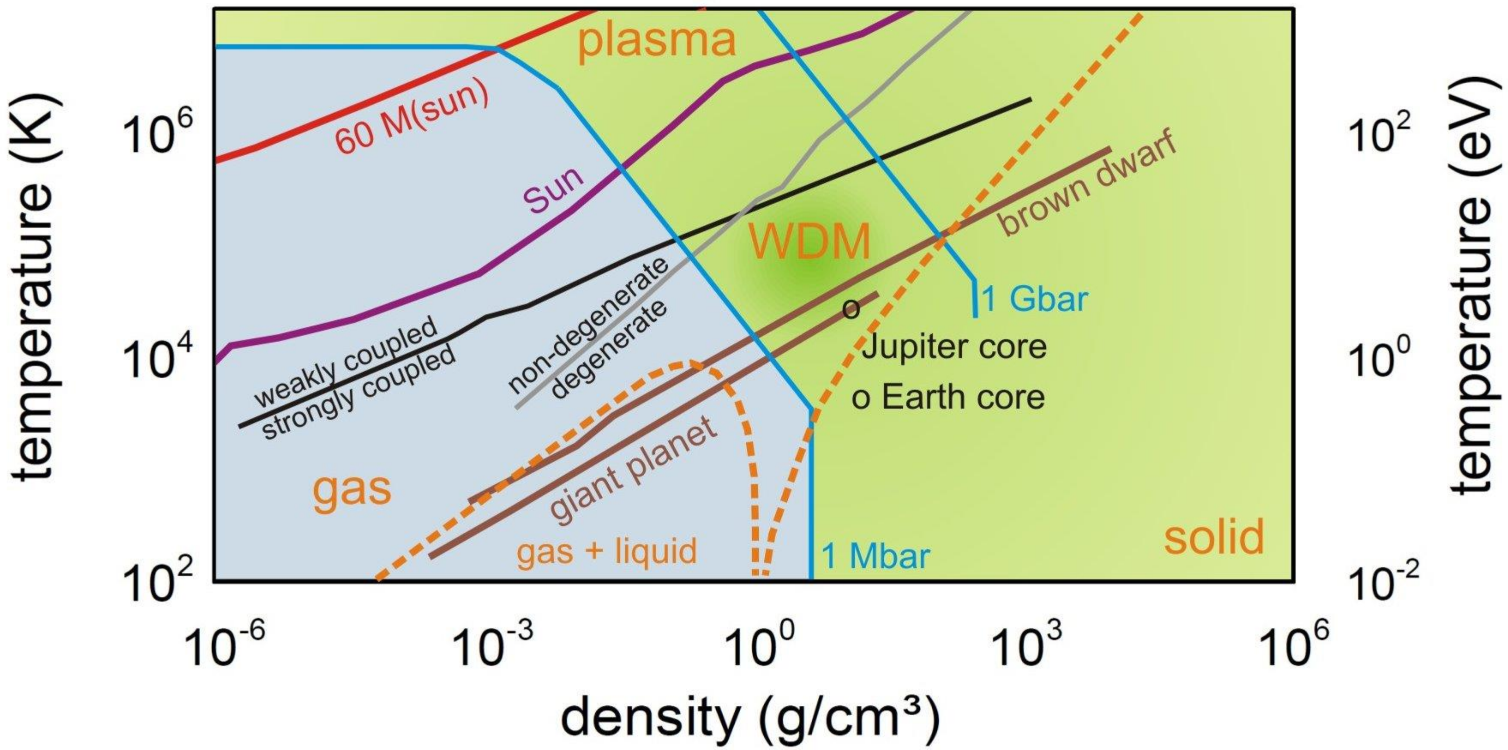
Ulf Zastrau
High Energy-Density (HED) science group
European XFEL, Schenefeld, Germany

EuXFEL – Jan 23, 2024

HED HiBEF



Condensed Matter <> **Warm Dense Matter** <> Hot Dense Matter



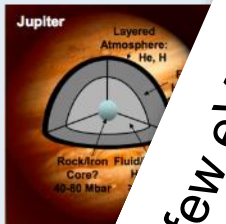
High free-electron density: penetration only up to critical density

$$n_c = \omega^2 \varepsilon_0 m / e^2$$

→ access to volumetric plasma parameters only by short wavelength radiation ($\omega > \omega_P$)

HED – research at extremes

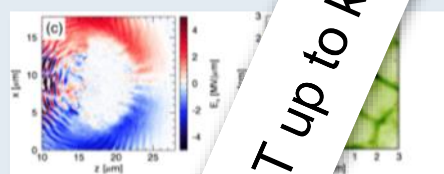
Laser Compression
Shock & ramp compr



XRD, IX

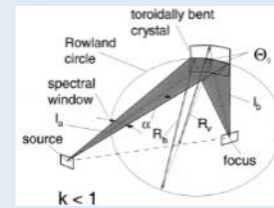
Long-p laser

Relativistic Laser-Plasmas
Electron transpor
Instabilities and filam ,
Particle acceler
High EM fie

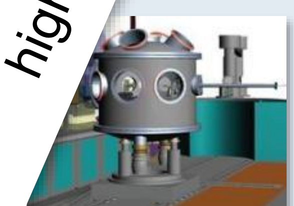


Multi-10 s laser

Advanced methods
Spectrometers
Advanced focusing
SAXS energy analyzer
Phase contrast imaging

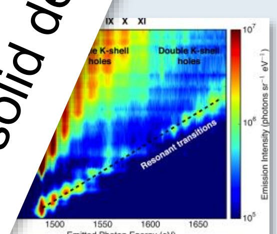


Diam vil Cells
Fast piezo DAC
Puls heated DAC
-stage DAC



18 to 25 keV

Isochor excitation
Tra roperties,
H oms, rates



XES, IXS, XRD
Tight focusing

Further projects
Isobaric heating
Cryogenic jet targets
High-rep solids targets
EMP-hard X-ray detectors
High-purity polarimetry
Laser-shocked DAC
GISAXS

high density $\rho > \rho_0$, T < few eV

solid density $\rho = \rho_0$, T up to keV

European XFEL HED HiBEF

Development of the HED-HIBEF instrument

2019
- First x-rays at HED
- Start of early user operation
- **X-ray only**

2020
- 1st **DAC** community experiment campaign
- 1st **pp-laser** experiment

2021
- Installation of **AGIPD 500K** aka "mini-half"
- 1st **RELAX** community experiment campaign

2022
- **dDAC** with long pulse trains

2023
- **Cryogenic jet target** with RELAX and pp-laser
- 1st **DiPOLE 100-X** community experiment campaign

2024
- We are here!
- Installation of **AGIPD 1M**
- Commissioning of **Pulsed Magnet Field (PMF)** platform
- Instrument Review

2025
- 6 month shutdown
- Installation of **Split-delay-line (SDL)**

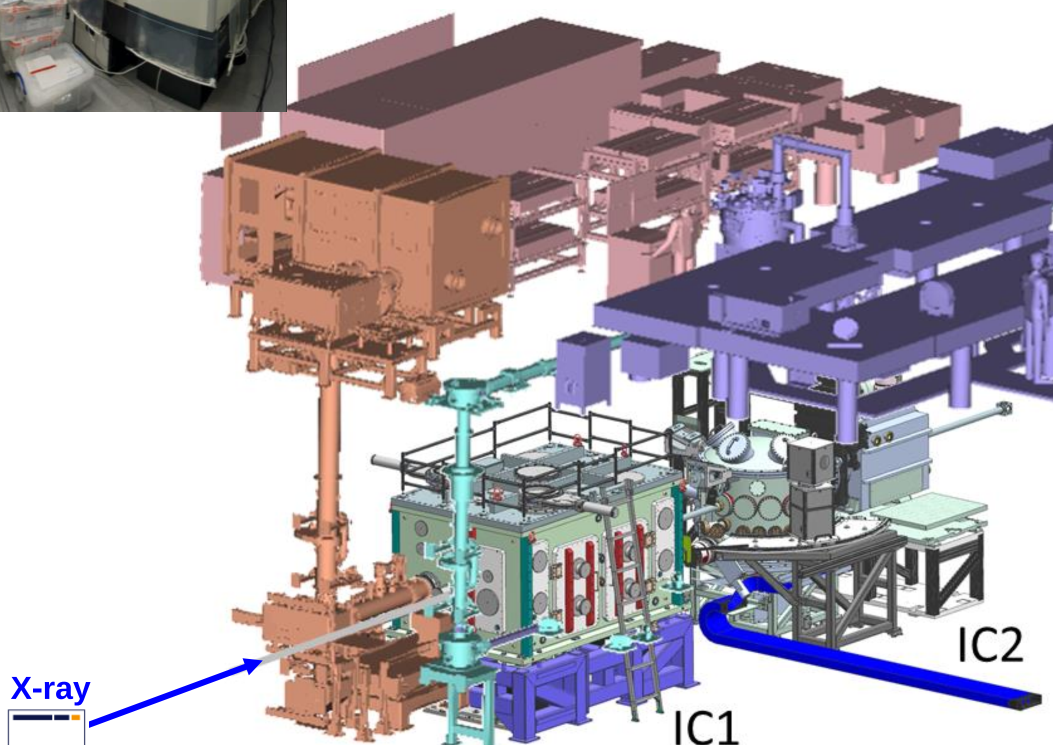
2026
- Super-conducting afterburner (SCU) prototype (**40-70 keV**)

Multi-100 TW ReLaX laser coupled to XFEL beam

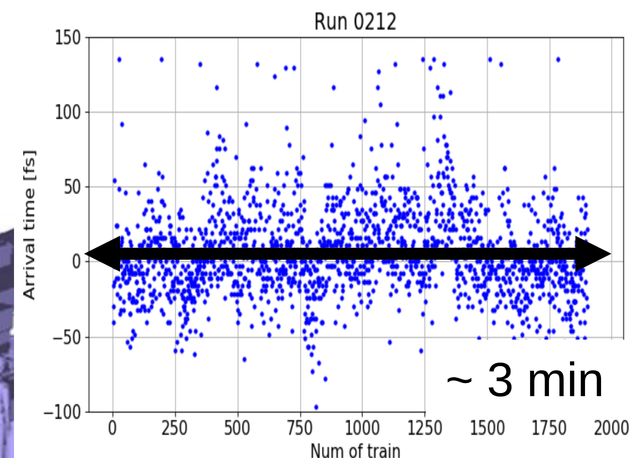
Ti:Sa 800 nm laser
≥ 100 TW, 10 Hz
≥ 3 J, ≤ 30 fs
I ≥ 10^{20} W.cm^{-2}

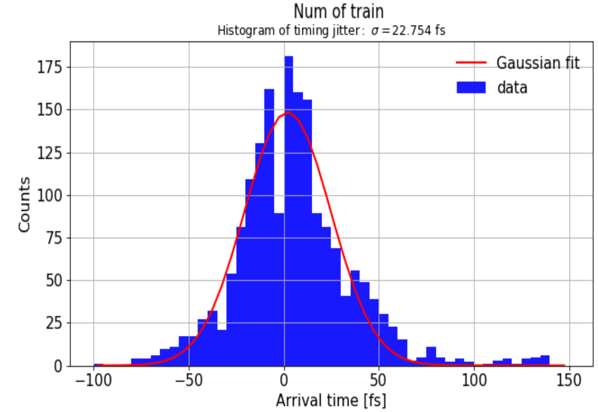
ReLaX laser

HiBEF USER CONSORTIUM



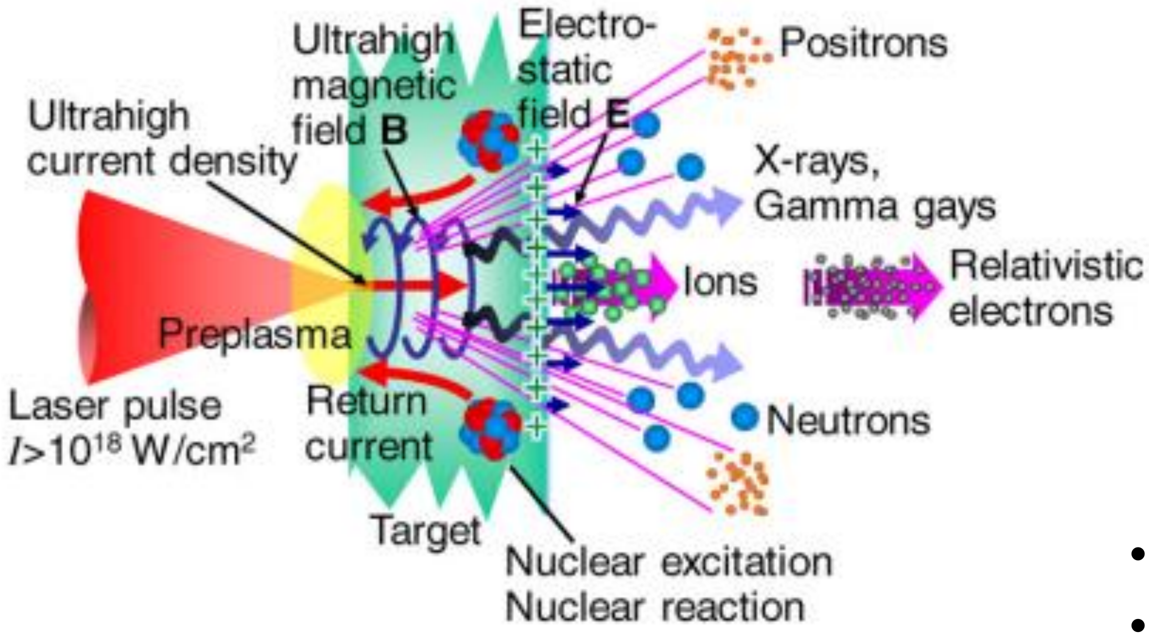
Pulse-to-pulse arrival jitter betweeen **x-ray and** RELAX **is 20-30 fs**





European XFEL HED HiBEF

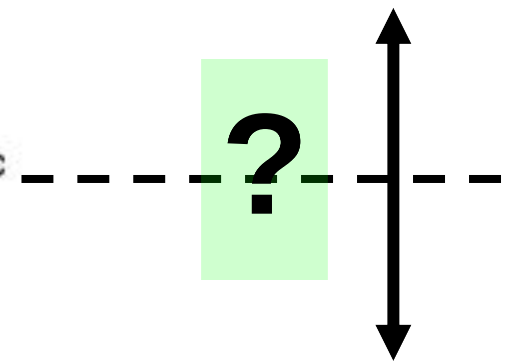
Femtosecond Laser Plasma



Ultra-short relativistic laser pulse interaction with solid target

Lateral extend of:

- Electron heating
- Reflux, return currents



- K-line emission
- Temperature
- Ionization states

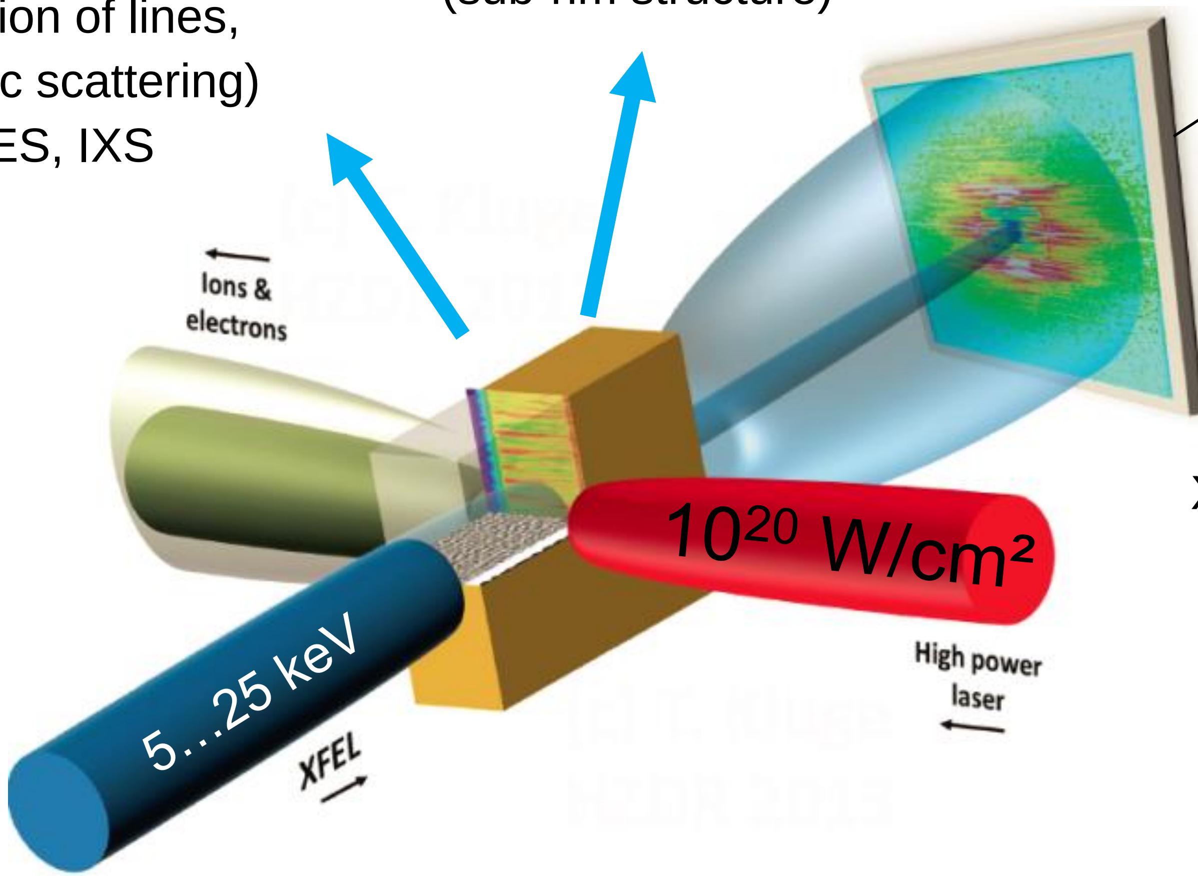
Daido, Nishiuchi and Pirozhkov Rep. Prob. Phys. 75, 056401 (2012)

X-ray probing of relativistic laser plasmas

X-ray spectroscopy
(emission of lines,
inelastic scattering)
XES, IXS

X-ray diffraction XRD
(sub-nm structure)

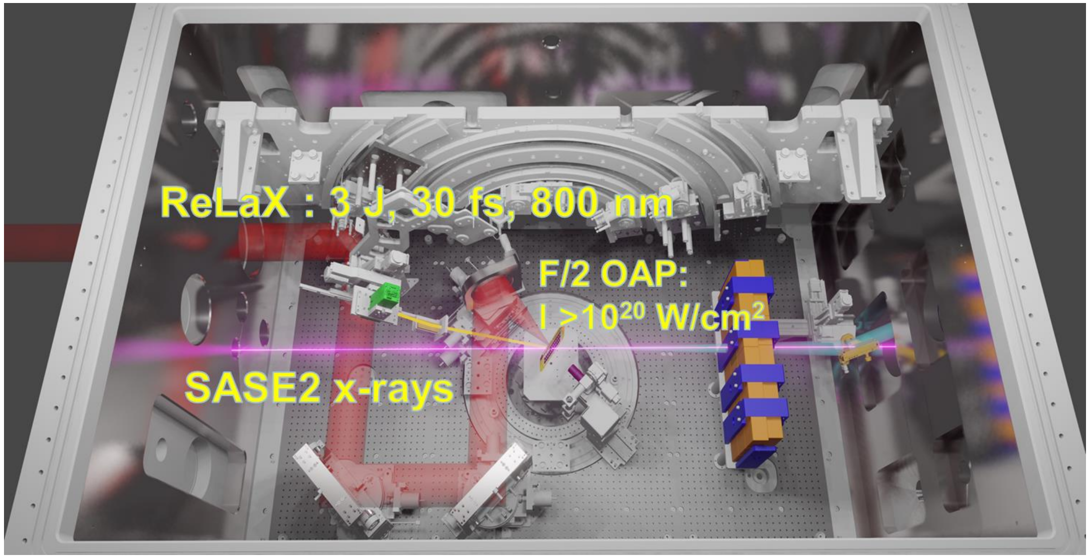
Phase
Contrast
Imaging PCI
(~µm structure)



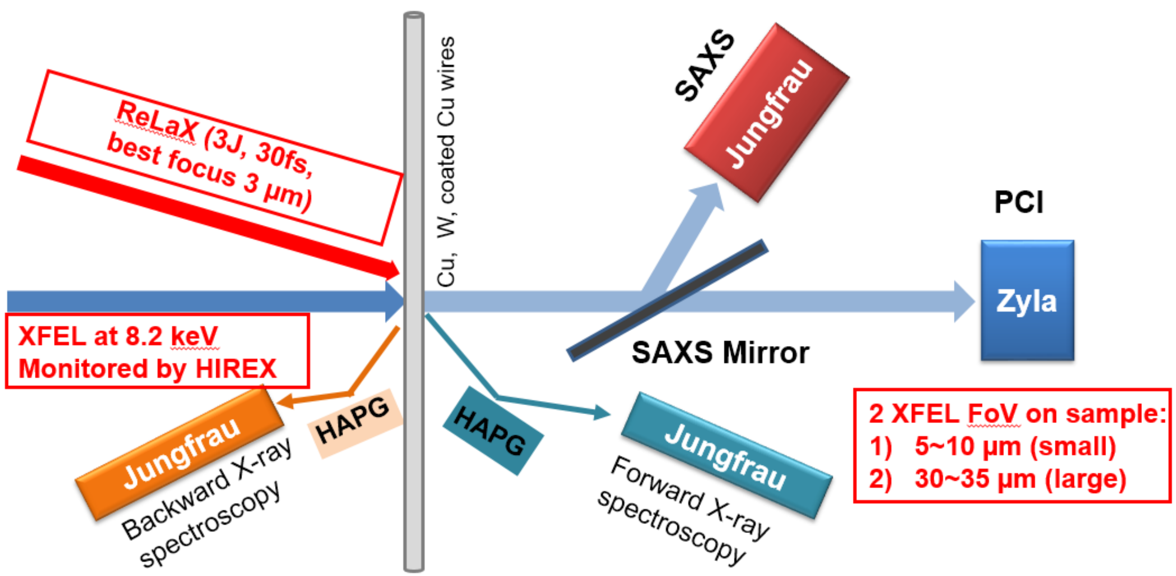
Small Angle
X-ray Scattering
(SAXS CDI)

Phys. Plasmas **21**, 033110 (2014)

Platform for Relativistic Plasma science: RELAX 100 TW at IC1

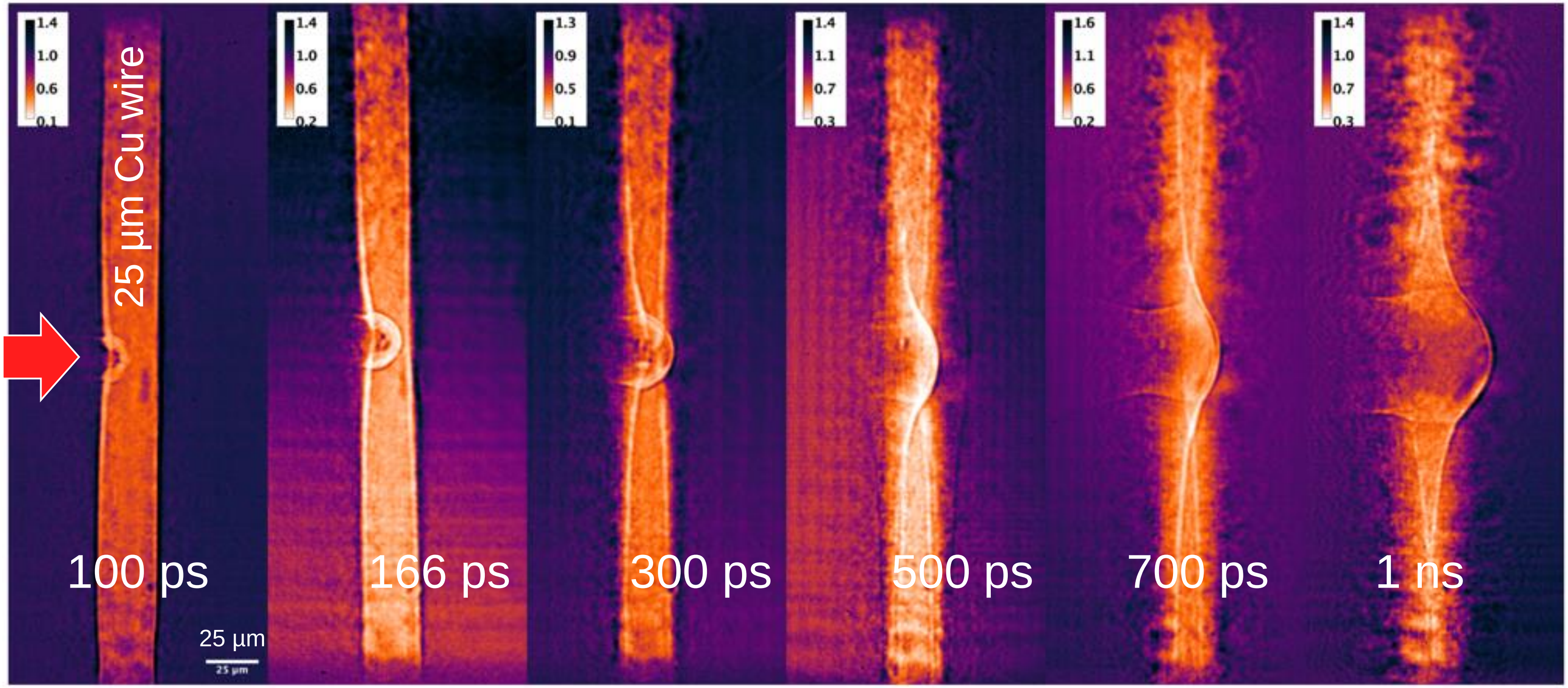


"Standard Configuration"
- 8 keV x-ray pulses
- SAXS + Spectroscopy + PCI
- Challenges on XFEL + laser + sample overlaps.
- Proper shielding of detectors against laser-induced background



Cylindrical compression of thin wires by irradiation of a Joule class short pulse laser (PI: Laso Garcia/ Toncian)

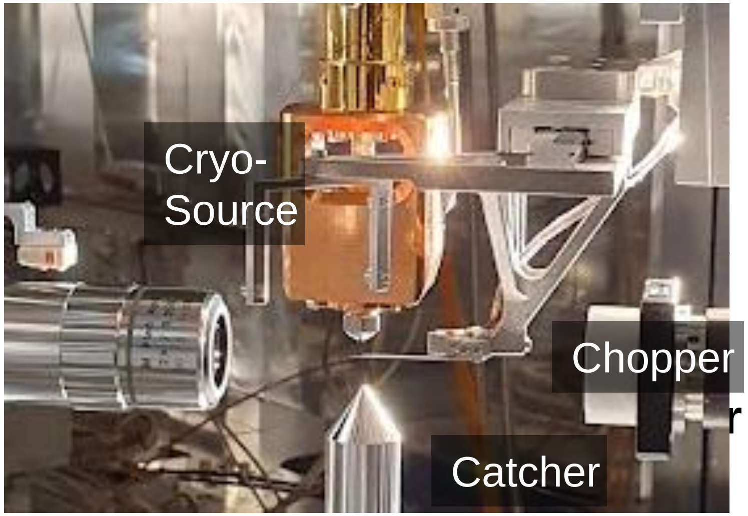
- Aim: Observation of sub ns scale dynamic of laser irradiated wires with new imaging PCI platform
- Results: ablative shock driven radial cylindrical compression of wire material observed for the first time



A. Laso Garcia, Y. Long et al. under submission (2023)

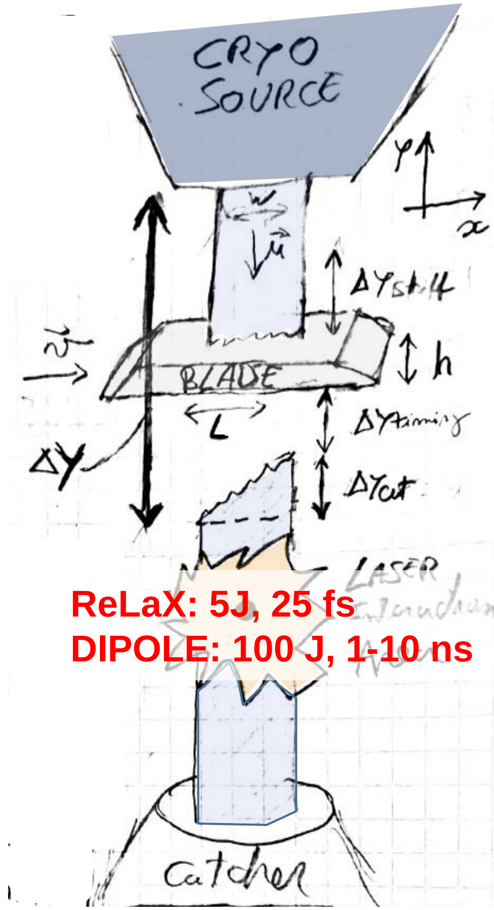
Cryogenic jet targets at HED

Plattform integration

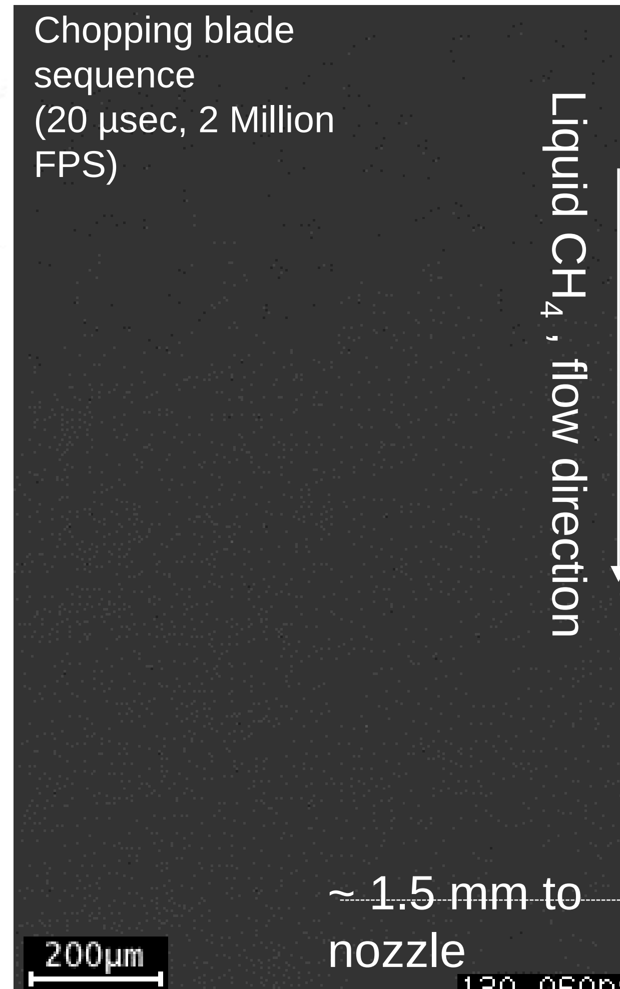


- **Piezo-driven Chopper device** protects the injector nozzle and maintain target stability
  - Creates a gap in the jet
  - Physically blocks particles, radiation and plasma propagation from the violent laser plasma interaction (ReLaX, DIPOLE)
  - Provides alternative path for plasma discharge
  - Operates at 10 Hz and scopes with beamline train-jitter (+/- 40 µsec)
  - Fast cutting speed (2 m/s) to minimize the nozzle-laser distance at high jet flow velocities (Δy < 3 mm)

Experimental Sketch



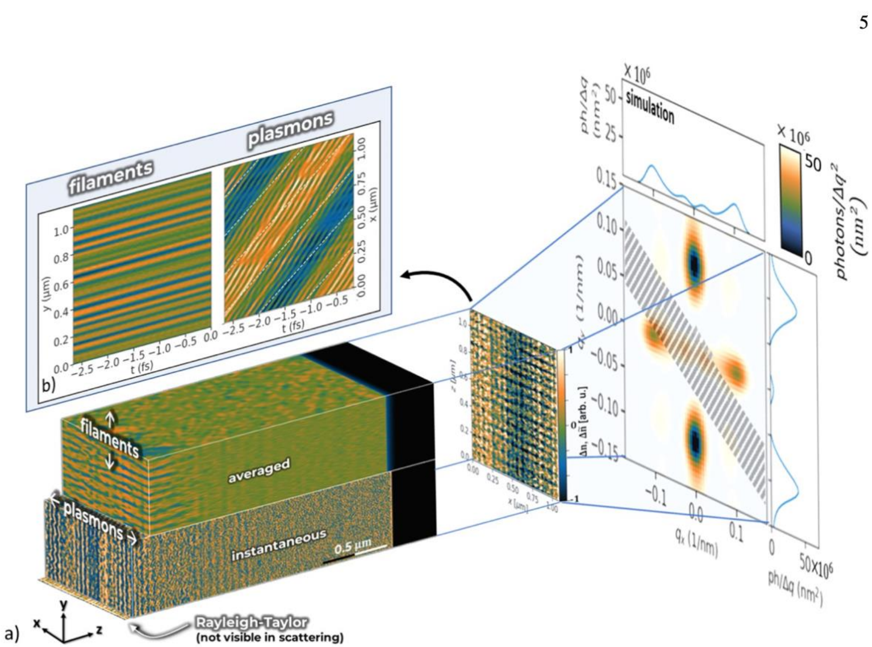
Implementation

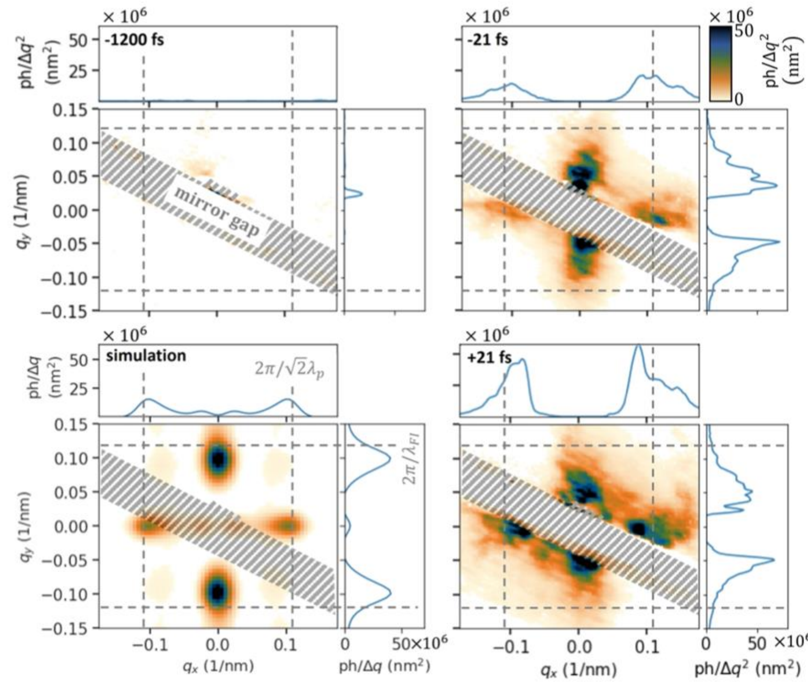


Daniel Loureiro & Sebastian Göde

Ultrafast expansion in relativisticly intense laser interaction with solids. PI: T. Kluge

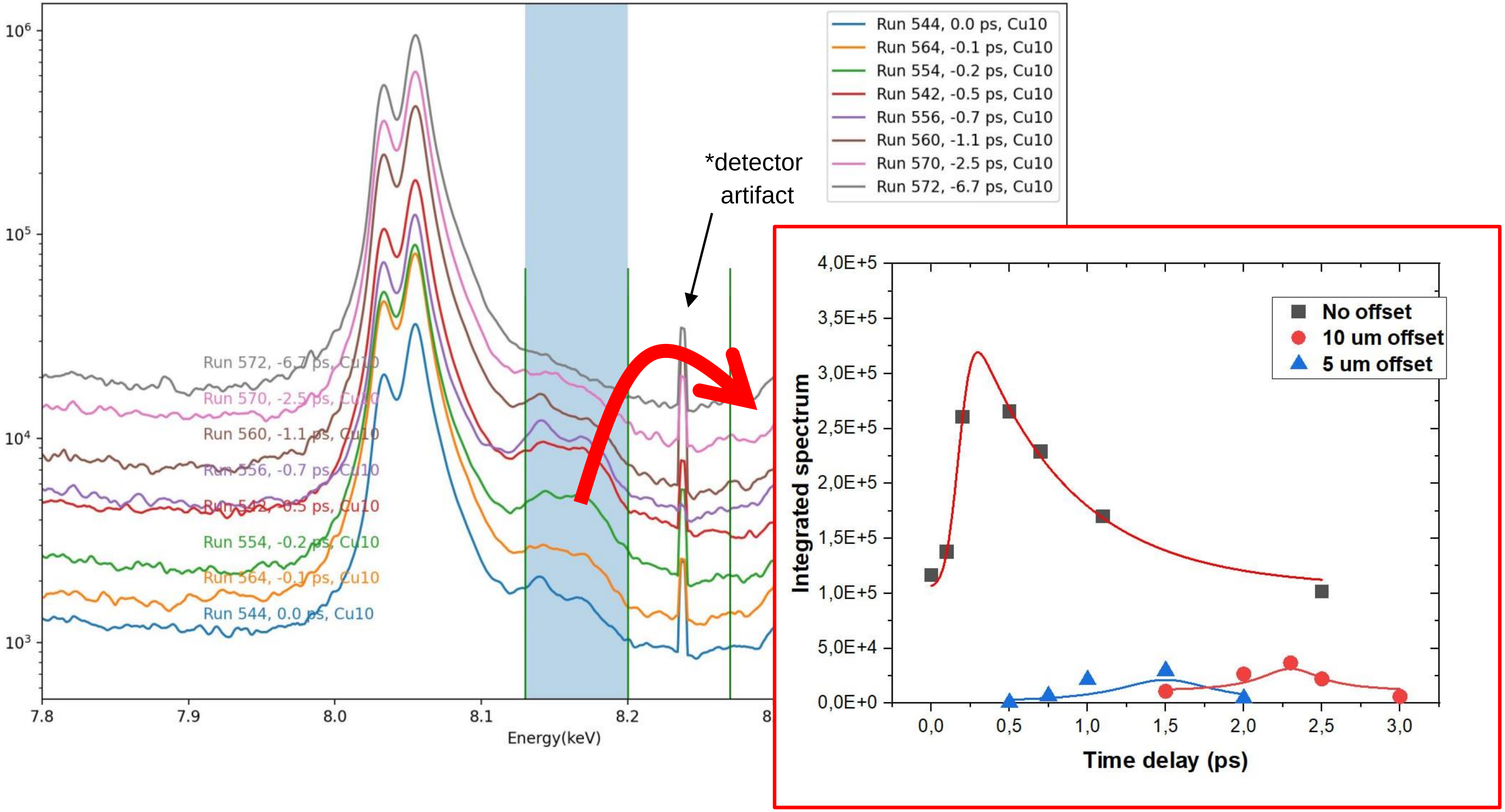
- Investigate ultra-fast instability processes in solids under extreme conditions at the nanometer level in relativistic plasmas
- Temporal evolution and discrimination between instabilities/ filamentation





P. Ordyna et al. submitted (2023)

Emission Spectroscopy from 10 µm Cu foil



Offset scan ("offset" here means physical offset between laser and x-ray best-focus spot in vert. direction for different delay scans)

The result of this part of the experiment was the first estimate of **the propagation velocity of the "ionization wave"** in the plasma (approx. 6 × 10^6 m/s).

PhD work of Mikhail Mishchenko, EuXFEL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to a world within our world.
RECOMMENDED
ADULT ENTERTAINMENT
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AT THE EARTH'S CORE
An AMERICAN INTERNATIONAL Release
DOUG McCLURE • PETER CUSHING
CAROLINE MUNRO
HARRY N. BLUM • MILTON SUBOTSKY • Edgar Rice Burroughs
KEVIN CONNOR • JOHN DARK

Science within planet Earth – silicates, carbonates

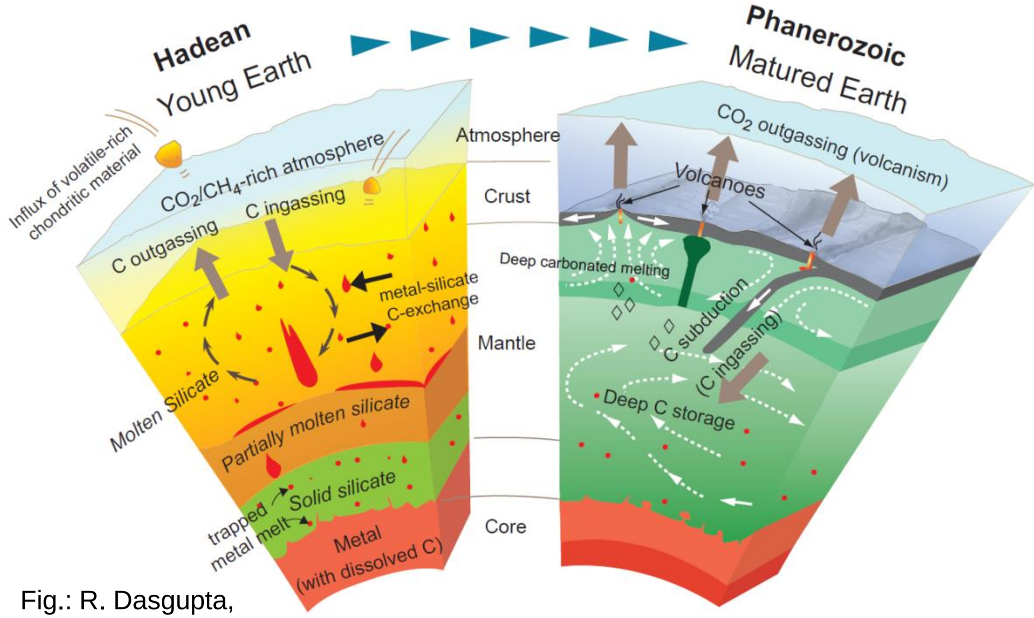


Fig.: R. Dasgupta,
Rev. Min. Geo. **75** (2013)

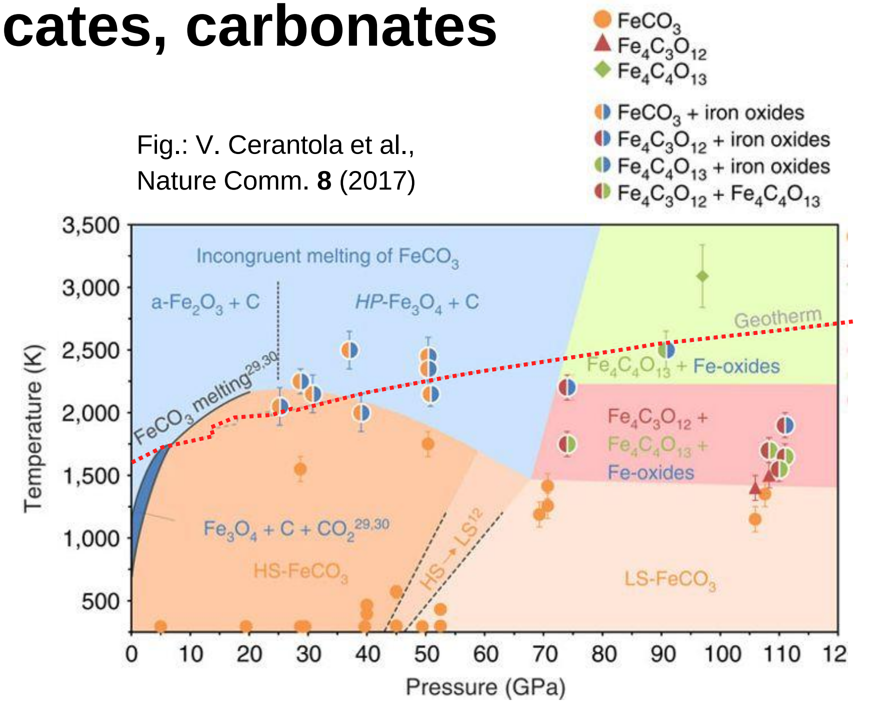
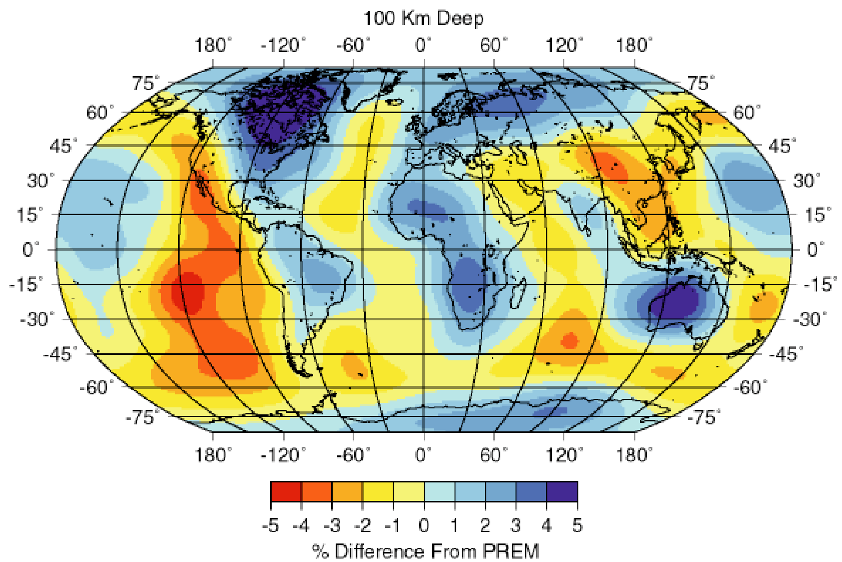


Fig.: V. Cerantola et al.,
Nature Comm. **8** (2017)



EARTH SCIENCE

Bridgmanite—named at last

The most abundant mineral in Earth's interior gets a name

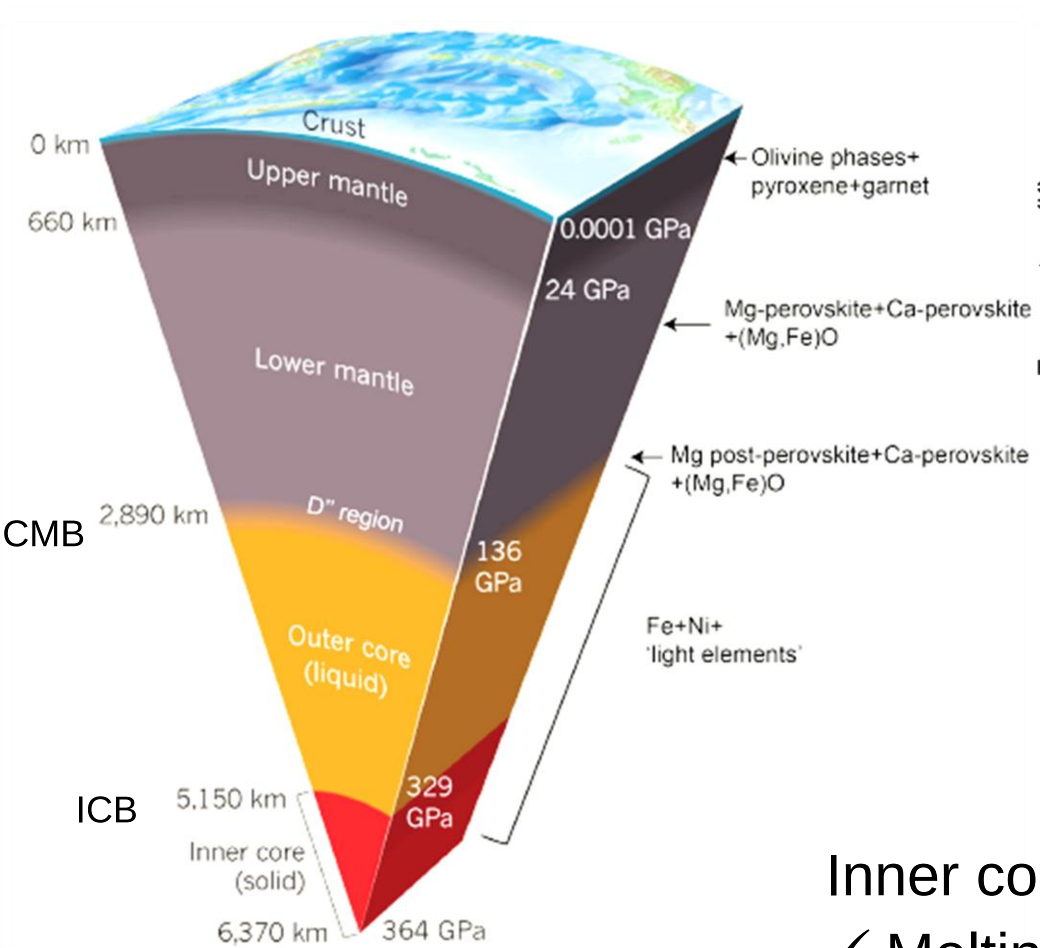
→ $MgSiO_3$
→ Seismic low velocity zones in the Earth's mantle

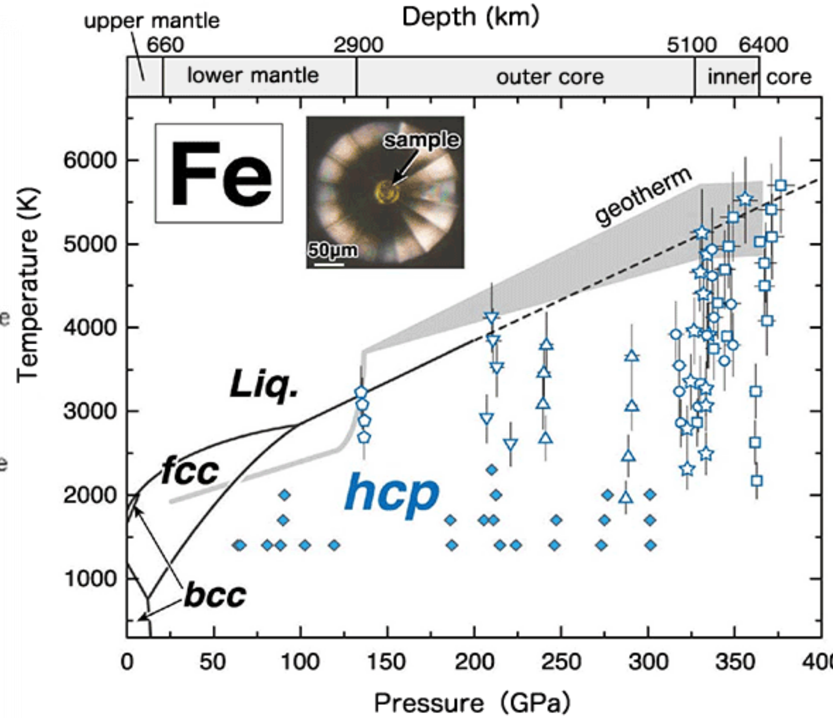
Science within planet Earth – the core – iron melt line

Tateno *et al.*, *Science* **330** (6002), 359 - 361 (2010)

CMB

ICB

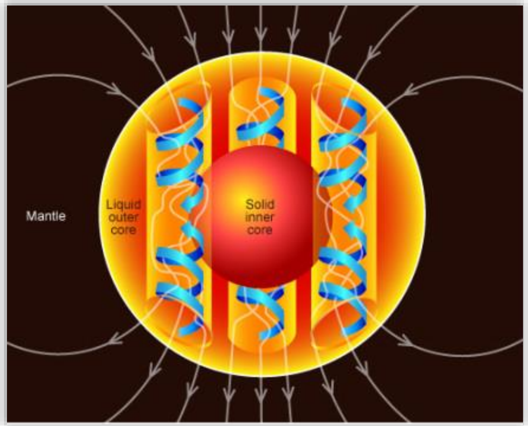




Inner core:

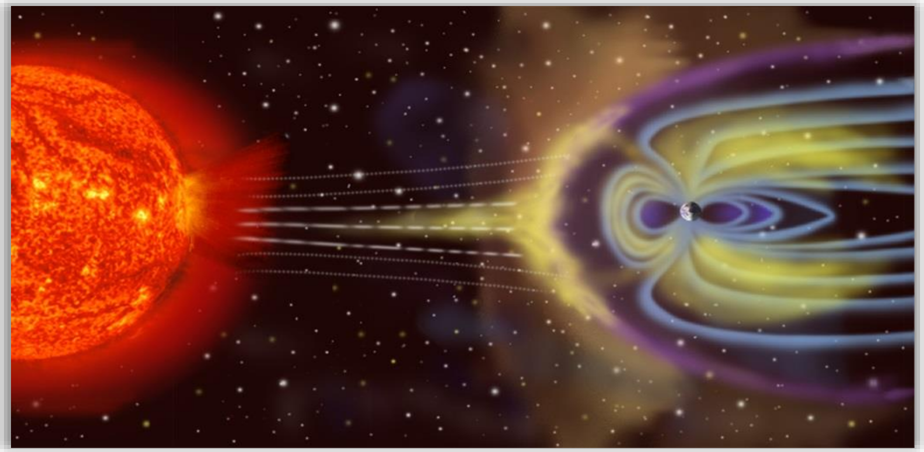
- ✓ Melting temperature at ICB is 6350 K
- ✓ hcp is the only stable configuration

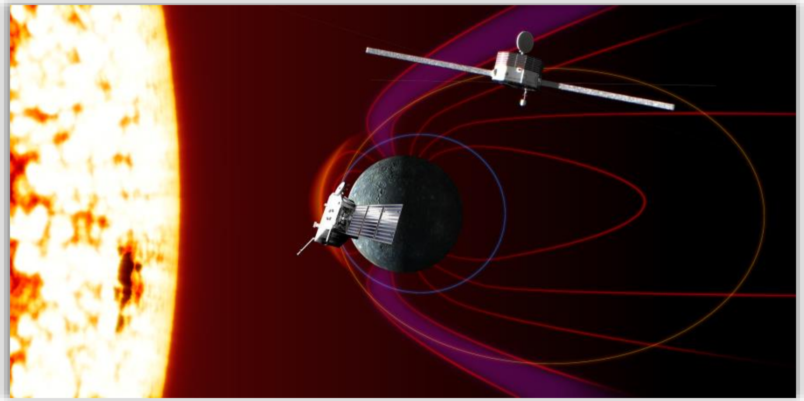
Earth dynamo theory – Fe core convection



Measure the Fe melting line
→determines boundary (inner/outer core)
Influence of impurities (S, Ni) ?
Measure conductivity, viscosity

Magnetic fields is prerequisite
for life (shield from stellar winds)



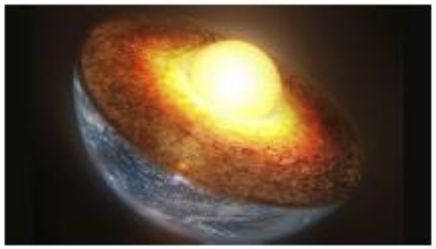


Credit: JAXA/ESA

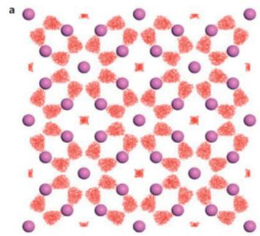
Mercury is much smaller than Earth
Has magnetic field (Venus, Mars not)
BepiColombo space mission

Material science, industrial applications

Structure and chemistry at extreme P/T conditions

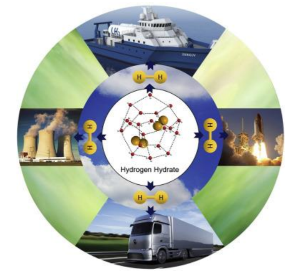


planetary interiors



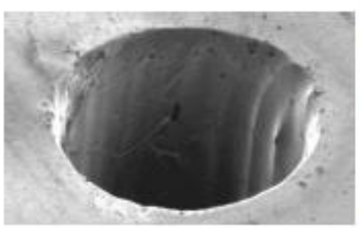
new materials

super conductivity



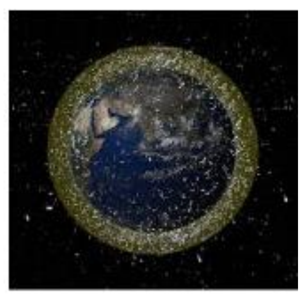
Hydrogen storage

Deformation at ultra-high strain rates



drilling

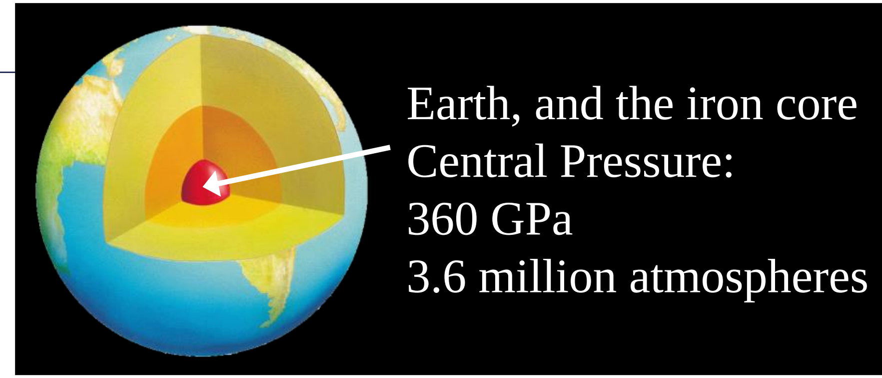
hardening, peening

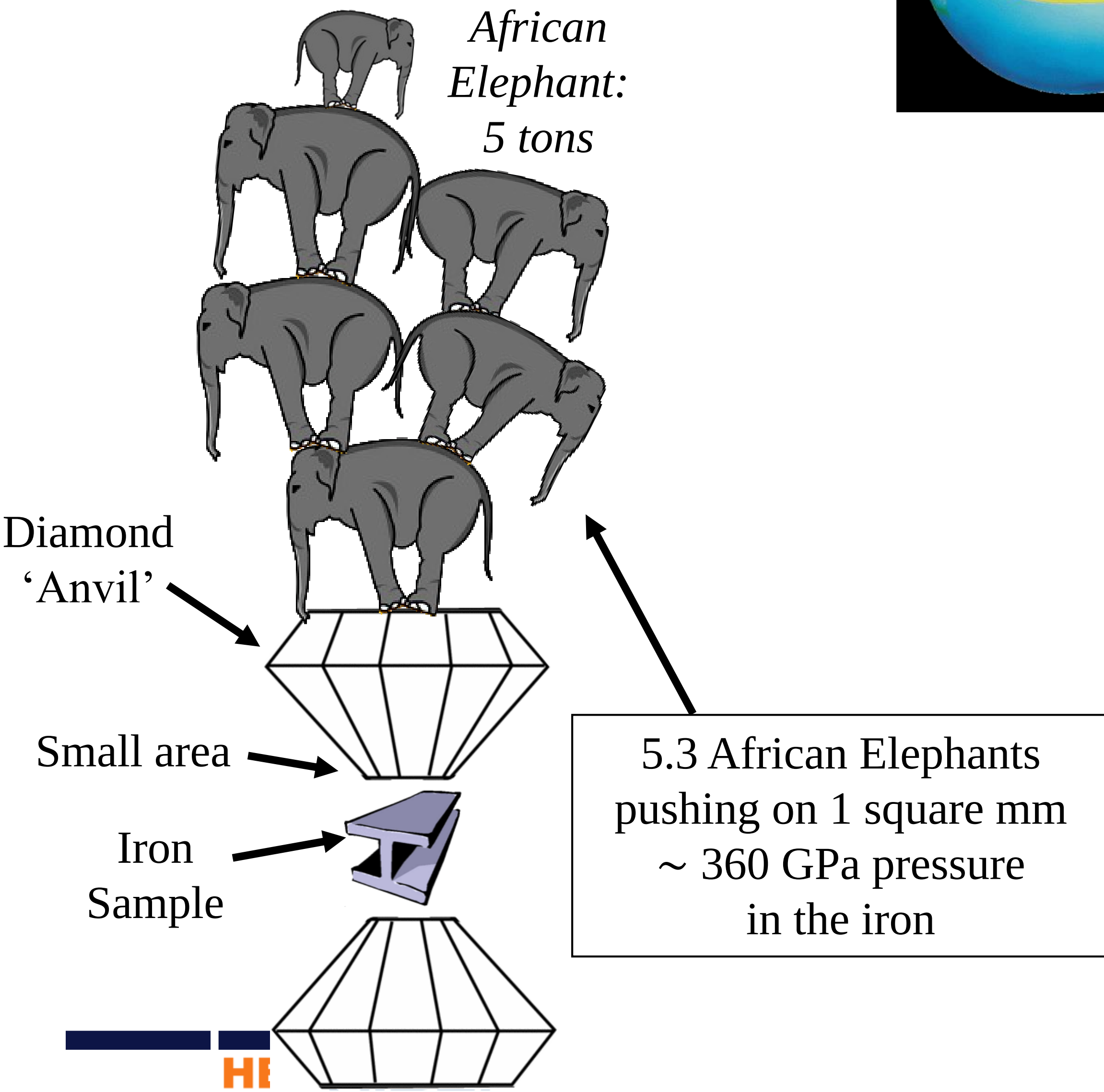


space debris

Orbit re-entry shields

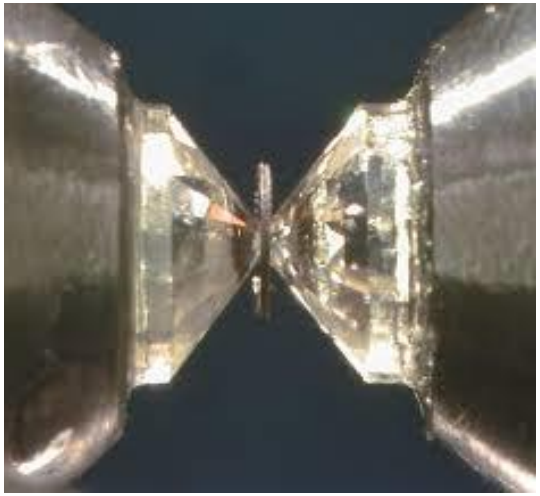
Putting on the Pressure:



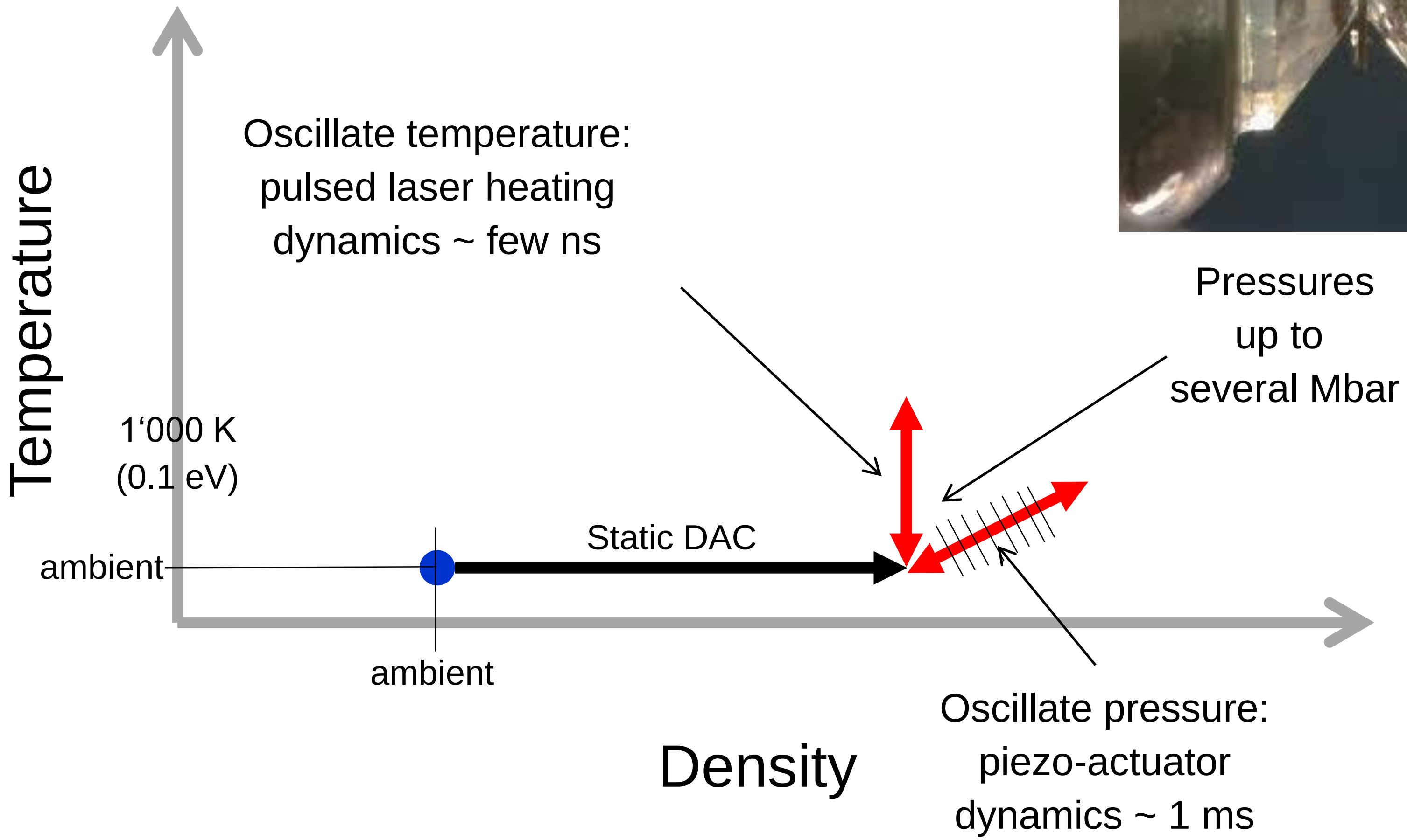


Courtesy of S. McWilliams

Preparation of extreme conditions at HED



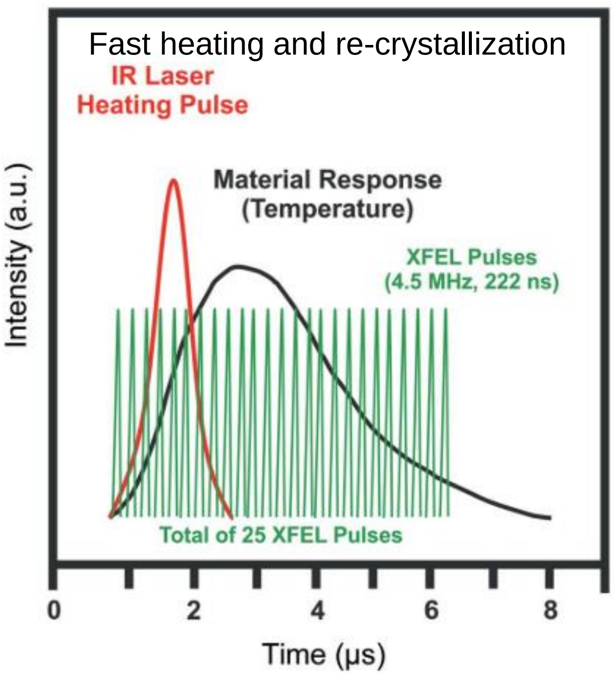
- Diamond Anvil Cells (DAC)



7 successful DAC (diamond-anvil-cell) experiments were performed in 2022 (5 at IC2, 2 at IC1)

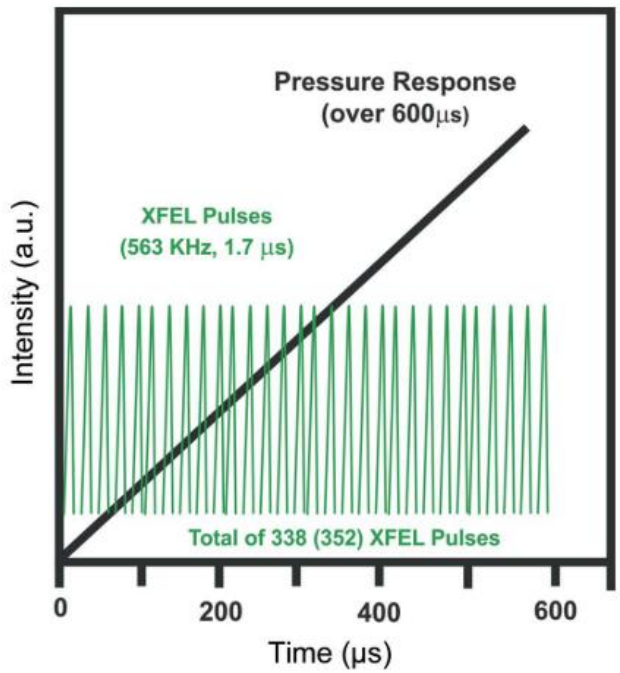
Liermann et al., J. Sync. Rad. **28**, 688 (2021)

µs pulsed laser heating DAC



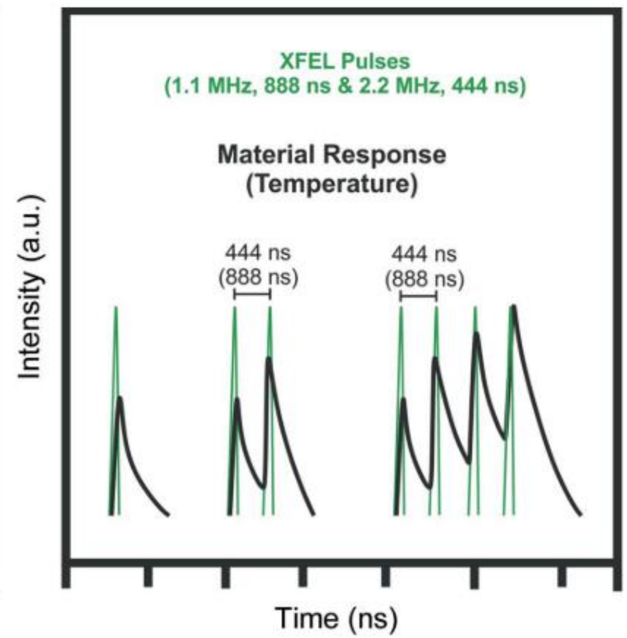
#2605 (Morard/Prescher)
Nov. 2021
#2844 (Bykova/Goncharov)
July 2022: C, N2, H2, …

Dynamic DAC
Medium compression rate over ms

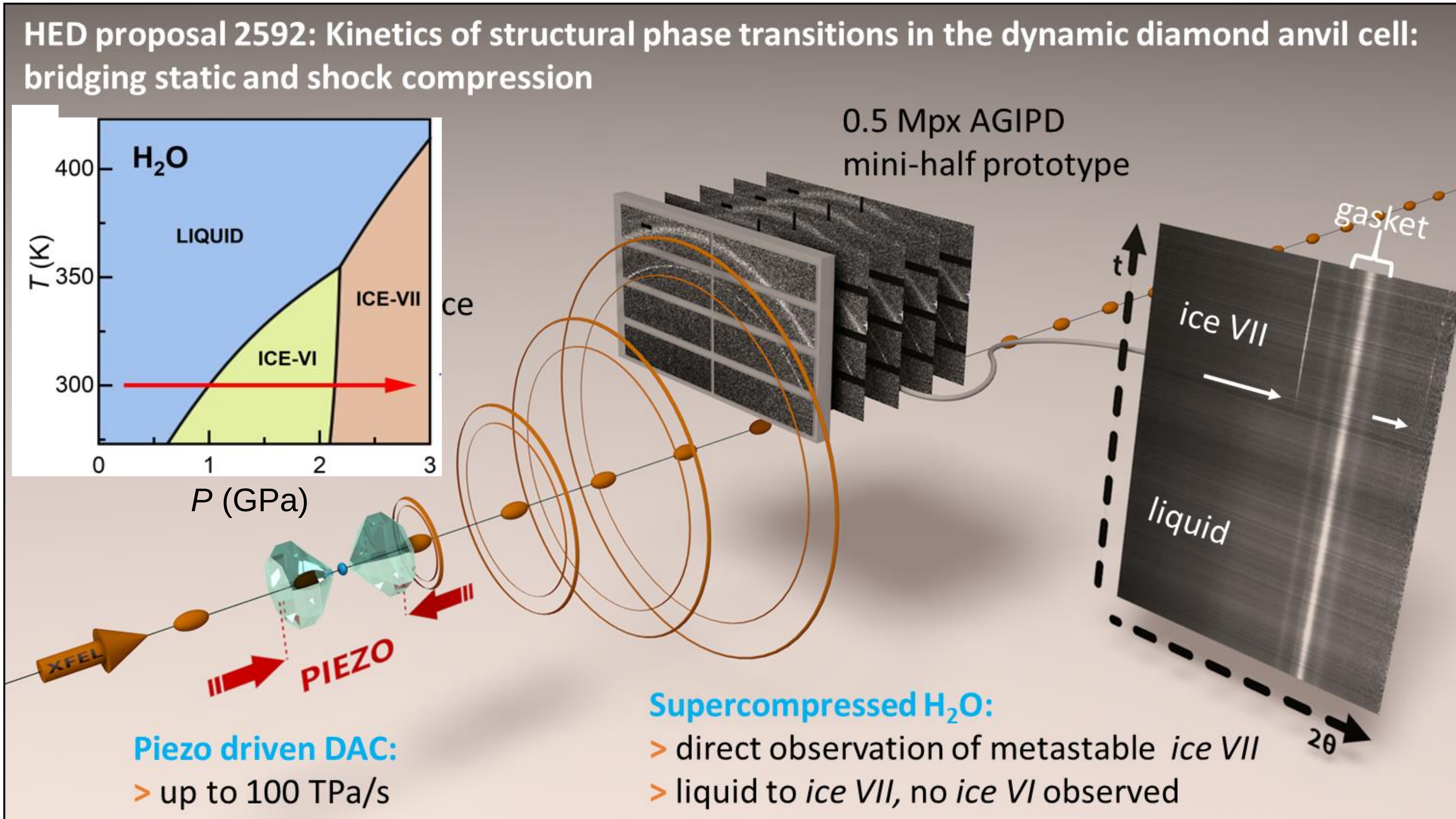


#2592 (Jenei/Liermann)
Nov. 2021: Bi, Ti, …
#2855 (Salamat/Schwartz) June 2022: metal superhydrides

MHz fs x-ray impulsive heating DAC



#2624 (Konopkova/Sternemann)
Sept. 2021: XES at IC1
#2590 (McMahon/Husband) Nov. 2021: Low-Z (H_2O, CH_4, etc)
#2804 (Cerantola/Sternemann)
May 2022: XES at IC1

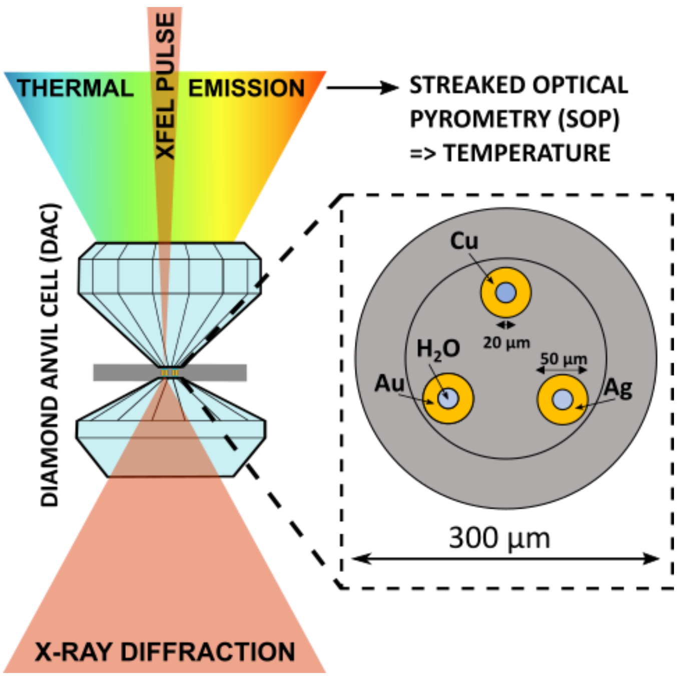


1.1 MHz, Nov 2021

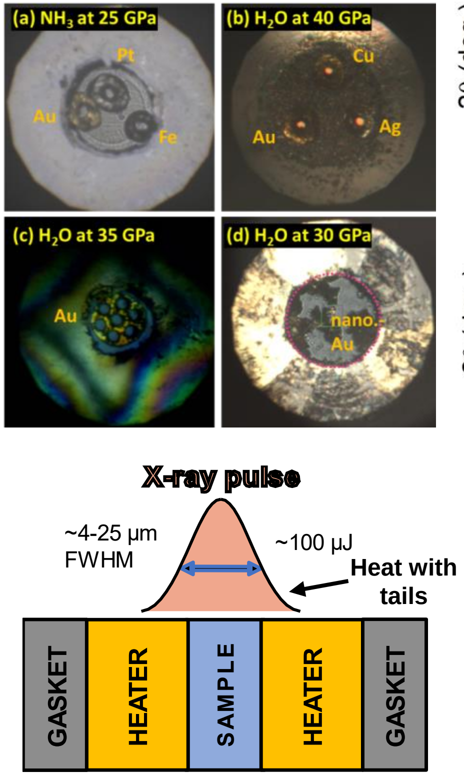
Experiment #2590: *X-ray Heating of Low-Z Materials at Static High Pressures*

DAC community proposal in November 2021

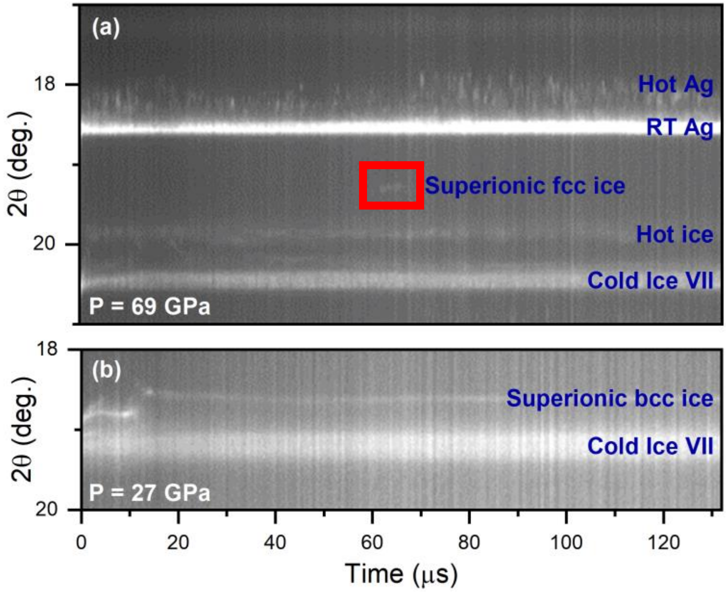
- XFEL heating of samples in DACs can be used to create extreme temperatures at high pressures
- Direct heating of **low-Z planetary ices** (e.g. H_2O, NH_3, CH_4) not very efficient => heat indirectly using a high-Z heater



H_2O and NH_3 samples

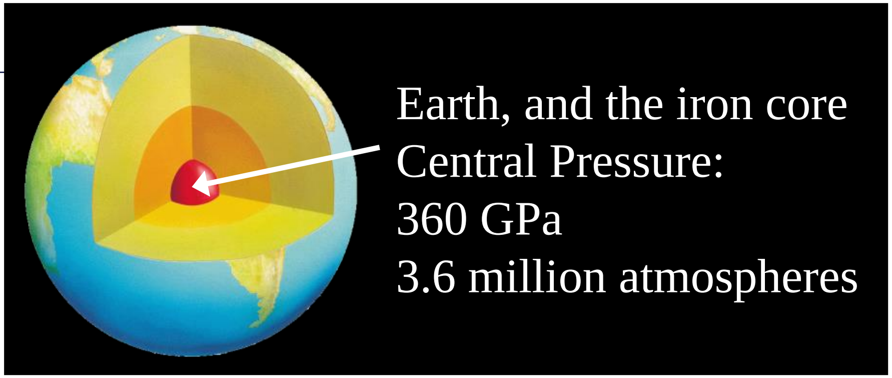


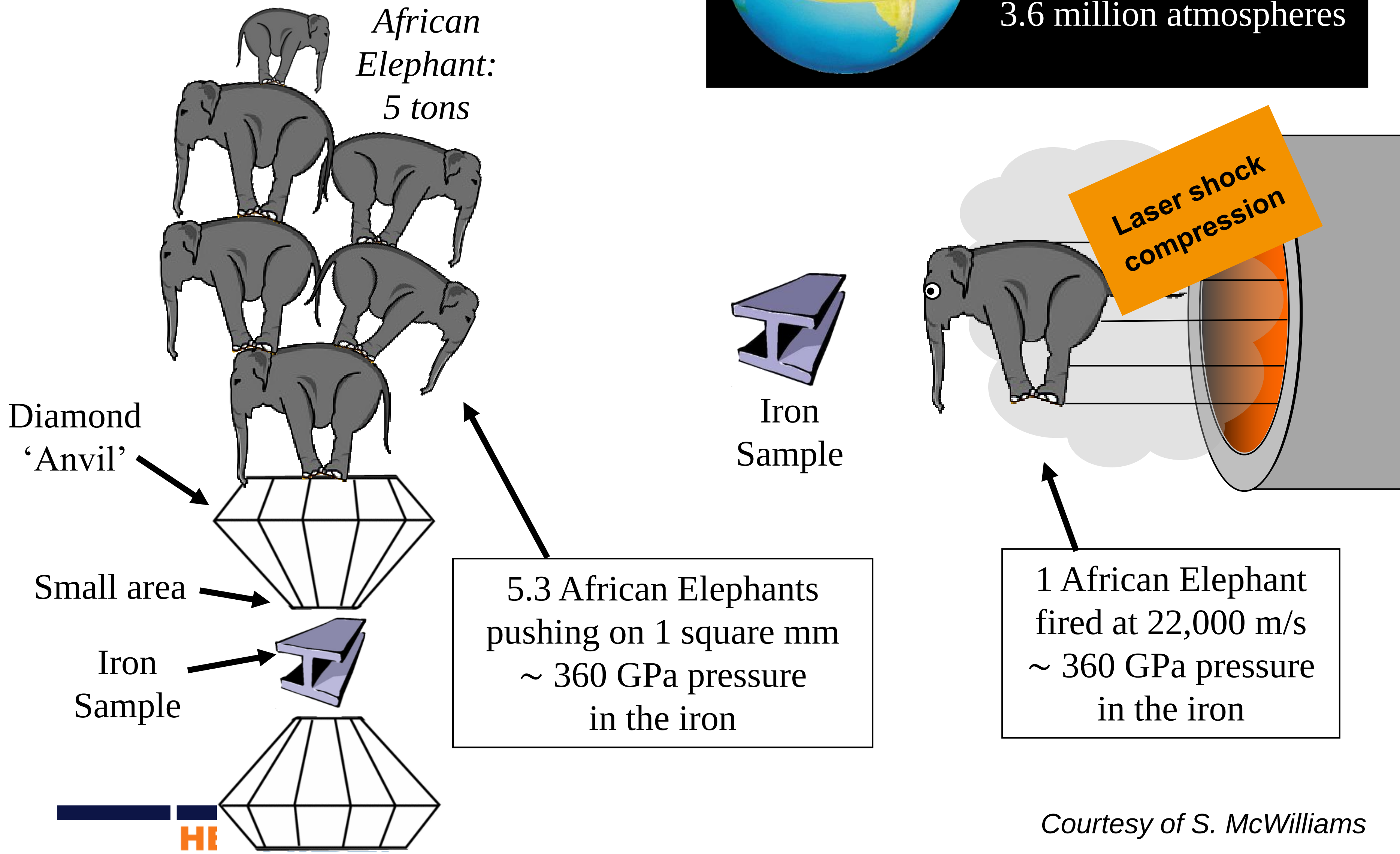
Irradiate samples with 300 pulses at 2.2 MHz



- Pulse-resolved X-ray diffraction data collected using the AGIPD mini-half determines thermal expansion of the sample during irradiation
- See evidence of bcc and fcc **superionic ice**, where protons are free to move within the oxygen lattice

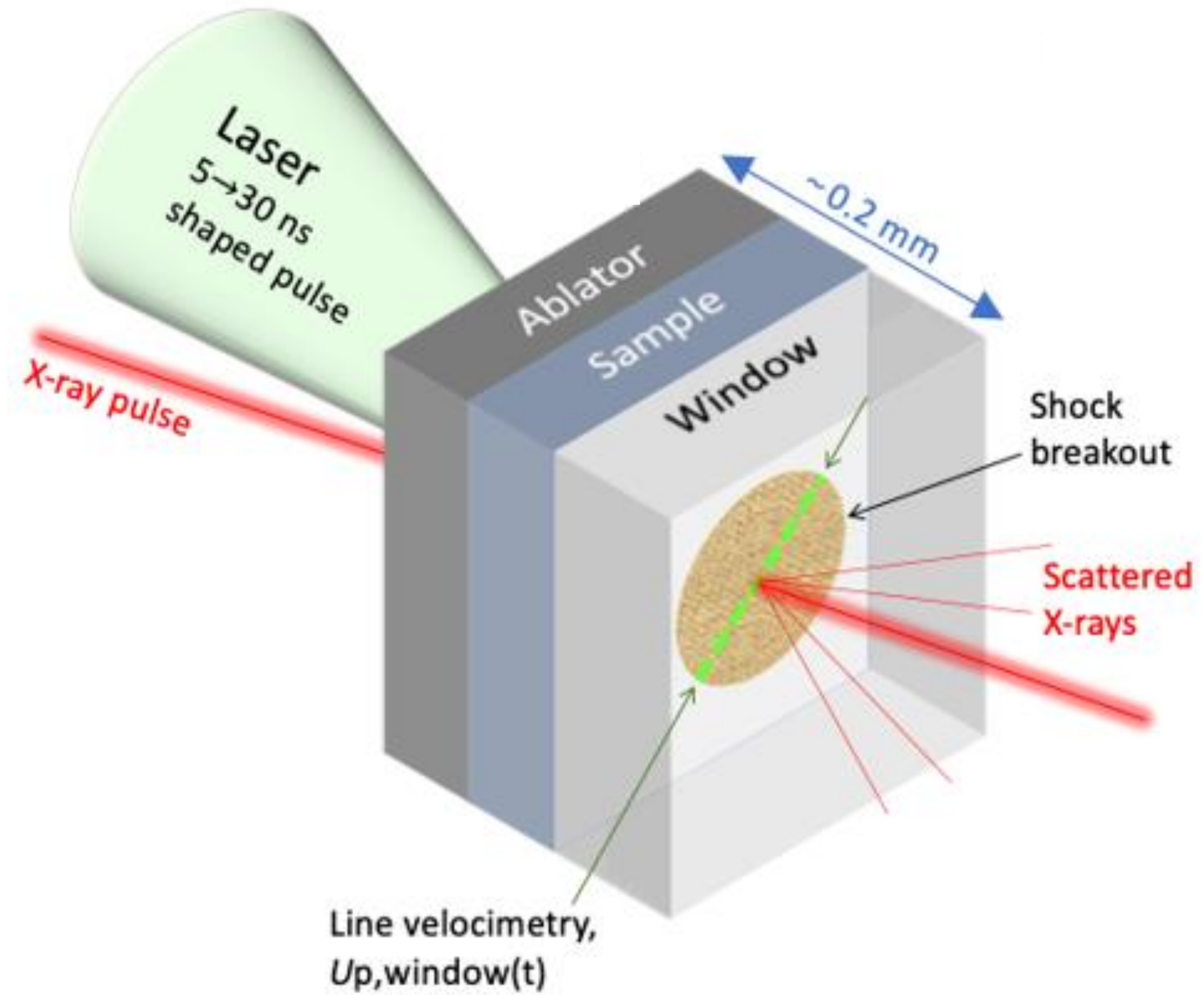
Putting on the Pressure:





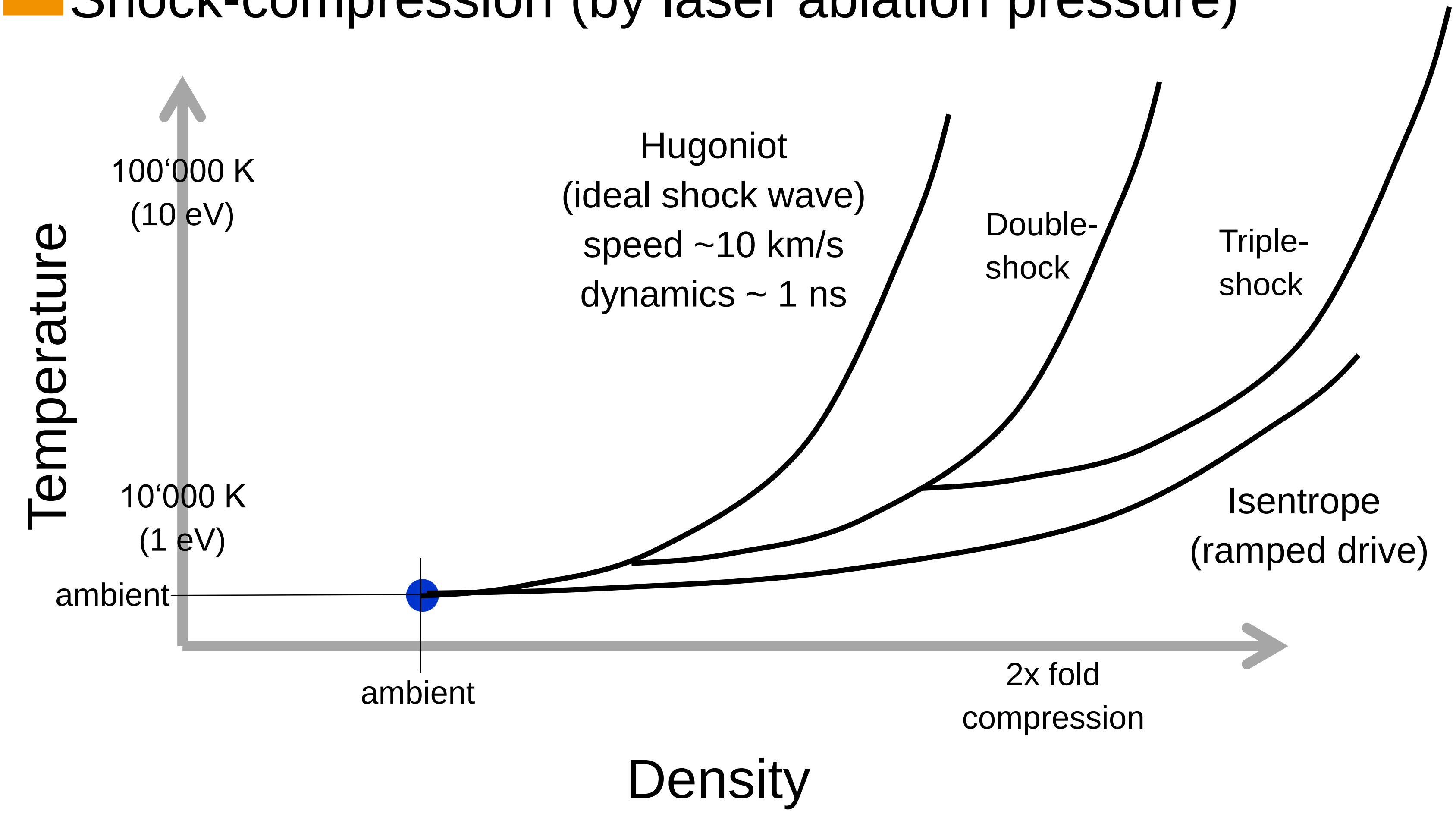
Courtesy of S. McWilliams

Studies of dynamically compressed matter

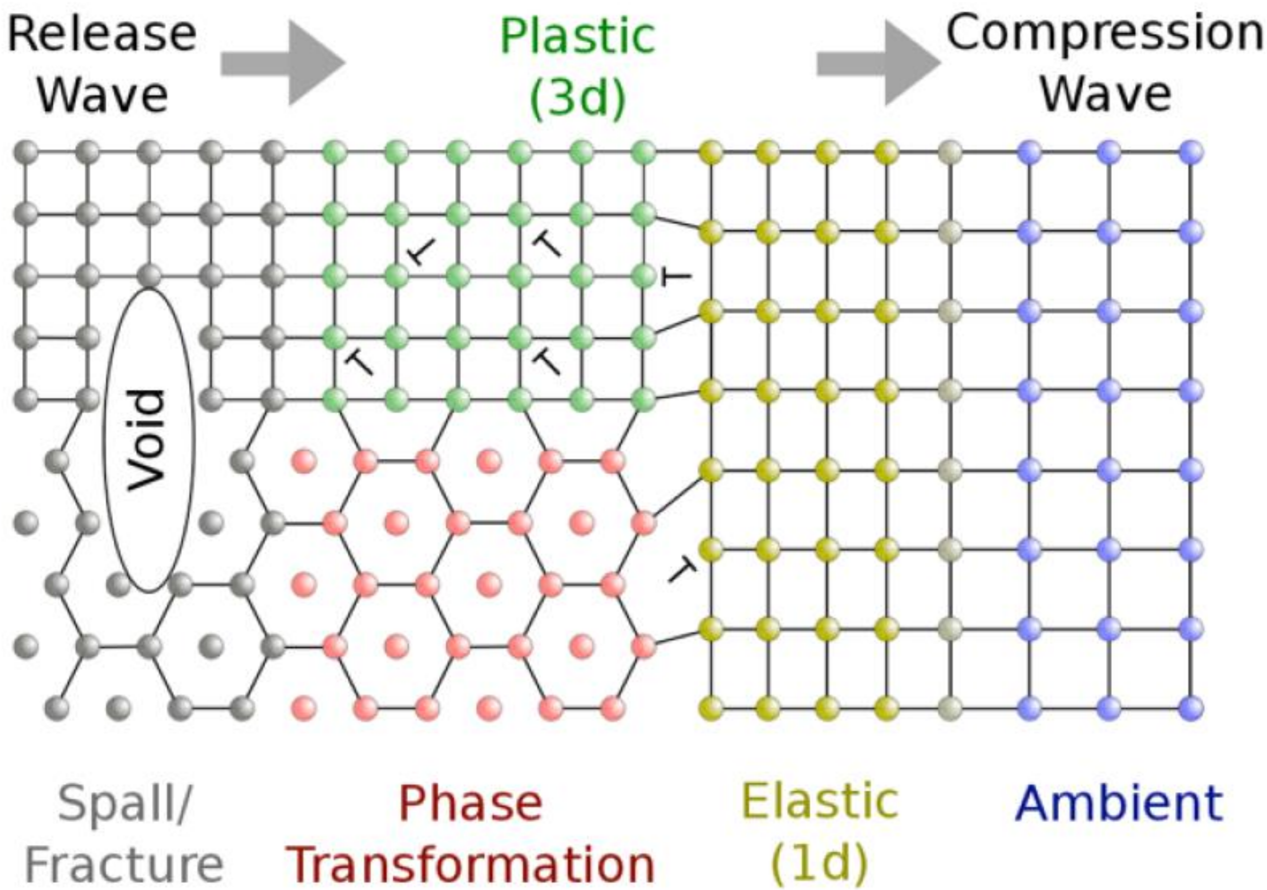


Preparation of extreme conditions at HED

- Shock-compression (by laser ablation pressure)



Strain rate dependence – dynamic material response



Mediated by defects
→ takes time!

Figure by A. Higginbotham after J. McNaney.

DiPOLE 100X : the most powerful driver installed at X-ray facility

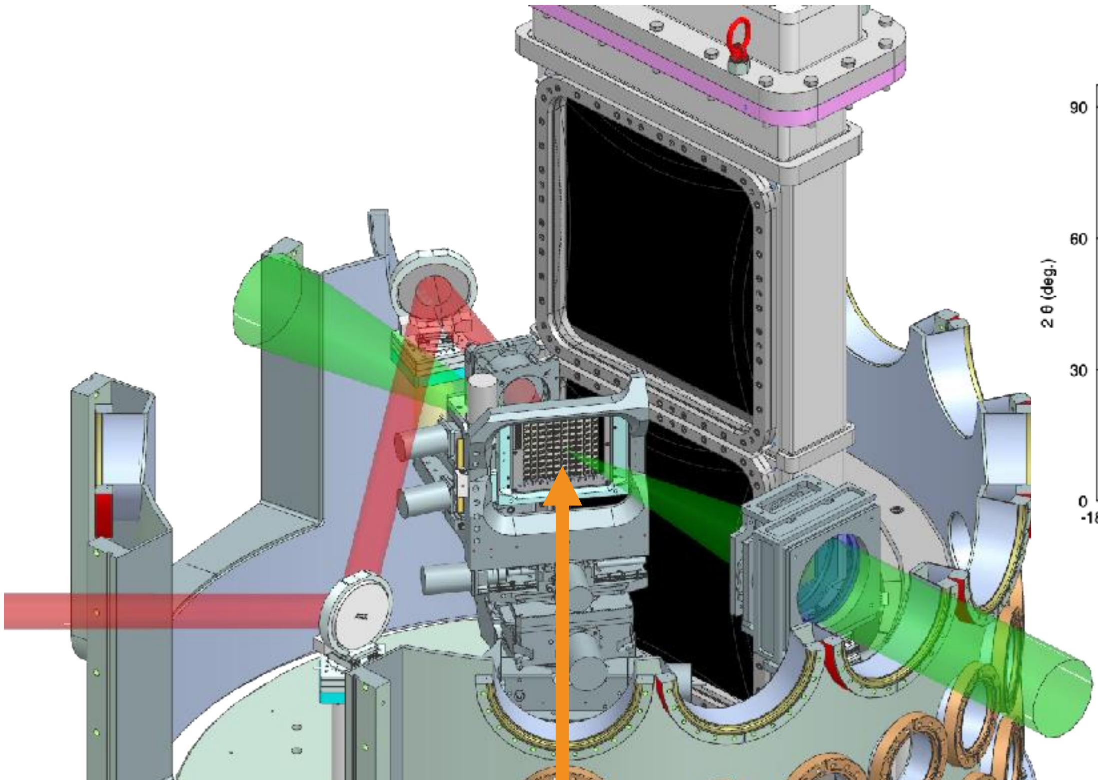
- Diode-pumped, >70 J, 15 ns, 10 Hz
- UK in-kind (EPSRC & STFC)
- 10 M£
- Delivered end 2019
- Commissioned off-line in 2020-2022
- First user experiment in May 2023

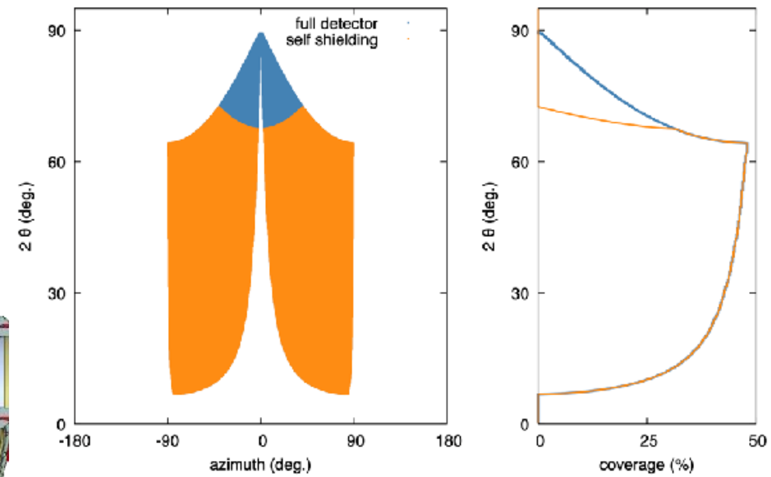
High Energy (DiPOLE 100X) and High Intensity (RELAX) lasers in HED/HiBEF laser bay

- 1. Will allow data to be collected thousands of times faster than at any other comparable facility worldwide (10 Hz vs. 7 min = 0.002 Hz)
- 2. High photon energies (18-24 keV) available at EuXFEL provide much more detailed atomic structure information (Large q-space)

New dynamic compression facility at the HED scientific instrument at European XFEL

2 VAREX detectors (10 Hz)





DiPOLE-100X (10 Hz)
40 J at 2ω/70 J at ω,
250 ∝μ/ 500 ∝μ

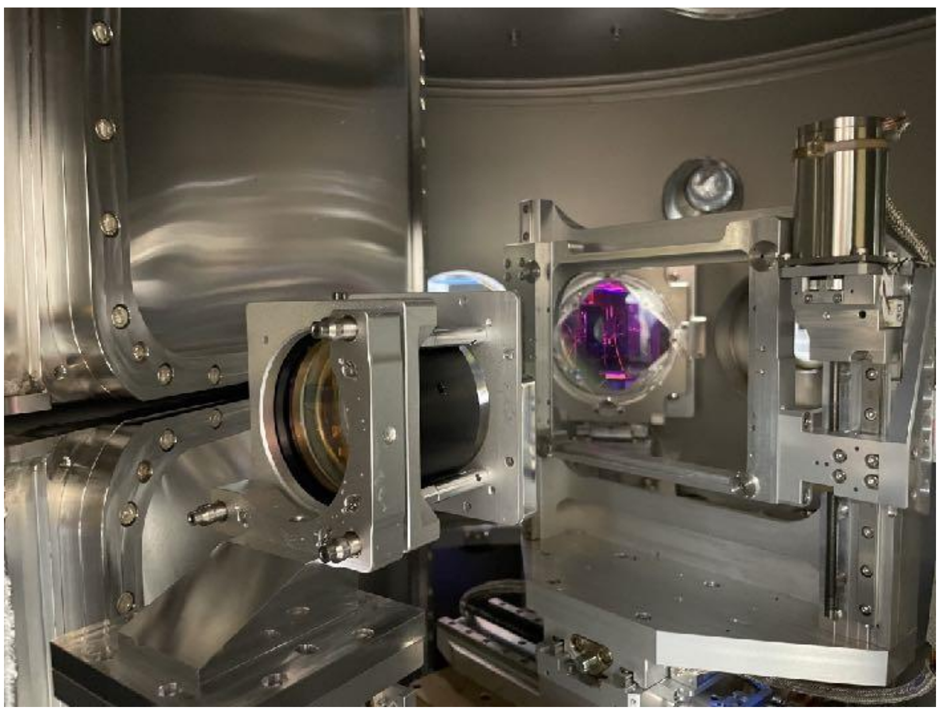
2 color VISAR & SOP (1 Hz)

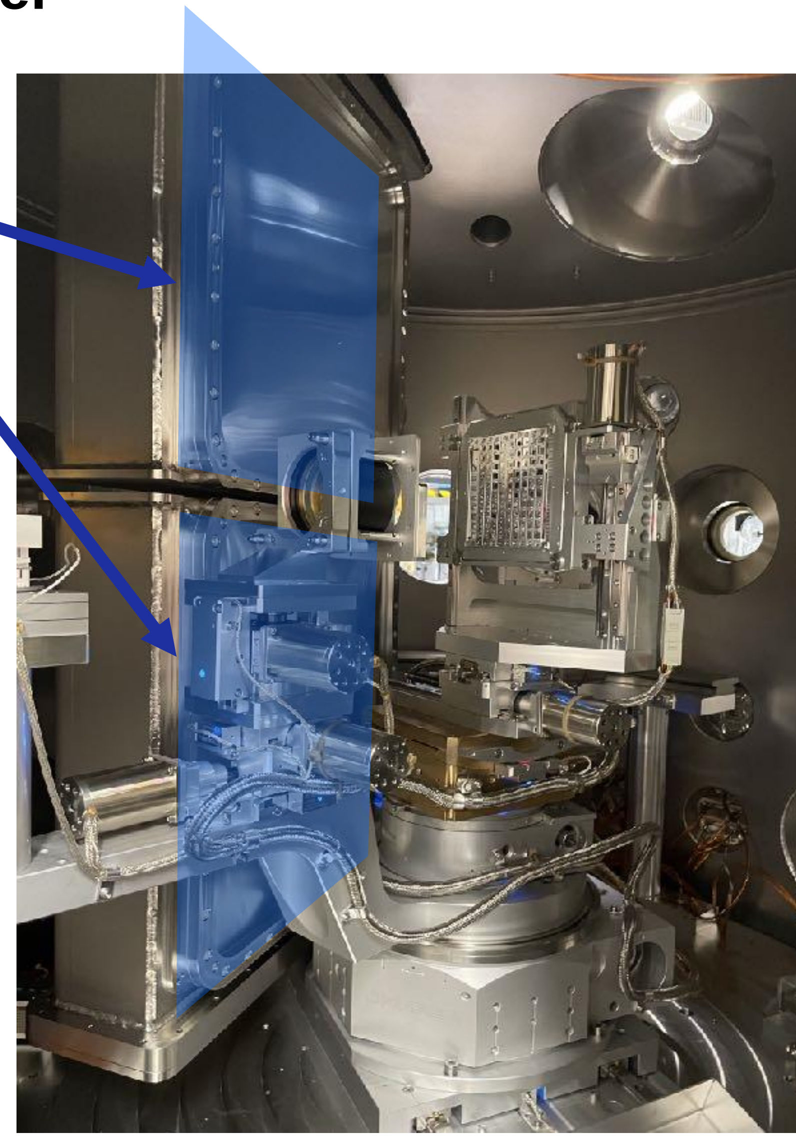
XFEL (14 - 24 keV)

European XFEL
HED HiBEF

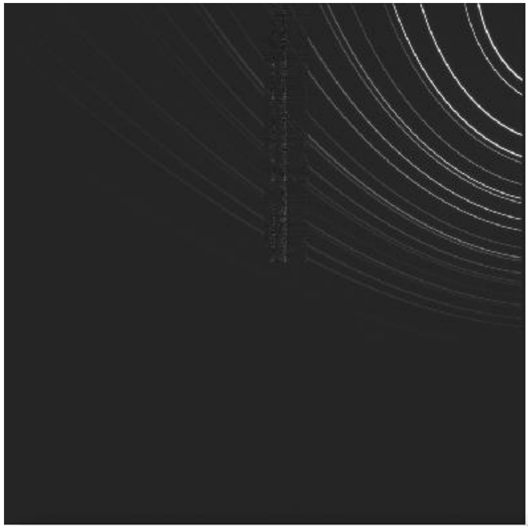
Experimental set up in IC2 chamber

VAREX large area
x-ray detector
for XRD



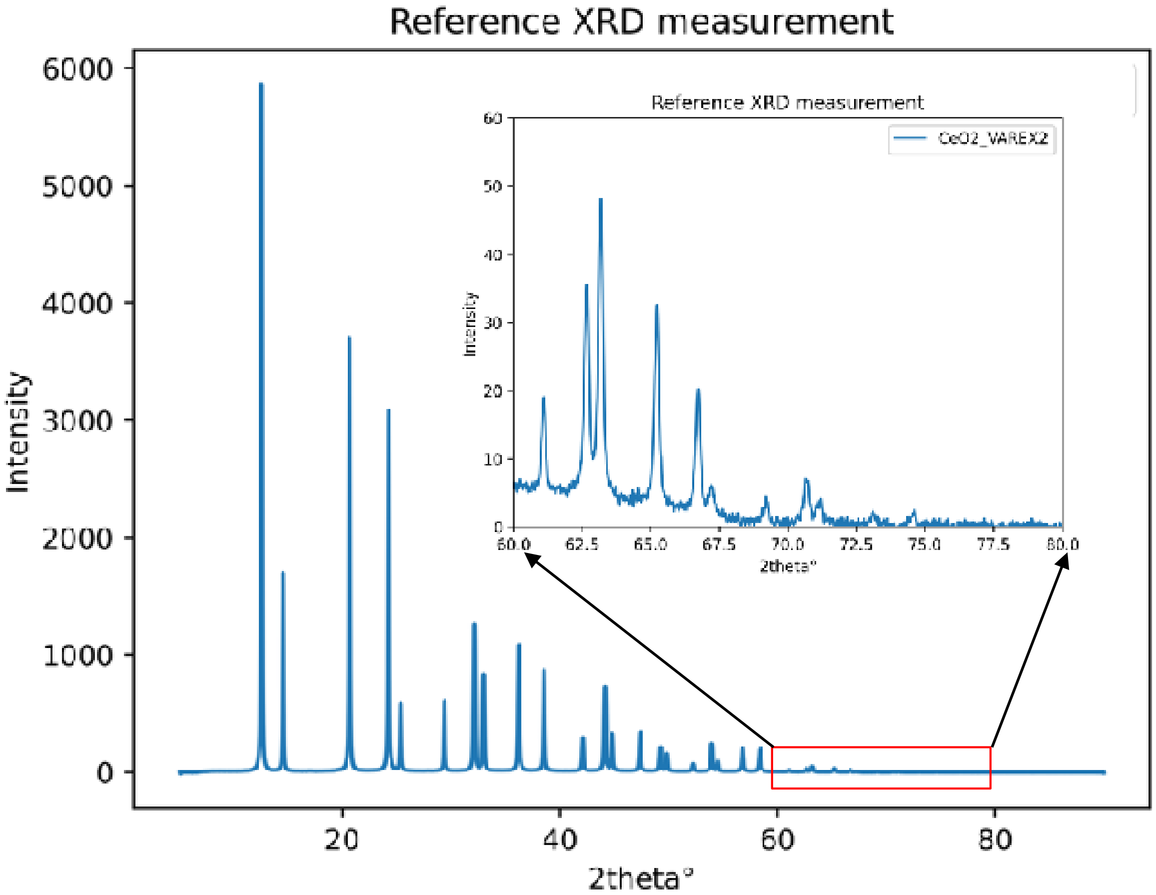


X-ray diffraction with two VAREX detectors



shot on CeO_2 calibrant:

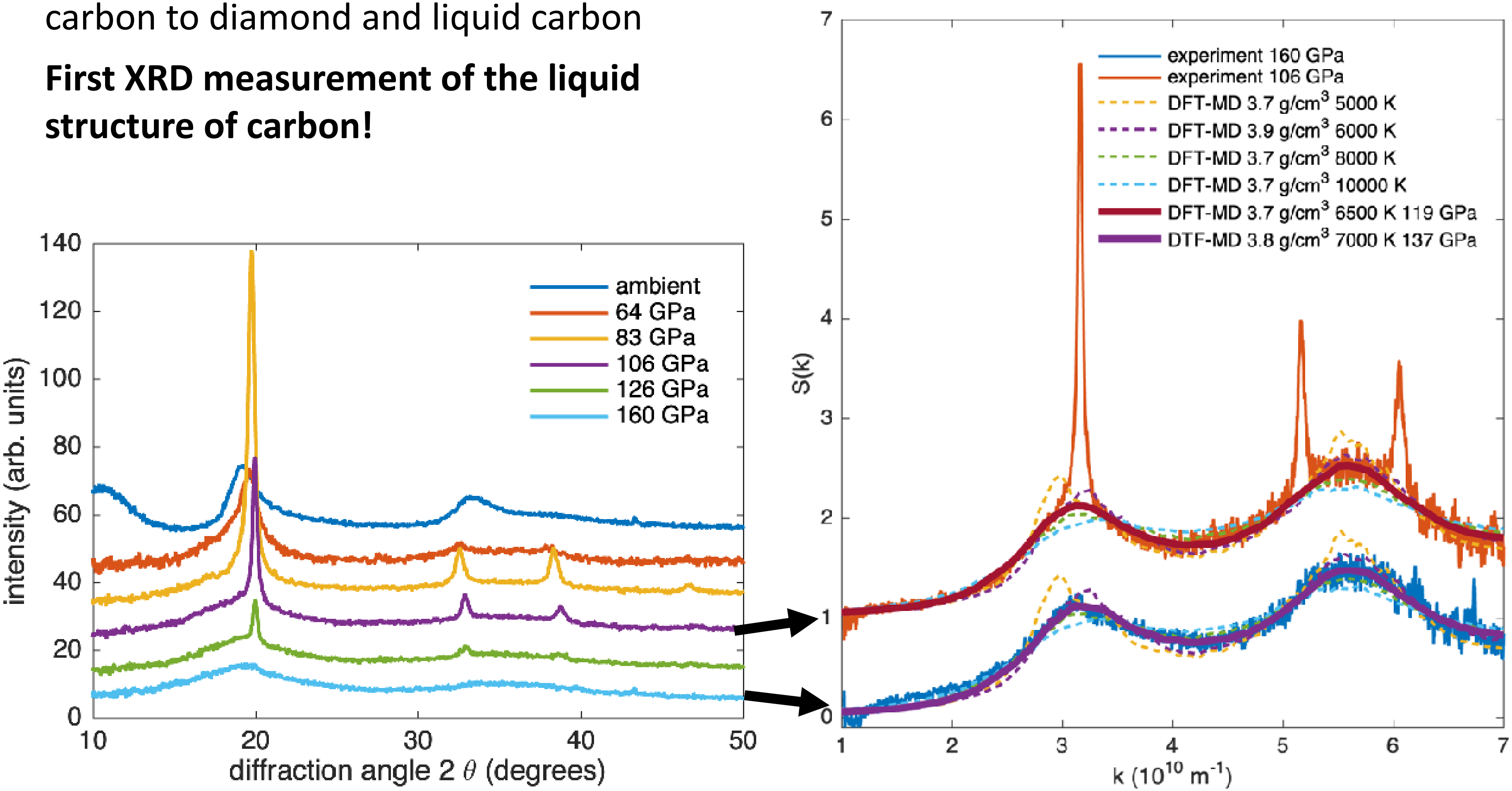
Single X-ray pulse of 18 keV and 400 µJ



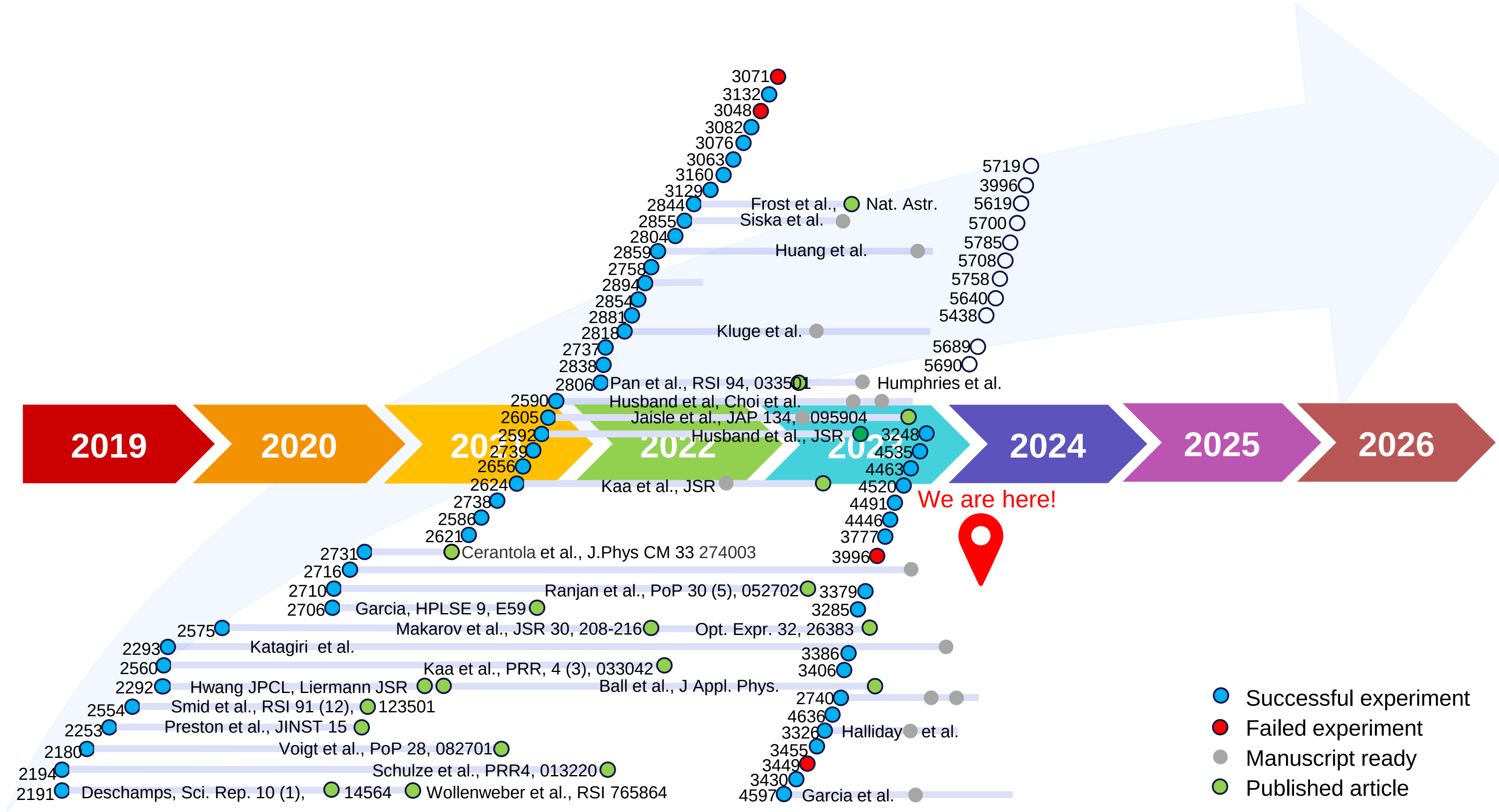
Dynamic compression of carbon polymorphs

Example: shock-induced transition of glassy carbon to diamond and liquid carbon

First XRD measurement of the liquid structure of carbon!



Publications



Instrument papers

- **General overview of the HED instrument**
  - Zastrau, Appel, Baehtz et al., J. Synchrotron Rad. (2021). 28, 1393–1416

- **DAC research**
  - Diffraction from Diamond Anvil Cell platform at HED - overview
    - ► *Liermann et al., JSR (2021). 28, 688-706*
  - MHz XFEL XRD and modeling of pulsed laser heated DAC
    - ► *N. Jaisle et al., J. Appl. Phys. 134 (9), 095904 (2023) – https://doi:10.1063/5.0149836*
  - MHz XRD set-up for dynamic compression experiments in the diamond anvil cell (dDAC)
    - ► *R.J. Husband et al., JSR 30 (4), 671–685 (2023), https://doi:10.1107/S1600577523003910*
  - Dynamic optical spectroscopy and pyrometry (SOP) under optical and x-ray laser
    - ► *O.B. Ball et al., J. Appl. Phys. 134 (5), 055901 (2023), https://doi:10.1063/5.0142196*
  - A von Hámos spectrometer for diamond anvil cell experiments
    - ► *Kaa et al., JSR 30 (4), 822–830 (2023): https://doi:10.1107/S1600577523003041*

- **ReLaX:** the HiBEF high-intensity short-pulse laser driver
  - A. Laso Garcia et al., High Power Laser Science and Engineering (2021) - https://doi.org/10.1017/hpl.2021.47

- Design and performance of the **SAXS** HAPG mirror
  - Smid et al., Review of Scientific Instruments 91, 123501 (2020)

- Design and performance of the **HAPG von-Hamos spectrometers**
  - Preston et al., Journal of Instrumentation, Volume 15 (2020)

- Design and performance of the **meV high resolution setup**
  - Wollenweber et al., Review of Scientific Instruments 92, 013101 (2021)

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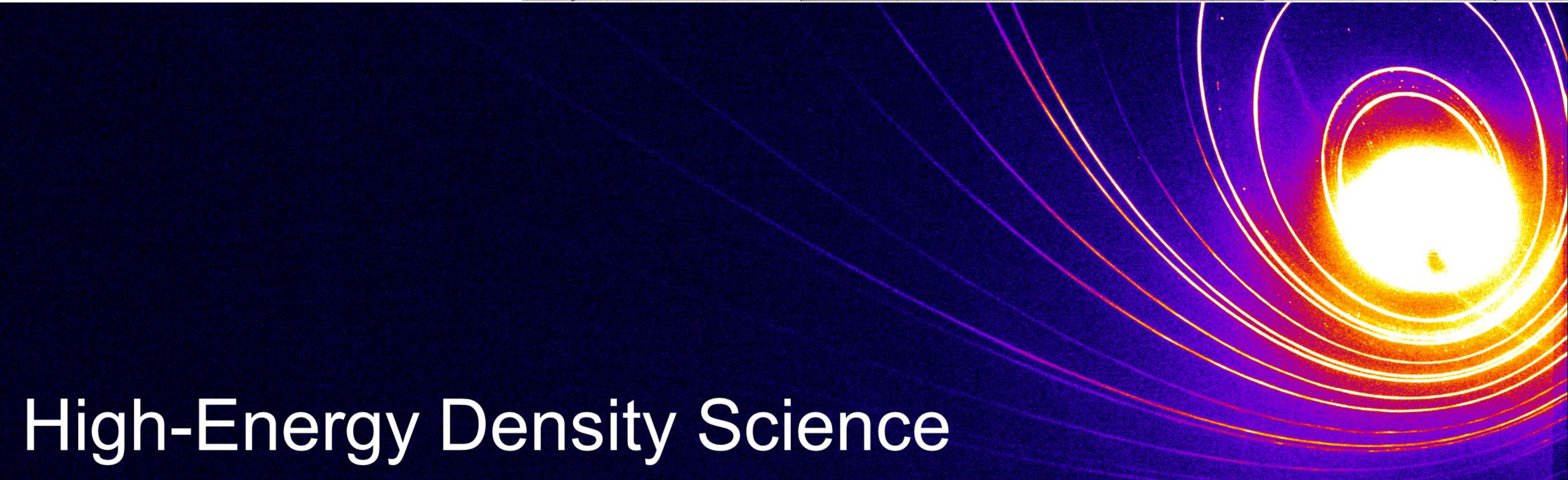
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Federal Ministry
of Education
and Research

European XFEL
HED HiBEF

HED-HIBEF group (2023)



High-Energy Density Science