“HED-HIBEF for IFE”

Current capabilities of HED-HIBEF for IFE research at EuXFEL

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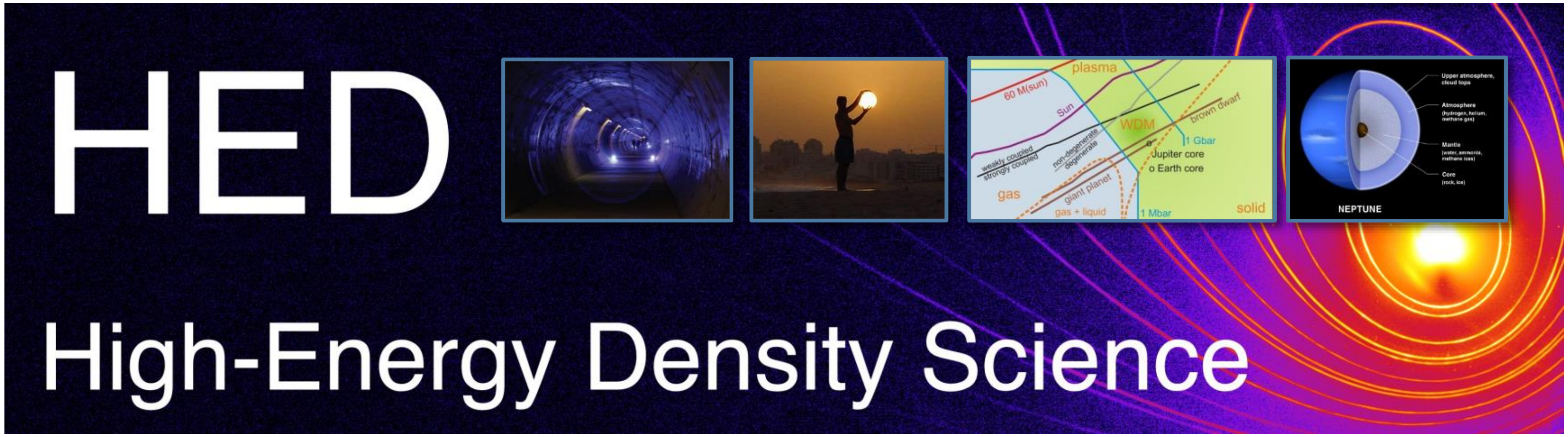
High Energy-Density (HED) science group
European XFEL, Schenefeld, Germany

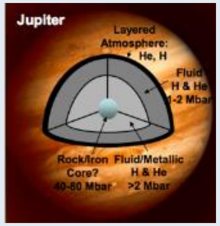
EuXFEL – June 11-12, 2024



HED – research at extremes

Laser Compression

Shock & ramp compression

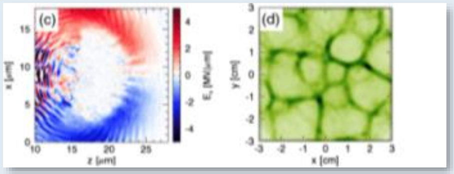


XRD, IXS, XES

Long-pulse ns laser

Relativistic Laser-Plasmas

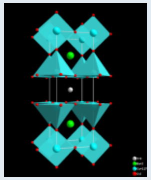
Electron transport,
Instabilities and filamentation,
Particle acceleration,
High EM fields



Multi-100 TW fs laser

Pulsed Magnetic Fields

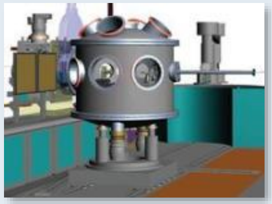
Solid state physics
New quantum states
Superconductivity



> 40 T pulsed coil, 600 µs detector, goniometer

Diamond Anvil Cells

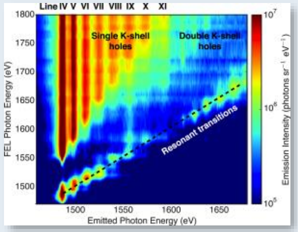
Fast dynamic piezo DAC
Pulsed laser heated DAC
X-ray heated DAC



18 to 25 keV

Isochoric X-ray excitation

Transport properties,
Hollow atoms, rates



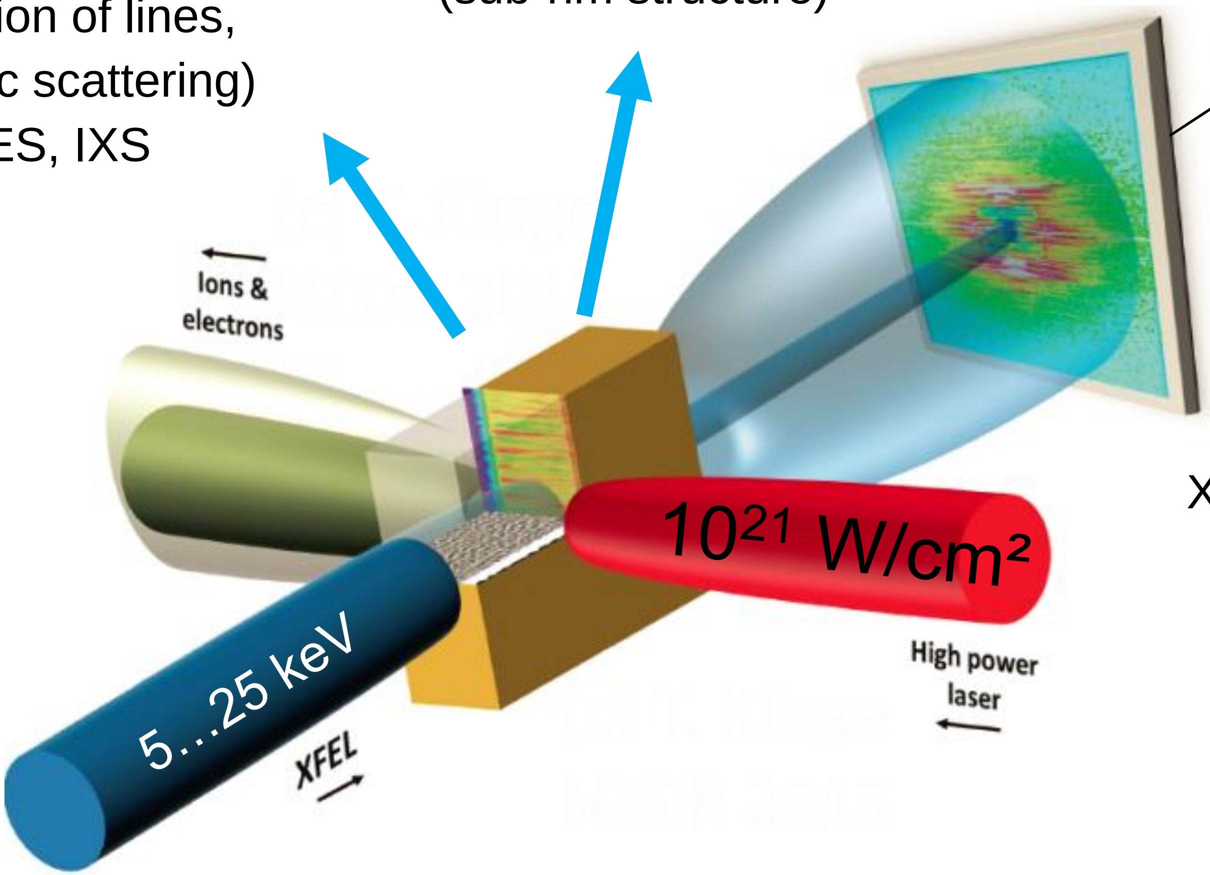
XES, IXS, XRD
Tight focusing

Cryogenic jet targets
High-rep solids targets

X-ray spectrometers
EMP-hard X-ray detectors

High-purity polarimetry

X-ray probing of relativistic laser plasmas



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

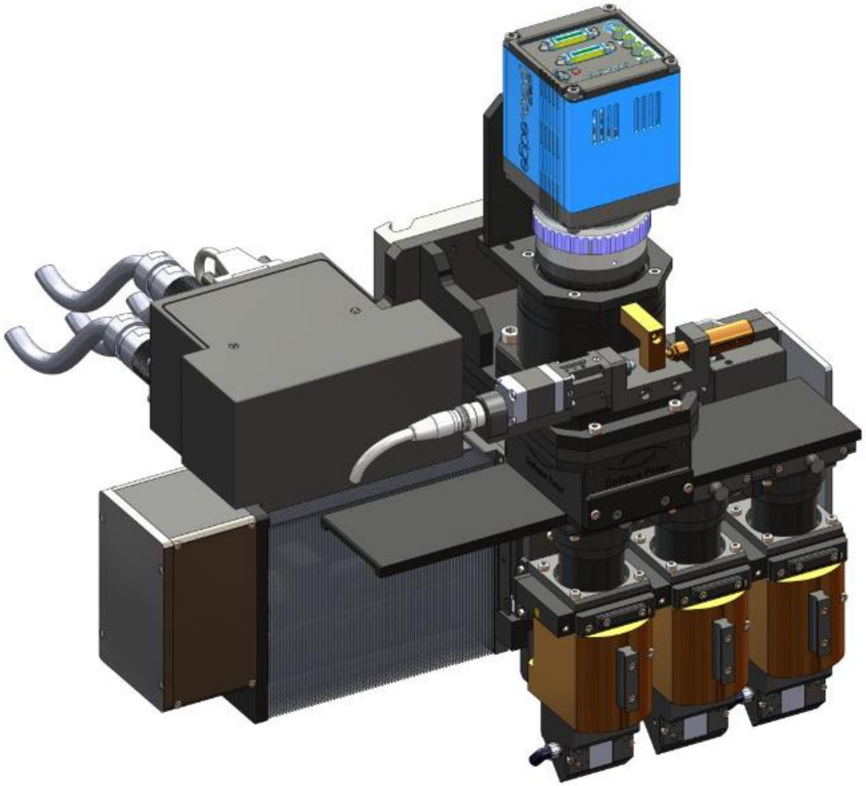
X-ray diffraction XRD
(sub-nm structure)

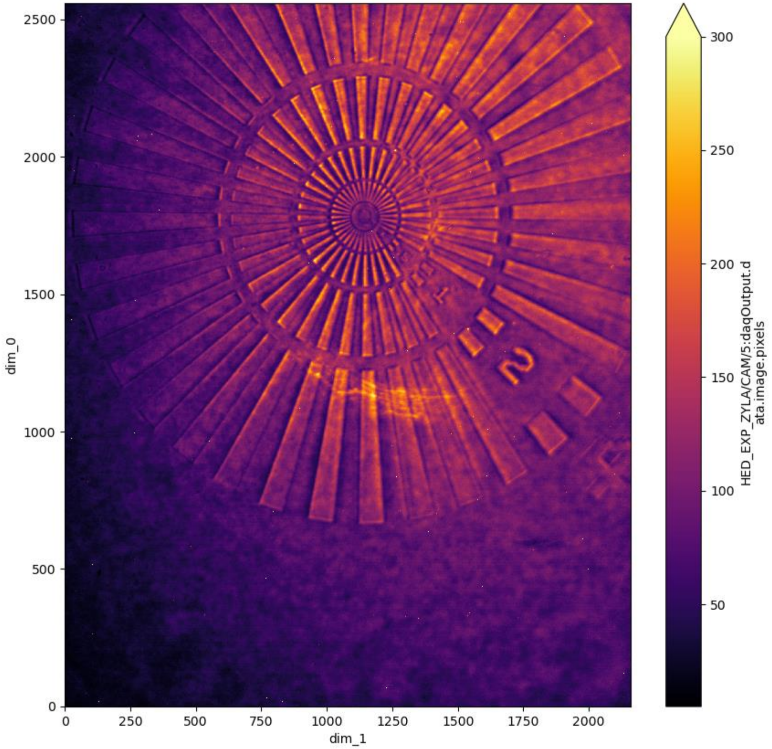
Phase
Contrast
Imaging PCI
(~µm structure)

Small Angle
X-ray Scattering
(SAXS CDI)

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

With an Optique Peter X-ray microscope system we can achieve high imaging resolutions

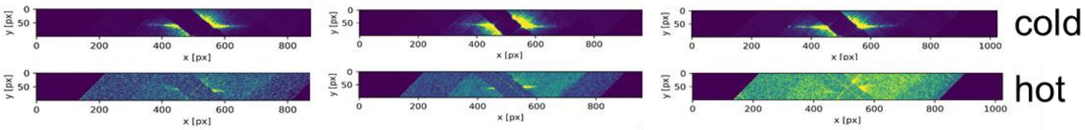


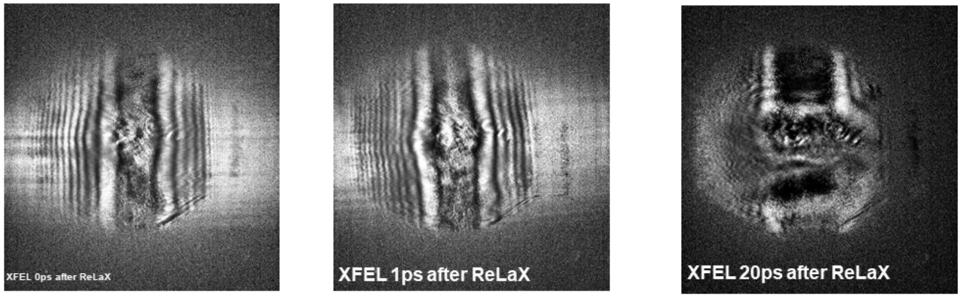


- Three objectives with different magnification (2X, 7.5X, 20X).
- Most commonly used is 7.5X which has a good compromise with FOV.
- Detector used is Andor ZYLA.
- 200nm was measured with monochromatic beam and CRL4b.
- The focus with other lens configurations can also be measured.

HED 2621/ USER COMMUNITY ASSISTED COMMISSIONING OF THE UHI LASER AT HED, IMPACT OF RELATIVISTIC PLASMA ENVIRONMENT ON X-RAY DIAGNOSTICS PI: TONCIAN

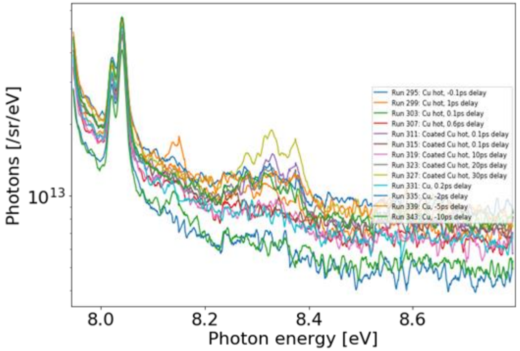
- **Hole boring in a 10 um Cu wire**



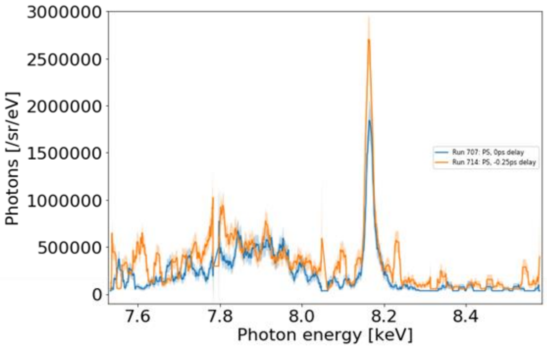


Demonstration of simultaneous SAXS and PCI: fs-dynamics with both nm- and µm-scale resolution

- **X-ray emission spectroscopy in Cu foils**

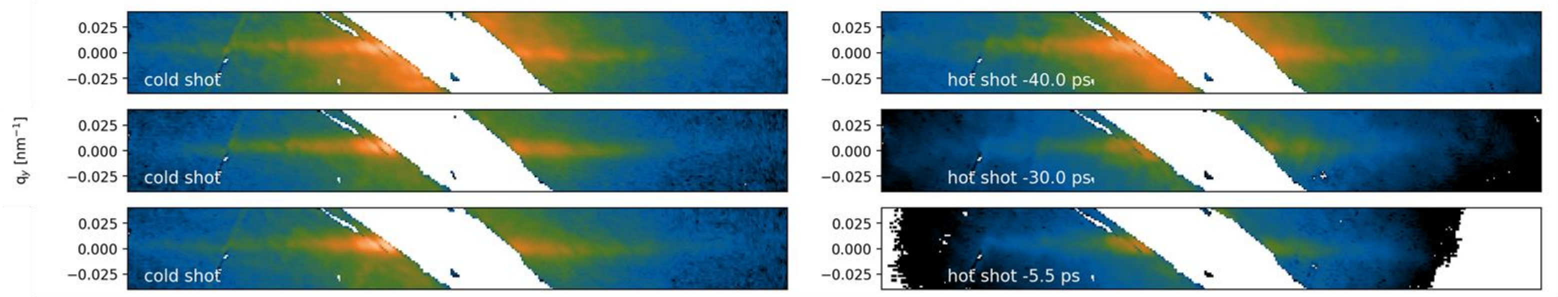


- **X-ray Thomson Scattering in plastic**

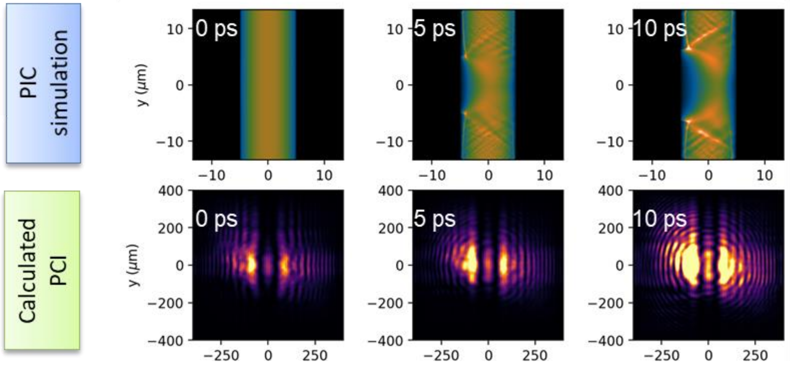


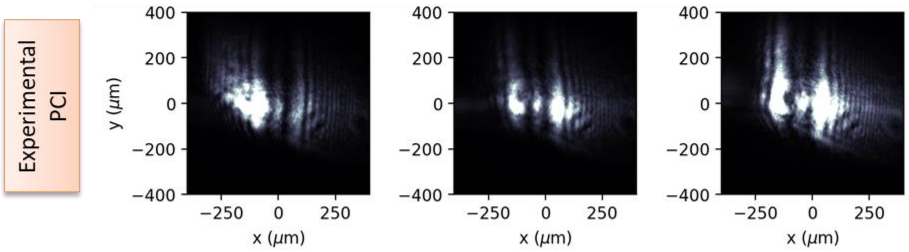
COMBINATION OF XES, SAXS AND IMAGING TO ACCESS MULTI-SCALE PHYSICS

- SAXS probing pre-plasma expansion in 10 µm Cu wires before the arrival of ReLaX main pulse



- Imaging probing of laser driven shock and target expansion



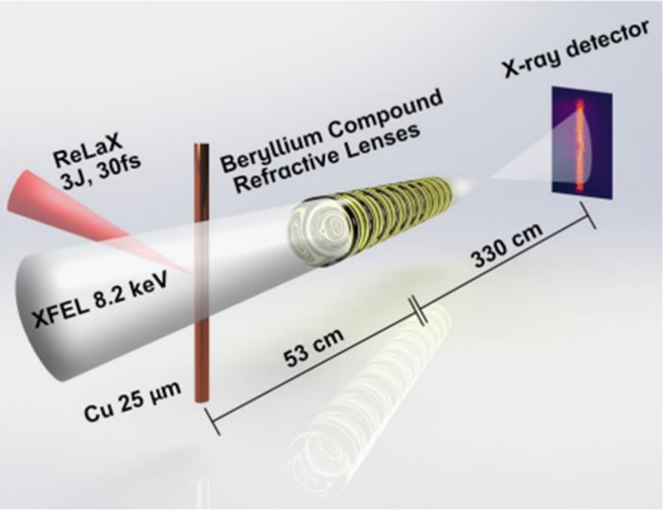


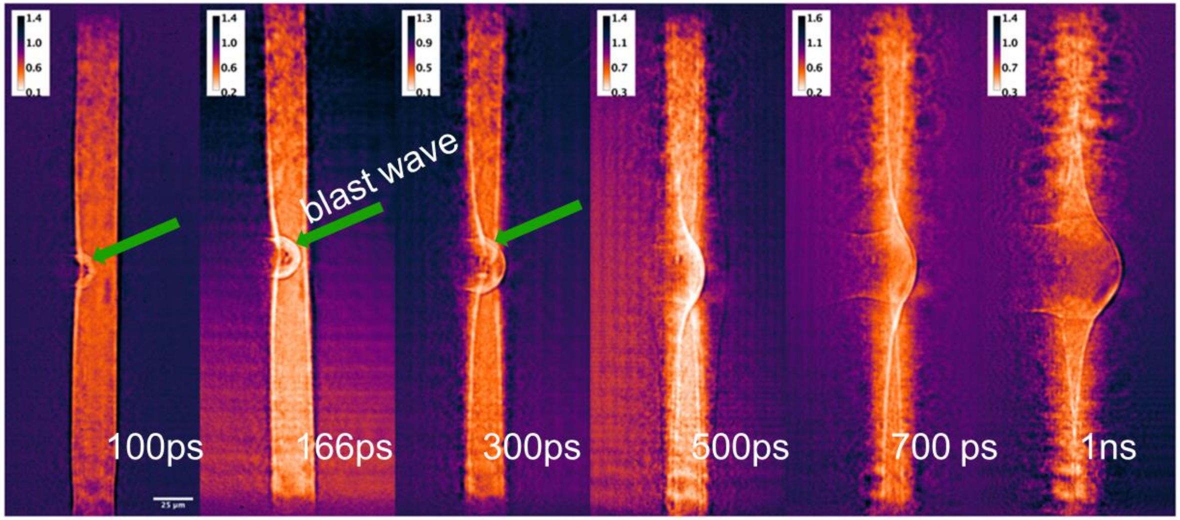
HED 4597/ WIRE IMPLOSION DRIVEN VIA SURFACE RETURN CURRENTS

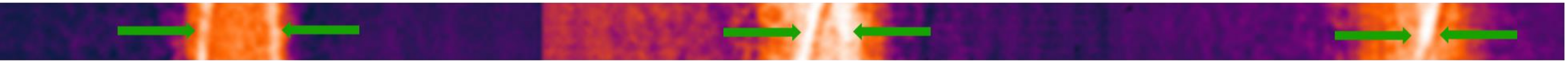
See platform poster

- **Now offered as ReLaX standard configuration 2**

Cu 25 µm wire shock imaging







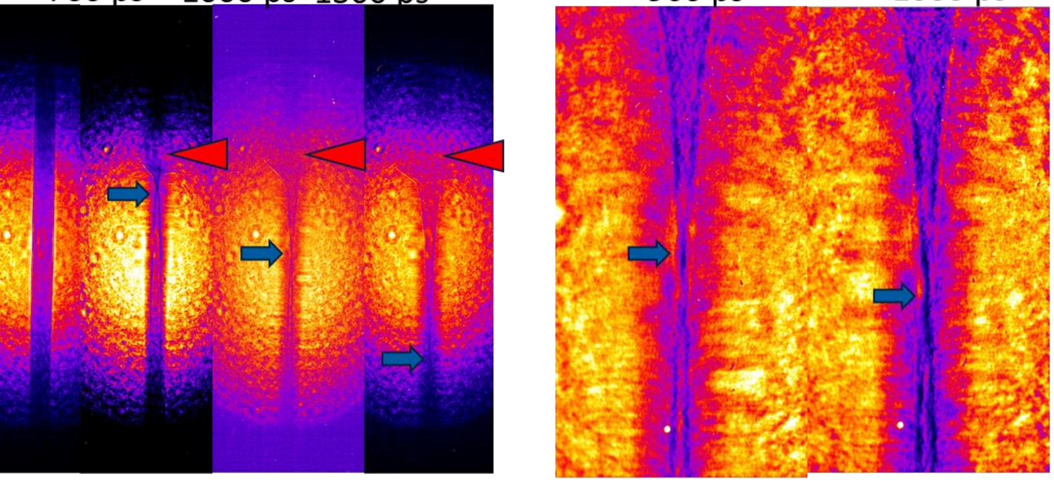
Cylindrical shock wave

A. Laso Garcia et al., arXiv:2402.06983
L. Yang et al., arXiv:2309.10626

HED 5689-HIBEF PA - GENERATION OF EXTREME PRESSURE STATES WITH CYLINDRICAL IMPLODING WIRES

Reconfirmation and extension of HED 4597 “Cylindrical compression of thin wires by irradiation of a Joule class short pulse laser“ demonstrating compression of Cu 10, 15, 25 µm and Al, C, PP, Fe, W

Cu 25 µm wire



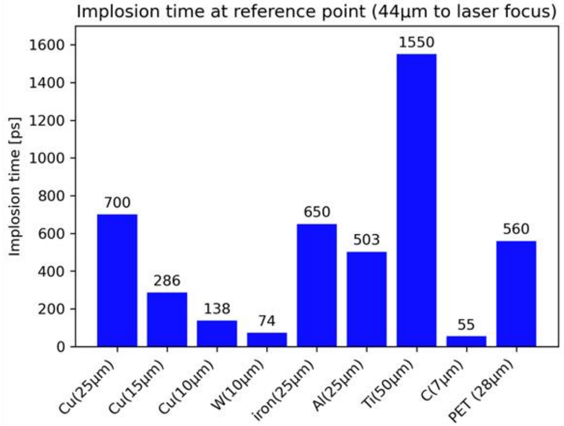
2x magnification

700 ps 1000 ps 1300 ps

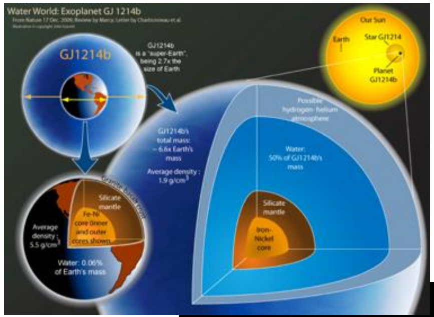
7.5x magnification

960 ps 1000 ps

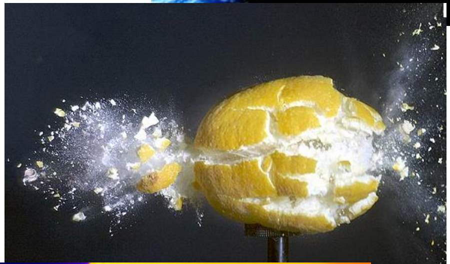
Expected implosion time for all materials predicted correctly by simulations

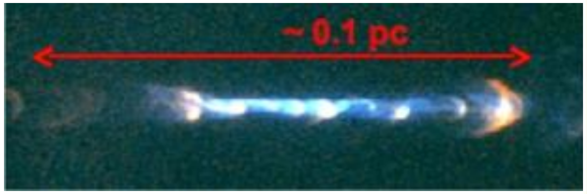


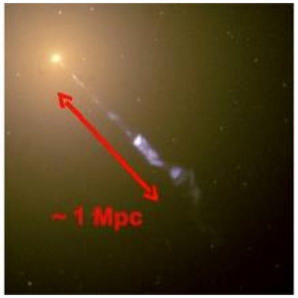
Shock Experiments

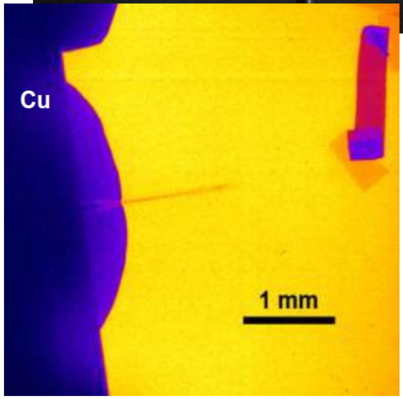


- Nanosecond high-energy lasers are used in multiple domains to generate extrem pressure states, high deformation rates and velocity outflows, relevant for
  - Equation of State of materials
  - Hypervelocity impacts (e.g. debris protection)
  - Material science: plastic deformation, failure, spallation
- Access of micro- to meso-structural data requires brilliant x-ray sources -> Combine such laser with X-FELs
- DiPOLE 100X enabels high number of data set due to it's high repetition rate

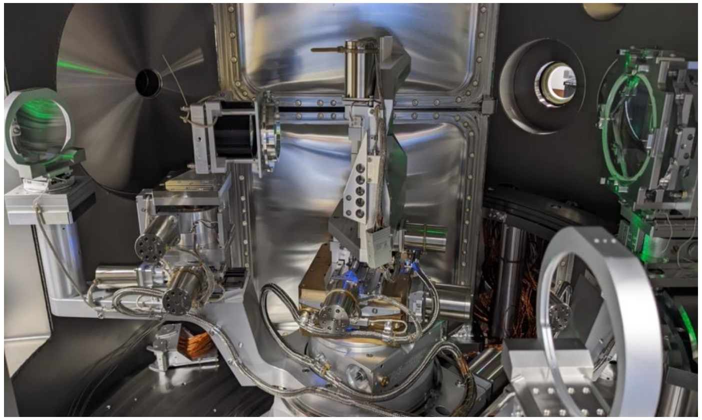




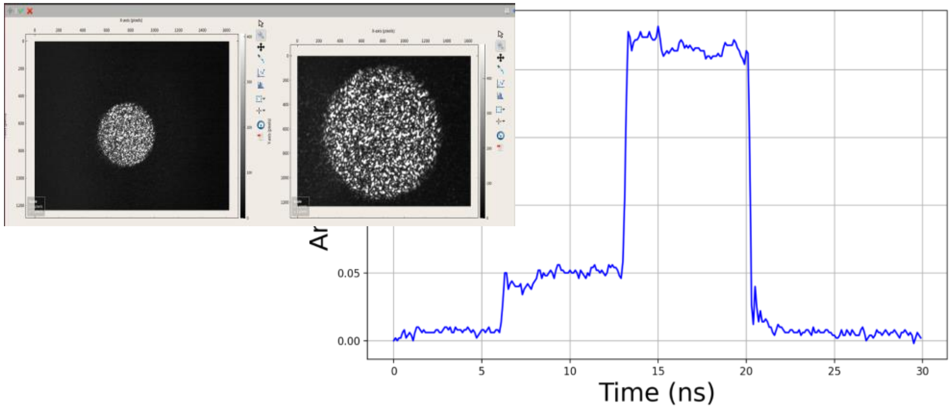


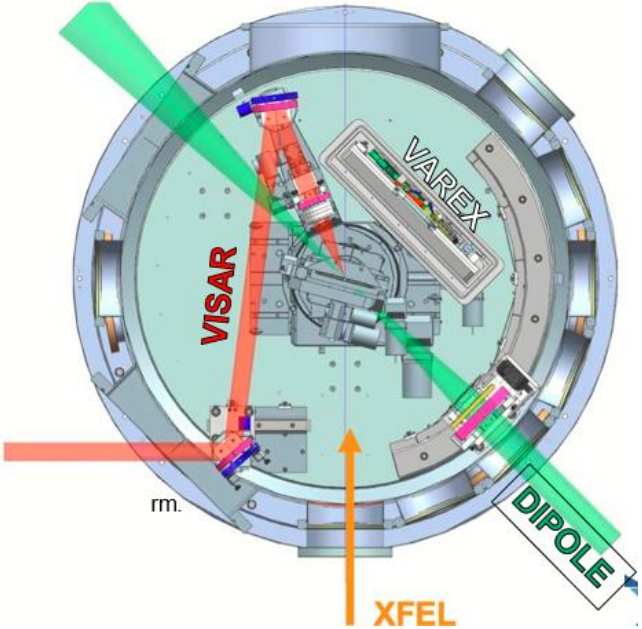


Direct laser compression platform for diffraction



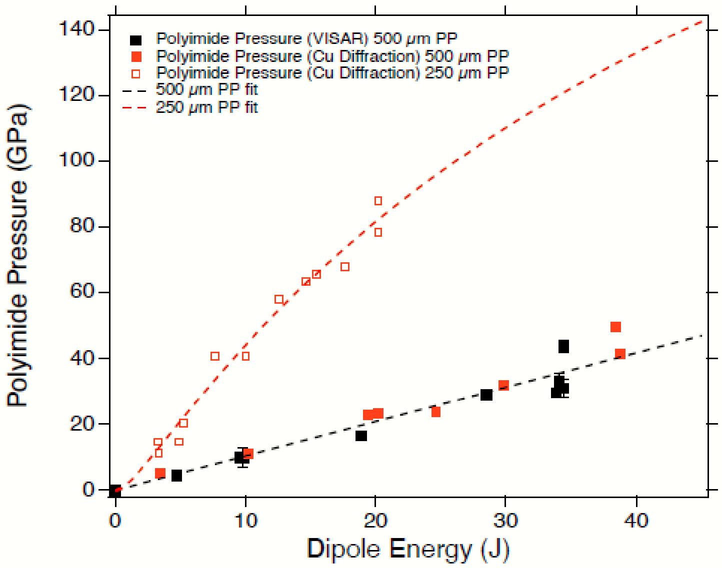
- Dedicated setup for diffraction with large area x-ray detector.
- Variable geometry for shock propagation vs. X-ray direction
- F/5 focussing optic, phase plates for 500, 250 and 100 mum focal spot available
- No noise on the detector due to laser plasma interaction

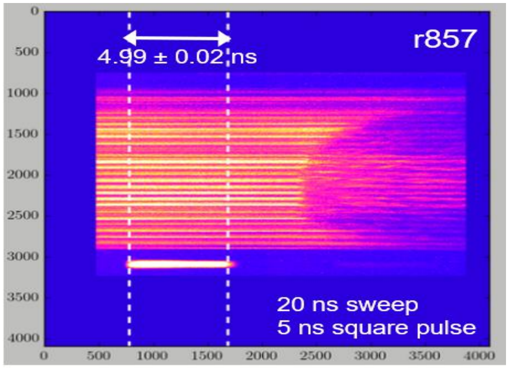




Shock platform capabilities

- VISAR system to get indepentdent pressure information for spatial and temporal evolution
- Ablation pressures for 10 ns pulses > 300 Gpa (100 mum phase plate)
- Timing fiducials on the streak camera for both laser and x-rays
- Full automatic scan of timing and energy reaching shot rates < 1 min





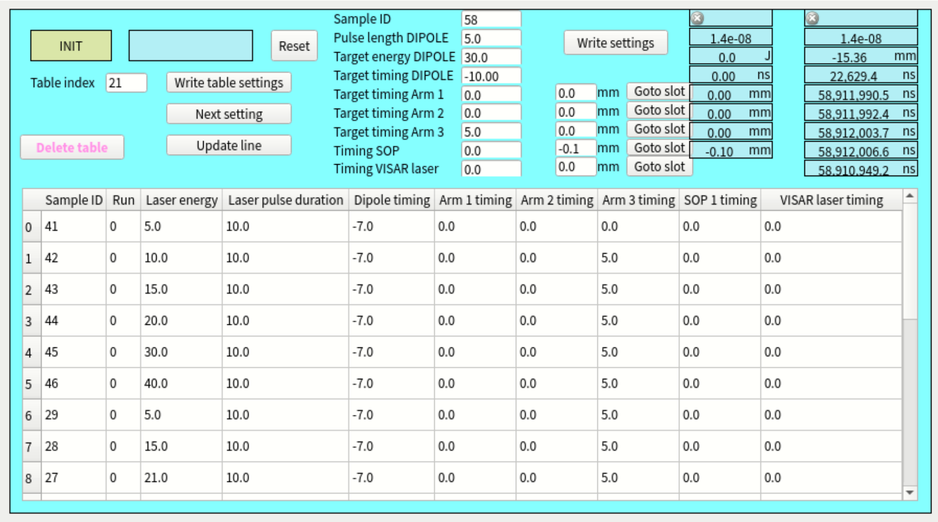


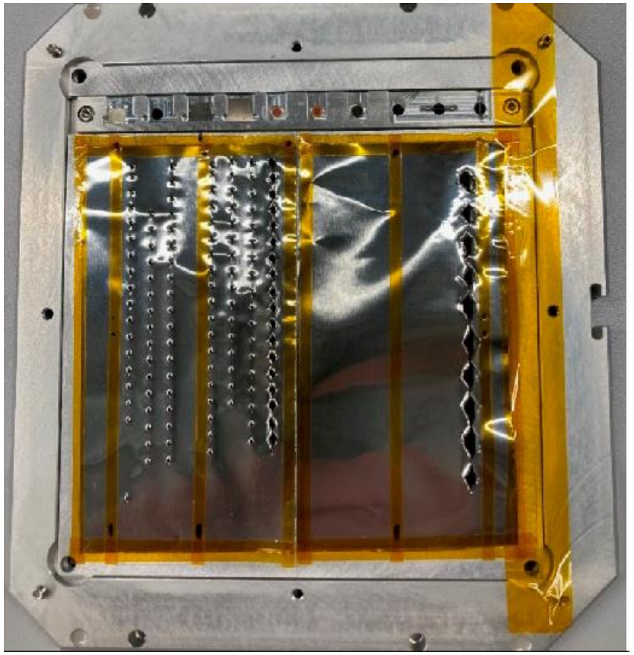
Table index 21

Sample ID 58
Pulse length DIPOLE 5.0
Target energy DIPOLE 30.0
Target timing DIPOLE -10.00
Target timing Arm 1 0.0 | 0.0 mm
Target timing Arm 2 0.0 | 0.0 mm
Target timing Arm 3 5.0 | 0.0 mm
Timing SOP 0.0 | -0.1 mm
Timing VISAR laser 0.0 | 0.0 mm

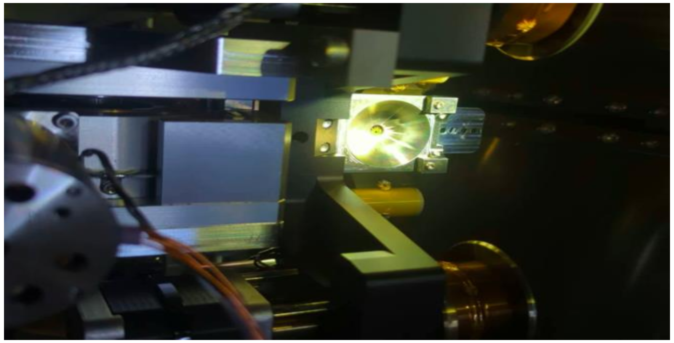
1.4e-08 | 1.4e-08
0.0 J | -15.36 mm
0.00 ns | 22,629.4 ns
0.00 mm | 58,911,990.5 ns
0.00 mm | 58,911,992.4 ns
0.00 mm | 58,912,003.7 ns
-0.10 mm | 58,912,006.6 ns
58,910,949.2 ns

	Sample ID	Run	Laser energy	Laser pulse duration	Dipole timing	Arm 1 timing	Arm 2 timing	Arm 3 timing	SOP 1 timing	VISAR laser timing
0	41	0	5.0	10.0	-7.0	0.0	0.0	0.0	0.0	0.0
1	42	0	10.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
2	43	0	15.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
3	44	0	20.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
4	45	0	30.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
5	46	0	40.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
6	29	0	5.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
7	28	0	15.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0
8	27	0	21.0	10.0	-7.0	0.0	0.0	5.0	0.0	0.0

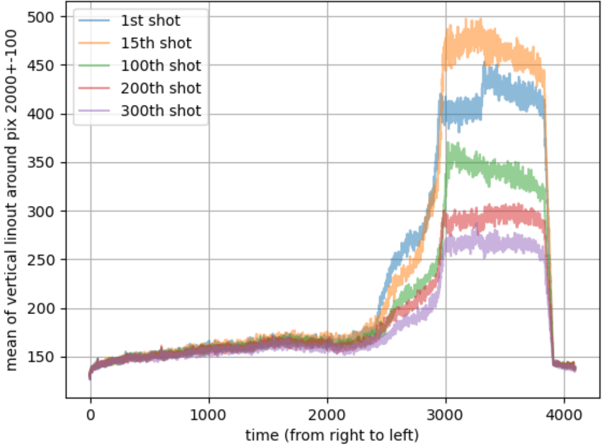
High-rep rate target delivery



- Low cross-section experiments require large shot numbers (100…1000)
- Important bottleneck (amongst other): sample delivery
- First test during first user experiment: 1 Hz on a 10 cm stripe
- Tape target run for 10 minutes @ 1 Hz: VISAR data stable, no x-ray data
- R&D project for next steps: integration, debris management, alignement verification

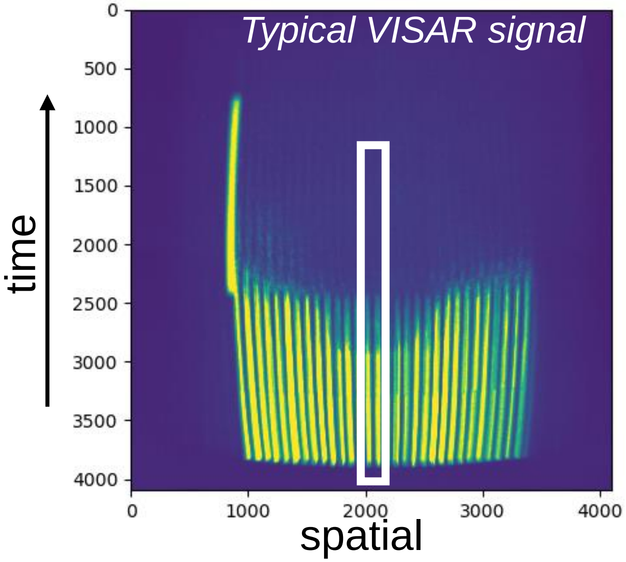


Breakout reproducibility:



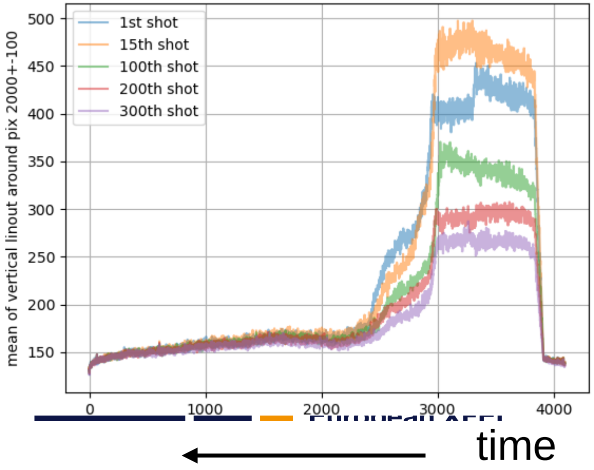
Strategic milestone towards high repetition rate laser-driven shock compression targets using DiPOLE

- 3 m of aluminized Kapton tape target moved at 15 mm/s
- DiPOLE fired at 1 Hz, full power (~37 J@2w)
- VISAR diagnostics at 0.5 Hz
- White light interferometry diagnostics shows focus reproducibility within 5 um
- 600 shots in 10 min

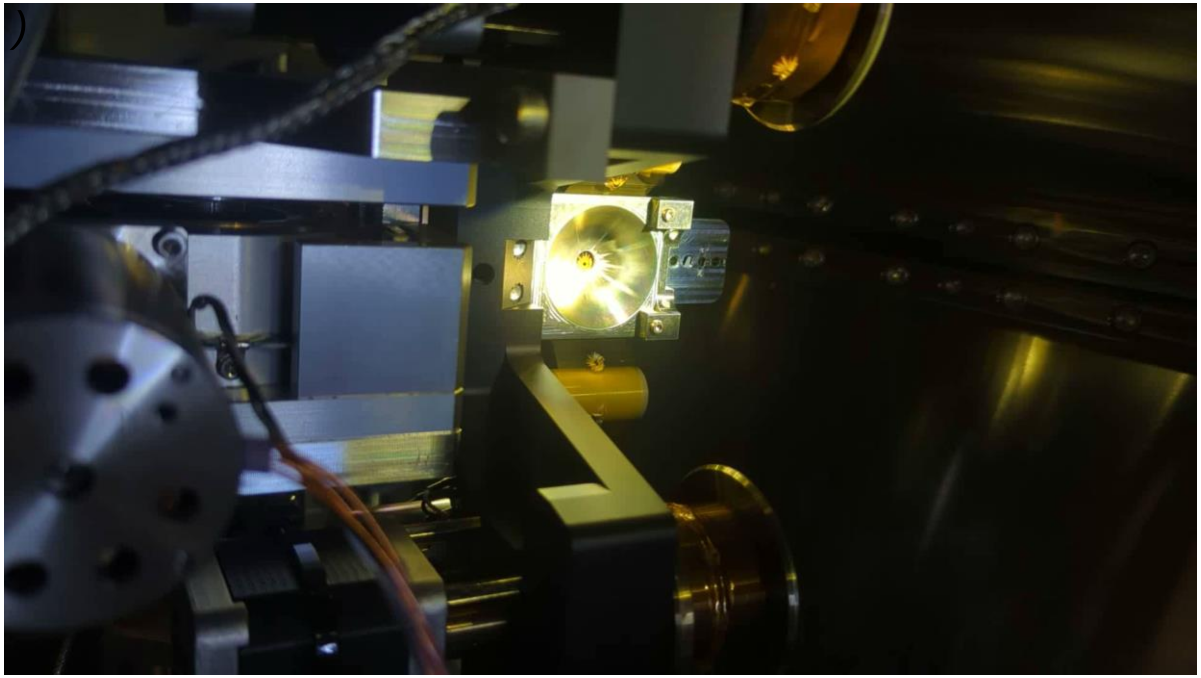


Typical VISAR signal

Breakout reproducibility

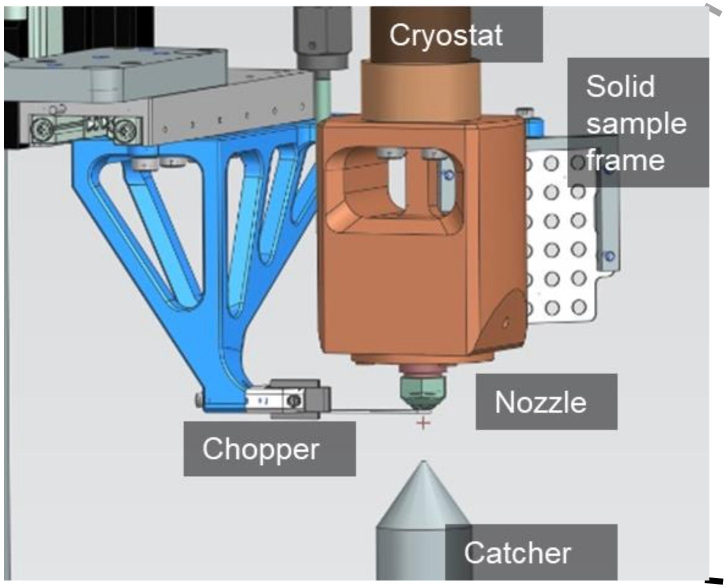


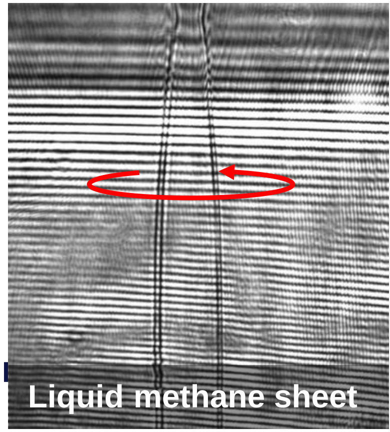
Rewinding the shot Kapton tape target – device built by STFC)

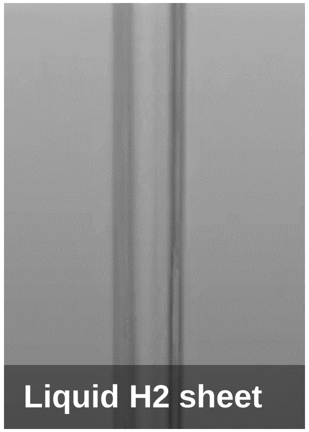


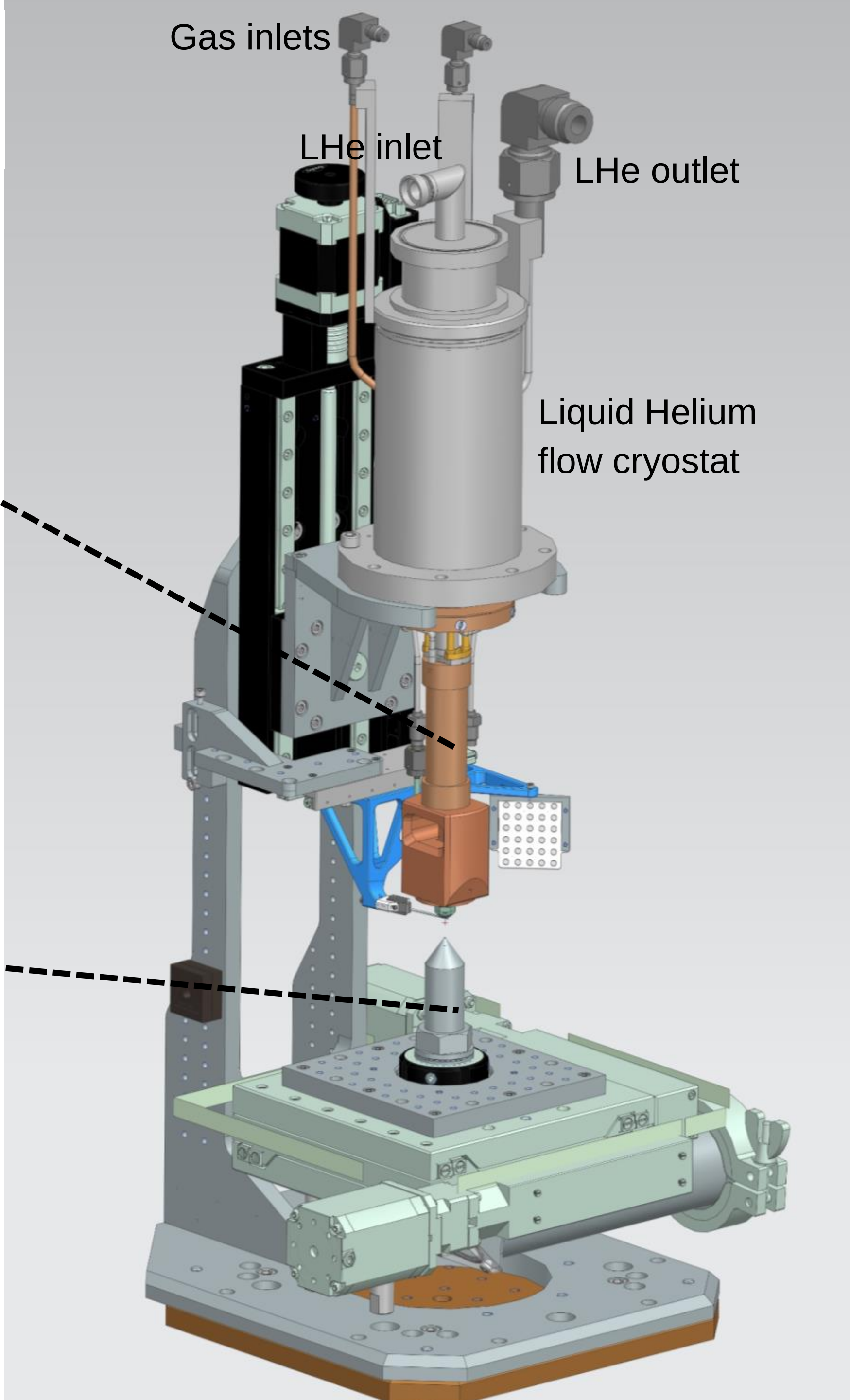
Debris free sample delivery

- High precision jet alignment (~1 micron)
- In-operation sample frame configuration
- Rotation of the full plattform by +/- 45 deg




Liquid methane sheet

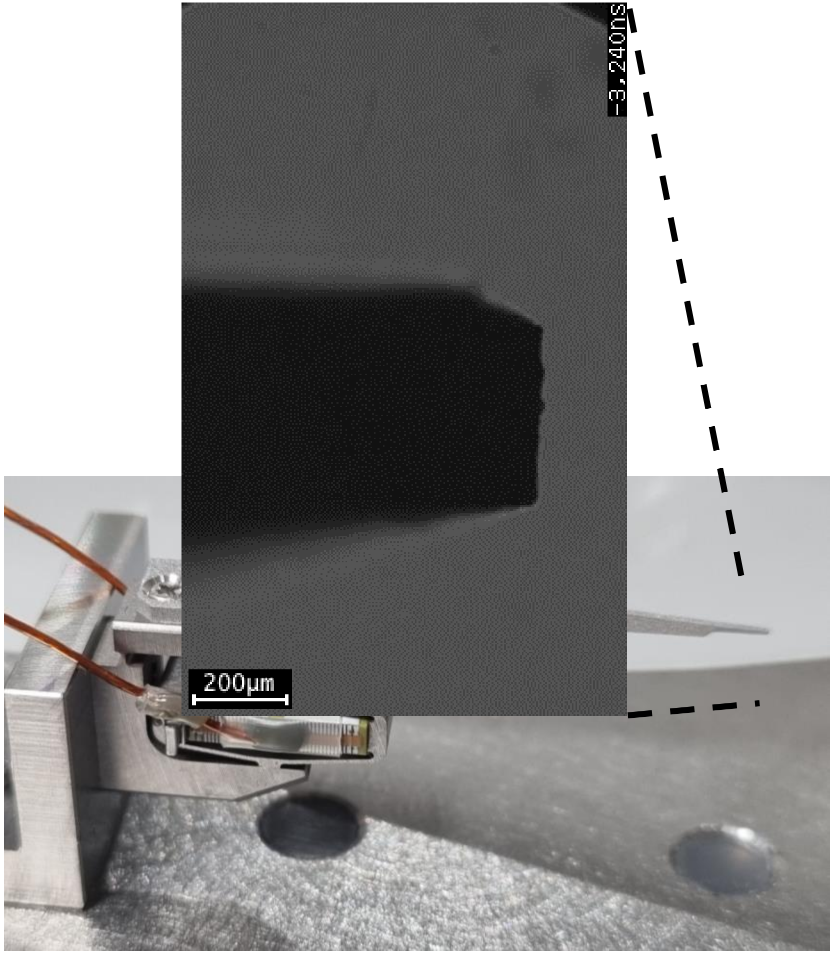

Liquid H2 sheet

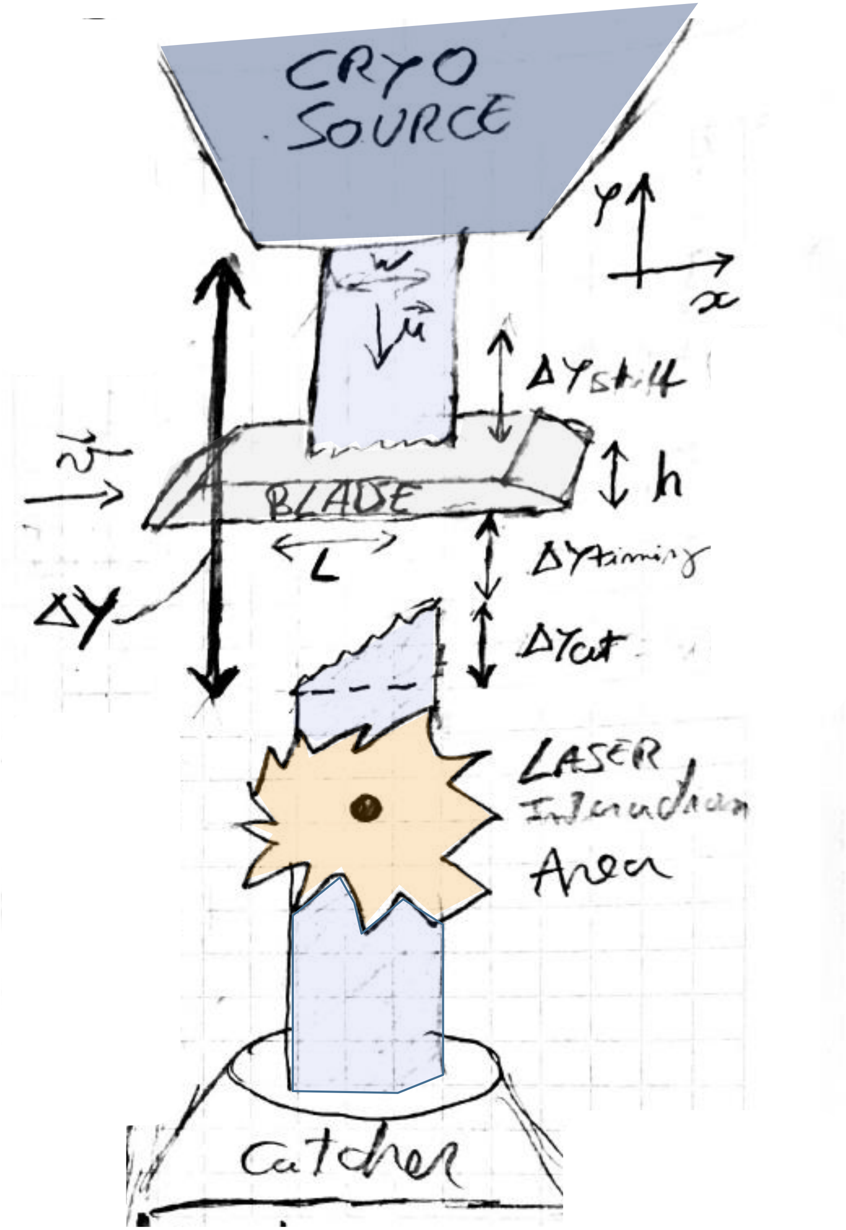


Achieving high repetition rate via large nozzle–interaction separation is not the best option…

CRYOJET PIEZO CHOPPER

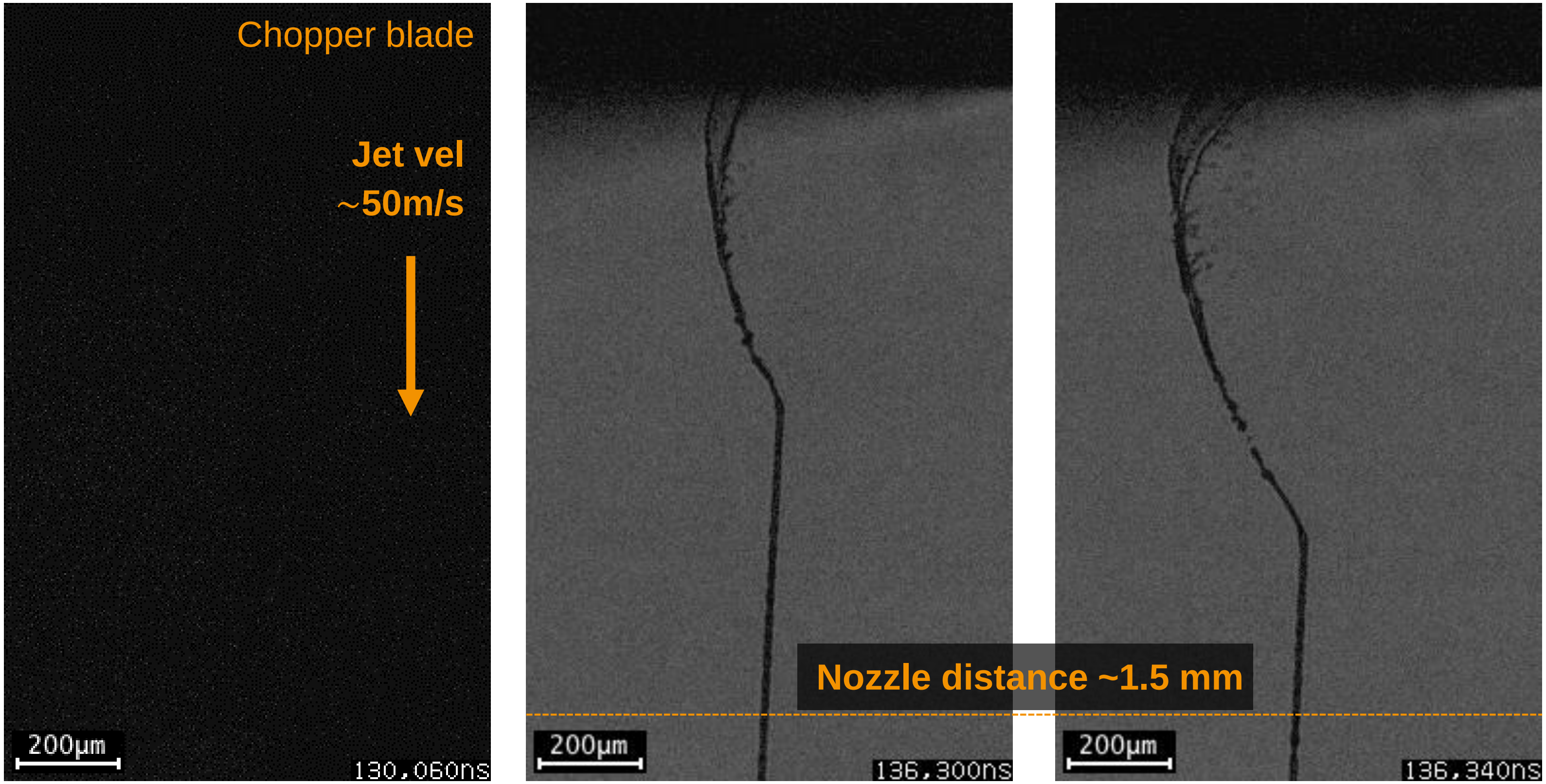
High speed recording with Shimadzu





Chopper performance characterization with Methane jet

- Chop sequence
- Chop series at 1Hz
- Chop series at 10Hz



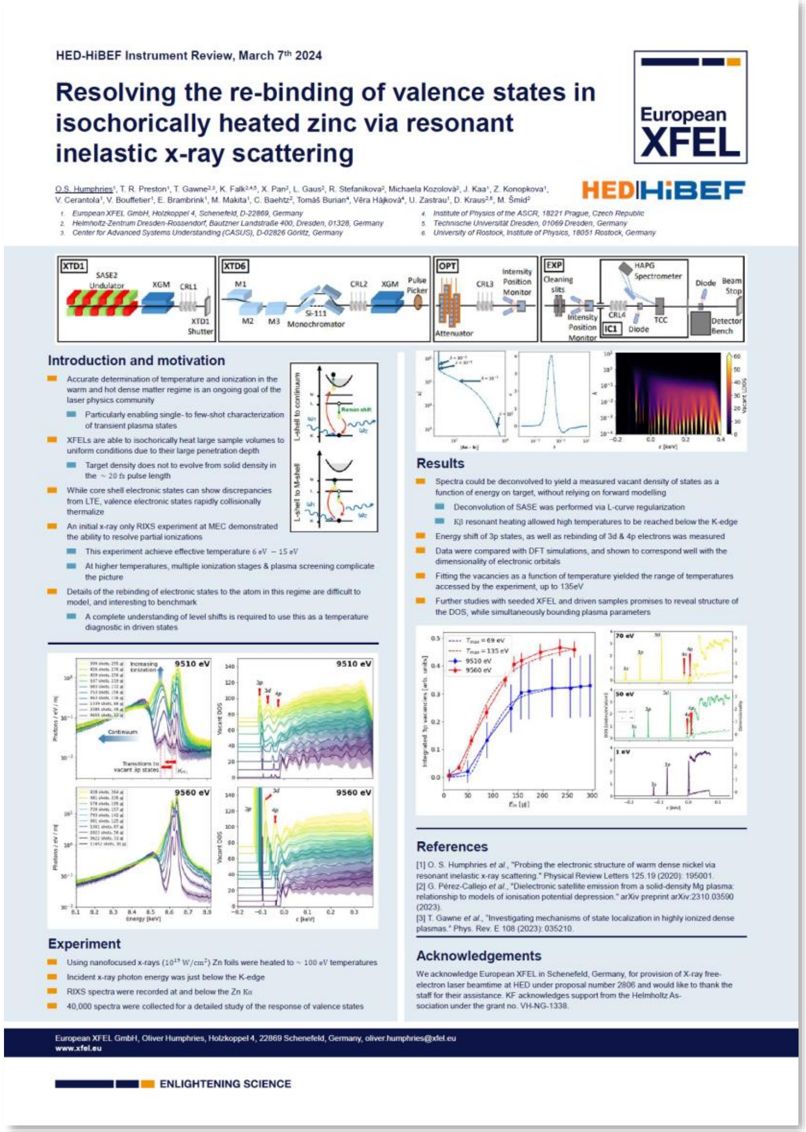
Chopper blade

Jet vel ~50m/s

Nozzle distance ~1.5 mm

Excellent cuting reproducibility enables nozzle to TCC distances of below 3 mm

X-ray single-pulse heating at HED-HIBEF



HED-HiBEF Instrument Review, March 7th 2024

Resolving the re-binding of valence states in isochorically heated zinc via resonant inelastic x-ray scattering

O.S. Humphries[1], T. R. Preston[1], T. Gawne[2,3], K. Falk[2,4,5], X. Pan[2], L. Gaus[2], R. Stefanikova[2], Michaela Kozolová[2], J. Kaa[1], Z. Konopkova[1], V. Cerantola[1], V. Bouffetier[1], E. Brambrink[1], M. Makita[1], C. Baehtz[2], Tomáš Burian[4], Věra Hájková[4], U. Zastrau[1], D. Kraus[2,6], M. Šmíd[2]

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3. Center for Advanced Systems Understanding (CASUS), D-02826 Görlitz, Germany
4. Institute of Physics of the ASCR, 18221 Prague, Czech Republic
5. Technische Universität Dresden, 01069 Dresden, Germany
6. University of Rostock, Institute of Physics, 18051 Rostock, Germany

Introduction and motivation

- Accurate determination of temperature and ionization in the warm and hot dense matter regime is an ongoing goal of the laser physics community
  - Particularly enabling single- to few-shot characterization of transient plasma states
- XFELs are able to isochorically heat large sample volumes to uniform conditions due to their large penetration depth
  - Target density does not to evolve from solid density in the ~ 20 fs pulse length
- While core shell electronic states can show discrepancies from LTE, valence electronic states rapidly collisionally thermalize
- An initial x-ray only RIXS experiment at MEC demonstrated the ability to resolve partial ionizations
  - This experiment achieve effective temperature 6 eV − 15 eV
  - At higher temperatures, multiple ionization stages & plasma screening complicate the picture
- Details of the rebinding of electronic states to the atom in this regime are difficult to model, and interesting to benchmark
  - A complete understanding of level shifts is required to use this as a temperature diagnostic in driven states

Experiment

- Using nanofocused x-rays (10^{19} W/cm^2) Zn foils were heated to ~ 100 eV temperatures
- Incident x-ray photon energy was just below the K-edge
- RIXS spectra were recorded at and below the Zn Kα
- 40,000 spectra were collected for a detailed study of the response of valence states

Results

- Spectra could be deconvolved to yield a measured vacant density of states as a function of energy on target, without relying on forward modelling
  - Deconvolution of SASE was performed via L-curve regularization
  - Kβ resonant heating allowed high temperatures to be reached below the K-edge
- Energy shift of 3p states, as well as rebinding of 3d & 4p electrons was measured
- Data were compared with DFT simulations, and shown to correspond well with the dimensionality of electronic orbitals
- Fitting the vacancies as a function of temperature yielded the range of temperatures accessed by the experiment, up to 135eV
- Further studies with seeded XFEL and driven samples promises to reveal structure of the DOS, while simultaneously bounding plasma parameters

References

[1] O. S. Humphries *et al.*, "Probing the electronic structure of warm dense nickel via resonant inelastic x-ray scattering." Physical Review Letters 125.19 (2020): 195001.
[2] G. Pérez-Callejo *et al.*, "Dielectronic satellite emission from a solid-density Mg plasma: relationship to models of ionisation potential depression." arXiv preprint arXiv:2310.03590 (2023).
[3] T. Gawne *et al.*, "Investigating mechanisms of state localization in highly ionized dense plasmas." Phys. Rev. E 108 (2023): 035210.

Acknowledgements

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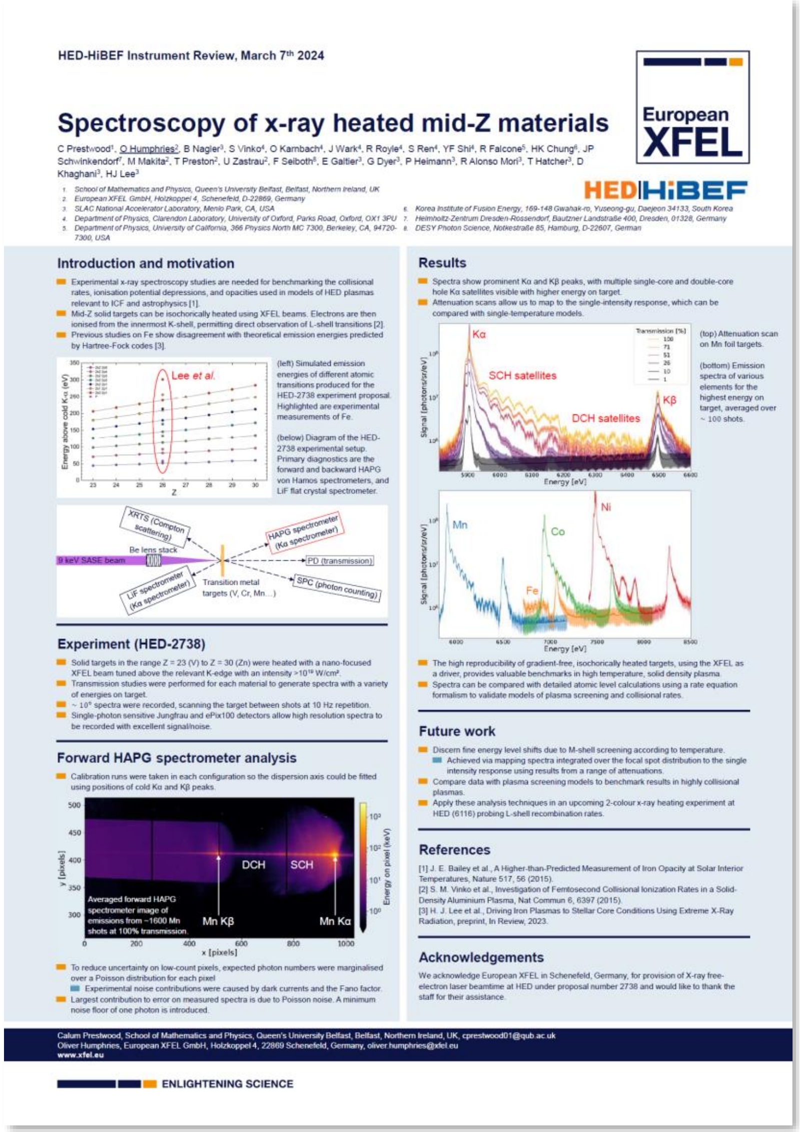

HED-HiBEF Instrument Review, March 7th 2024

Spectroscopy of x-ray heated mid-Z materials

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Introduction and motivation

- Experimental x-ray spectroscopy studies are needed for benchmarking the collisional rates, ionisation potential depressions, and opacities used in models of HED plasmas relevant to ICF and astrophysics [1].
- Mid-Z solid targets can be isochorically heated using XFEL beams. Electrons are then ionised from the innermost K-shell, permitting direct observation of L-shell transitions [2].
- Previous studies on Fe show disagreement with theoretical emission energies predicted by Hartree-Fock codes [3].

(left) Simulated emission energies of different atomic transitions produced for the HED-2738 experiment proposal. Highlighted are experimental measurements of Fe.

(below) Diagram of the HED-2738 experimental setup. Primary diagnostics are the forward and backward HAPG von Hamos spectrometers, and LiF flat crystal spectrometer.

Experiment (HED-2738)

- Solid targets in the range Z = 23 (V) to Z = 30 (Zn) were heated with a nano-focused XFEL beam tuned above the relevant K-edge with an intensity >10^{19} W/cm^2.
- Transmission studies were performed for each material to generate spectra with a variety of energies on target.
- $\sim 10^{6}$ spectra were recorded, scanning the target between shots at 10 Hz repetition.
- Single-photon sensitive Jungfrau and ePix100 detectors allow high resolution spectra to be recorded with excellent signal/noise.

Forward HAPG spectrometer analysis

- Calibration runs were taken in each configuration so the dispersion axis could be fitted using positions of cold Kα and Kβ peaks.

Averaged forward HAPG spectrometer image of emissions from ~1600 Mn shots at 100% transmission.

- To reduce uncertainty on low-count pixels, expected photon numbers were marginalised over a Poisson distribution for each pixel
  - Experimental noise contributions were caused by dark currents and the Fano factor.
- Largest contribution to error on measured spectra is due to Poisson noise. A minimum noise floor of one photon is introduced.

Results

- Spectra show prominent Kα and Kβ peaks, with multiple single-core and double-core hole Kα satellites visible with higher energy on target.
- Attenuation scans allow us to map to the single-intensity response, which can be compared with single-temperature models.

(top) Attenuation scan on Mn foil targets.

(bottom) Emission spectra of various elements for the highest energy on target, averaged over ~ 100 shots.

- The high reproducibility of gradient-free, isochorically heated targets, using the XFEL as a driver, provides valuable benchmarks in high temperature, solid density plasma.
- Spectra can be compared with detailed atomic level calculations using a rate equation formalism to validate models of plasma screening and collisional rates.

Future work

- Discern fine energy level shifts due to M-shell screening according to temperature.
  - Achieved via mapping spectra integrated over the focal spot distribution to the single intensity response using results from a range of attenuations.
- Compare data with plasma screening models to benchmark results in highly collisional plasmas.
- Apply these analysis techniques in an upcoming 2-colour x-ray heating experiment at HED (6116) probing L-shell recombination rates.

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[3] H. J. Lee et al., Driving Iron Plasmas to Stellar Core Conditions Using Extreme X-Ray Radiation, preprint, In Review, 2023.

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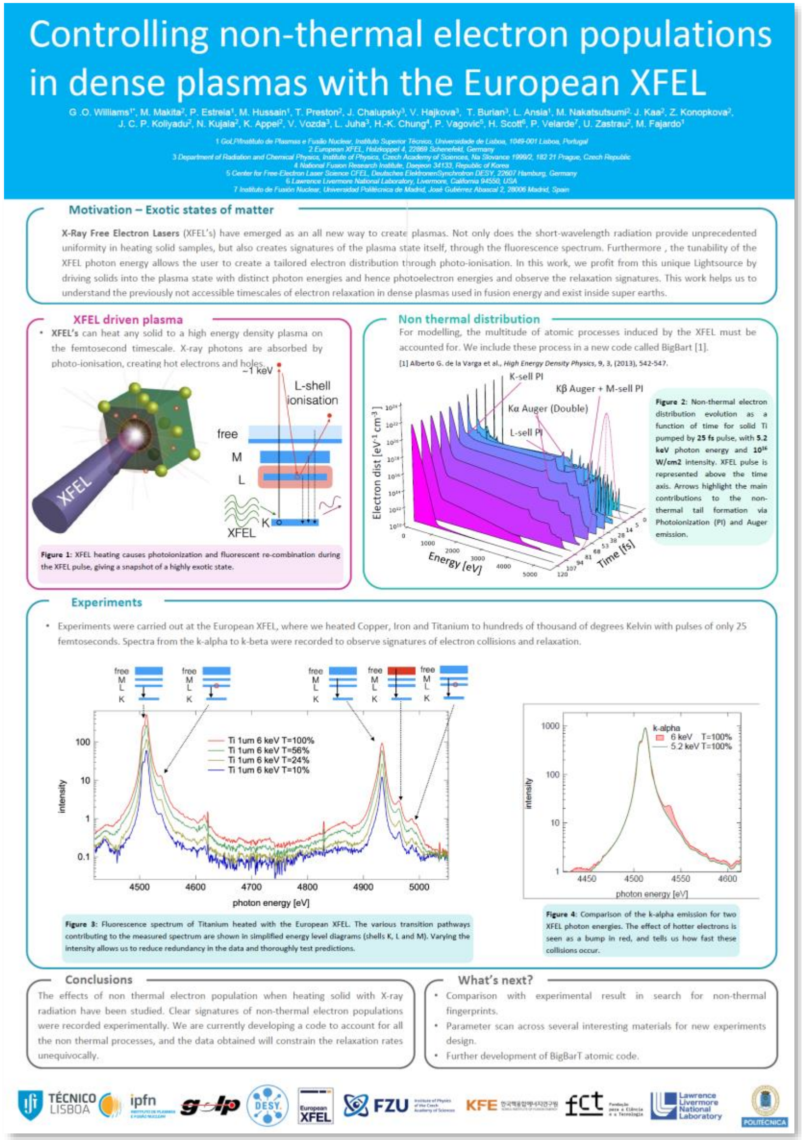
X-ray single pulse heating at HED-HIBEF



Controlling non-thermal electron populations in dense plasmas with the European XFEL

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Motivation – Exotic states of matter

X-Ray Free Electron Lasers (XFEL's) have emerged as an all new way to create plasmas. Not only does the short-wavelength radiation provide unprecedented uniformity in heating solid samples, but also creates signatures of the plasma state itself, through the fluorescence spectrum. Furthermore , the tunability of the XFEL photon energy allows the user to create a tailored electron distribution through photo-ionisation. In this work, we profit from this unique Lightsource by driving solids into the plasma state with distinct photon energies and hence photoelectron energies and observe the relaxation signatures. This work helps us to understand the previously not accessible timescales of electron relaxation in dense plasmas used in fusion energy and exist inside super earths.

XFEL driven plasma

- **XFEL's** can heat any solid to a high energy density plasma on the femtosecond timescale. X-ray photons are absorbed by photo-ionisation, creating hot electrons and holes.

Figure 1: XFEL heating causes photoionization and fluorescent re-combination during the XFEL pulse, giving a snapshot of a highly exotic state.

Non thermal distribution

For modelling, the multitude of atomic processes induced by the XFEL must be accounted for. We include these process in a new code called BigBart [1].

[1] Alberto G. de la Varga et al., *High Energy Density Physics*, 9, 3, (2013), 542-547.

Figure 2: Non-thermal electron distribution evolution as a function of time for solid Ti pumped by **25 fs** pulse, with **5.2 keV** photon energy and **10^{16} W/cm2** intensity. XFEL pulse is represented above the time axis. Arrows highlight the main contributions to the non-thermal tail formation via Photoionization (PI) and Auger emission.

Experiments

- Experiments were carried out at the European XFEL, where we heated Copper, Iron and Titanium to hundreds of thousand of degrees Kelvin with pulses of only 25 femtoseconds. Spectra from the k-alpha to k-beta were recorded to observe signatures of electron collisions and relaxation.

Figure 3: Fluorescence spectrum of Titanium heated with the European XFEL. The various transition pathways contributing to the measured spectrum are shown in simplified energy level diagrams (shells K, L and M). Varying the intensity allows us to reduce redundancy in the data and thoroughly test predictions.

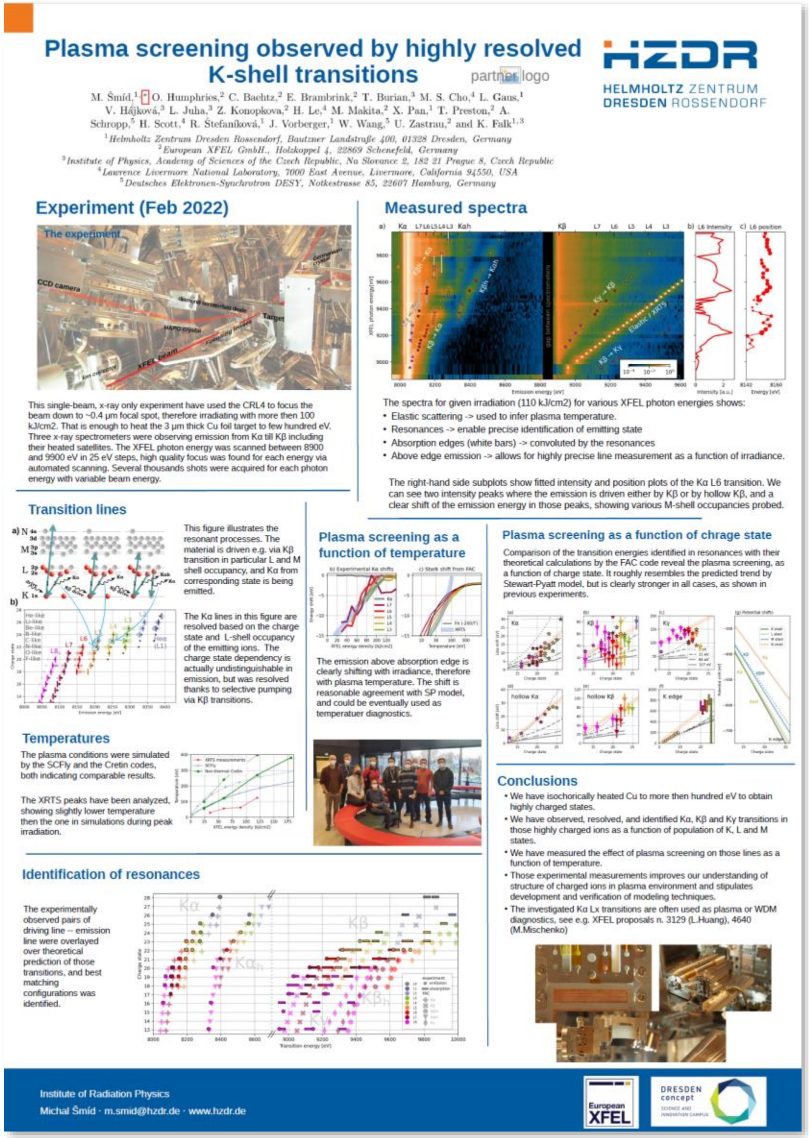
Figure 4: Comparison of the k-alpha emission for two XFEL photon energies. The effect of hotter electrons is seen as a bump in red, and tells us how fast these collisions occur.

Conclusions

The effects of non thermal electron population when heating solid with X-ray radiation have been studied. Clear signatures of non-thermal electron populations were recorded experimentally. We are currently developing a code to account for all the non thermal processes, and the data obtained will constrain the relaxation rates unequivocally.

What's next?

- Comparison with experimental result in search for non-thermal fingerprints.
- Parameter scan across several interesting materials for new experiments design.
- Further development of BigBarT atomic code.



Plasma screening observed by highly resolved K-shell transitions

partner logo

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Experiment (Feb 2022)

This single-beam, x-ray only experiment have used the CRL4 to focus the beam down to ~0.4 µm focal spot, therefore irradiating with more then 100 kJ/cm2. That is enough to heat the 3 µm thick Cu foil target to few hundred eV. Three x-ray spectrometers were observing emission from Kα till Kβ including their heated satellites. The XFEL photon energy was scanned between 8900 and 9900 eV in 25 eV steps, high quality focus was found for each energy via automated scanning. Several thousands shots were acquired for each photon energy with variable beam energy.

Measured spectra

The spectra for given irradiation (110 kJ/cm2) for various XFEL photon energies shows:

- Elastic scattering -> used to infer plasma temperature.
- Resonances -> enable precise identification of emitting state
- Absorption edges (white bars) -> convoluted by the resonances
- Above edge emission -> allows for highly precise line measurement as a function of irradiance.

The right-hand side subplots show fitted intensity and position plots of the Kα L6 transition. We can see two intensity peaks where the emission is driven either by Kβ or by hollow Kβ, and a clear shift of the emission energy in those peaks, showing various M-shell occupancies probed.

Transition lines

This figure illustrates the resonant processes. The material is driven e.g. via Kβ transition in particular L and M shell occupancy, and Kα from corresponding state is being emitted.

The Kα lines in this figure are resolved based on the charge state and L-shell occupancy of the emitting ions. The charge state dependency is actually undistinguishable in emission, but was resolved thanks to selective pumping via Kβ transitions.

Plasma screening as a function of temperature

The emission above absorption edge is clearly shifting with irradiance, therefore with plasma temperature. The shift is reasonable agreement with SP model, and could be eventually used as temperatuer diagnostics.

Plasma screening as a function of chrage state

Comparison of the transition energies identified in resonances with their theoretical calculations by the FAC code reveal the plasma screening, as a function of charge state. It roughly resembles the predicted trend by Stewart-Pyatt model, but is clearly stronger in all cases, as shown in previous experiments.

Temperatures

The plasma conditions were simulated by the SCFly and the Cretin codes, both indicating comparable results.

The XRTS peaks have been analyzed, showing slightly lower temperature then the one in simulations during peak irradiation.

Identification of resonances

The experimentally observed pairs of driving line -- emission line were overlayed over theoretical prediction of those transitions, and best matching configurations was identified.

Conclusions

- We have isochorically heated Cu to more then hundred eV to obtain highly charged states.
- We have observed, resolved, and identified Kα, Kβ and Kγ transitions in those highly charged ions as a function of population of K, L and M states.
- We have measured the effect of plasma screening on those lines as a function of temperature.
- Those experimental measurements improves our understanding of structure of charged ions in plasma environment and stipulates development and verification of modeling techniques.
- The investigated Kα Lx transitions are often used as plasma or WDM diagnostics, see e.g. XFEL proposals n. 3129 (L.Huang), 4640 (M.Mischenko)

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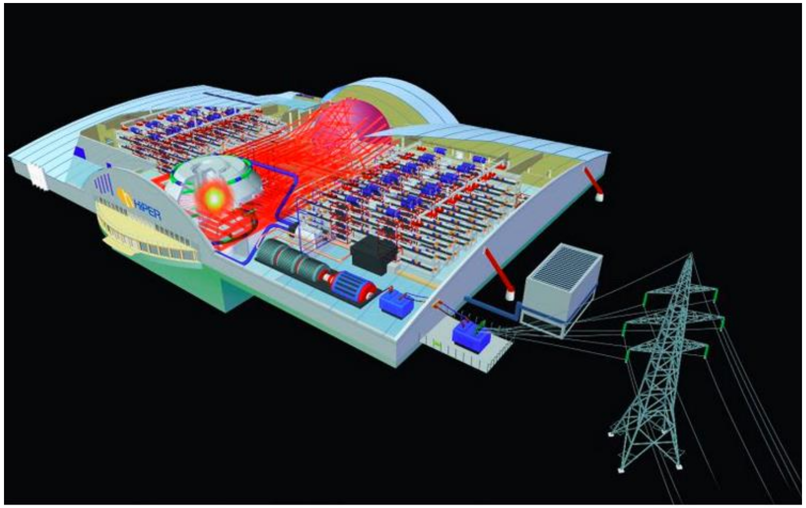
Towards higher pressures: Laser upgrade

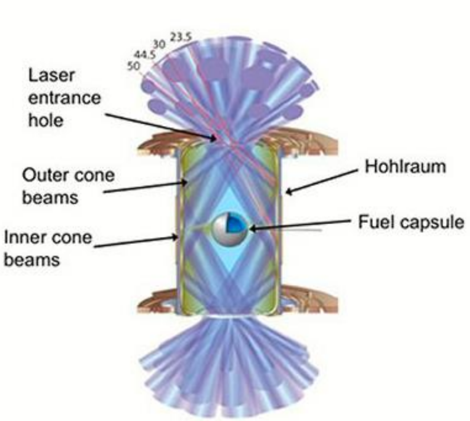
- Laser energy presently limits pressure range, compression times and sample dimensions
- In particular ion-electron demixing (1-2 TPa range) and off-Hugoniot compression would profit of multi-KJ at XFEL, Lab-Astro requires multi-beam setups
- THRILL: EU project (Horizon-infra 2022, 4 year project, 10 M€ budget)
- Development of a laser amplifier with more than 1 kJ pulse energy with repetition rate of ~1 shot/minute (presently ~1 shot/h)
- Cooled amplifier techniques, beam transport, optics developement, …

A multi kJ laser would open new domain of physics and keep XFEL competitive

Fusion related research



- Fusion research gains new public interest after NIF results and foundation of start-up companies
- Present installations (DiPOLE and RELAX) can study related fundamental physics
  - EOS for early stage ablabtion processes
  - Hydrodynamic instabilities
  - Interaction physics for fast/shock ignition
- Further studies would require multi-kJ system possibly multi-beamline system – XFEL could offer unique diagnostic capabilities



Fusion research center at XFEL

Future Inertial Fusion Energy (IFE) research at HED-HIBEF

- High-repetition rate (10 Hz) high-energy laser experiments (main collaboration with UKRI-STFC / University of Oxford) → technology required for an IFE power plant (which needs to run at ~10 Hz)

- IFE science using optical lasers and XFEL probing:
  - **Study of ablators**: Equation of state of ablator materials at a few Mbar (i.e., comparable to the initial shock in common ICF implosion designs); evolution of micro- and nanoscale scale heterogeneities with high resolution phase contrast imaging and small angle scattering.
  - **Laser-plasma interaction**: Intense laser-matter interaction and energy transport relevant to shock ignition (~10^{16} W/cm^2) & fast ignition (>10^{18} W/cm^2); test low-compression approaches to fusion energy; investigate converging shocks or miniature implosions triggered by the ReLaX laser.
  - **Hydrodynamic instabilities**: Apply phase contrast imaging capabilities together with spectroscopy probing of plasma conditions.
  - **Relevant conditions with multi-beam geometry**: High energy shock with DIPOLE laser to create highly compressed state then hit by high-intensity RELAX laser; XFEL diagnostics allows to study properties of hot dense matter (ionization, opacity, conductivities, ..) with unprecedented accuracy.

- Future upgrade to kJ drive laser energies planned (HIBEF 2.0)
  → Create conditions that are even more relevant to IFE

- Capabilities of HIBEF at EuXFEL are currently superior to the LCLS in the US where a strong IFE program has already been initiated.

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