

HED science with intense heavy-ion pulses at GSI/FAIR

P. Neumayer

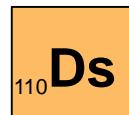
3rd workshop on Studies of Dynamically Compressed Matter with X-rays

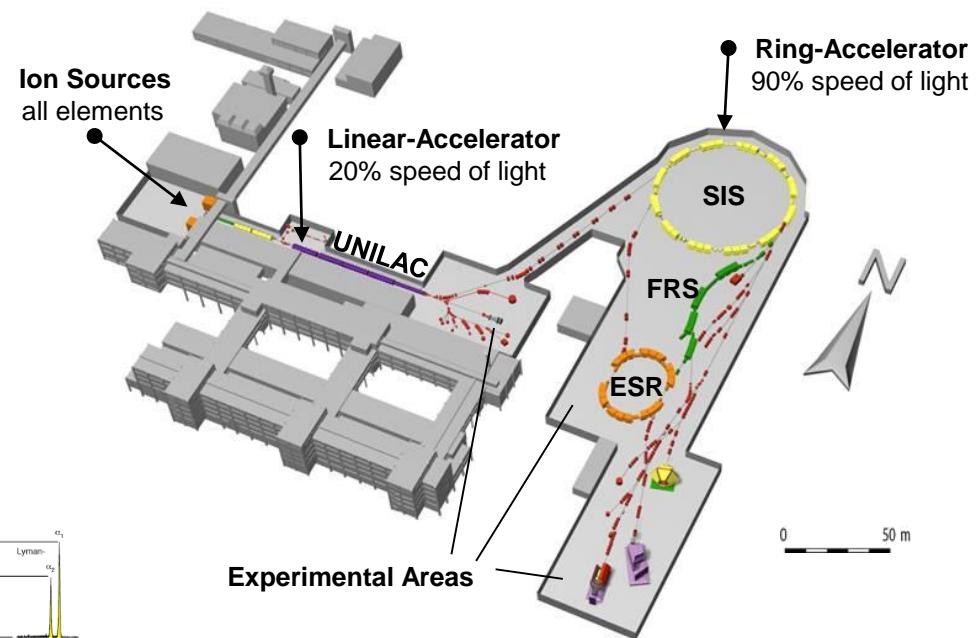
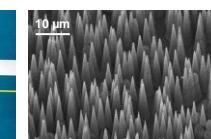
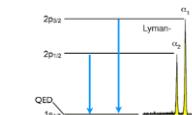
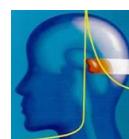
ESRF - Grenoble - France

January 14-15, 2021

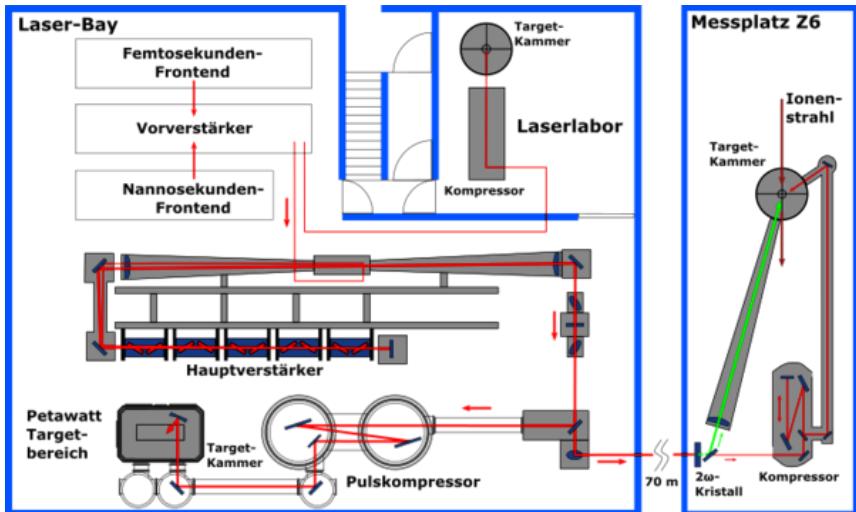


- Nuclear Physics
- Biophysics & radiation medicine
- Atomic Physics
- Materials Research
- Plasma Physics
- Accelerator technology

 ^{110}Ds



PHELIX: A Hybrid Ti:Sa/Nd:glass CPA laser



	Long pulse	Short pulse
Pulse duration	0.7 – 20 ns	0.7- 20 ps
Energy	0.3 – 1 kJ	200 J
Max intensity	10^{16} W/cm^2	10^{21} W/cm^2
Rep rate	1 shot every 90 min	
Contrast	50 dB	120 dB

PHELIX is a user facility

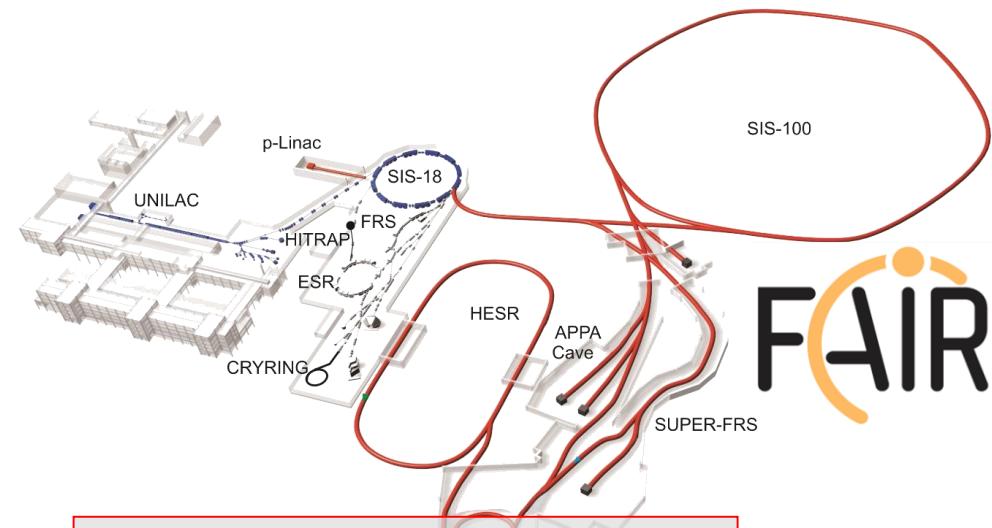
Access through external advisory committee

- 1-2 proposal calls per year
- typ. 10 user experiments (2+1) weeks)
- approx. 500 shots on target per year

Physics topics:

- Ion stopping in hot plasmas
- Shock physics / EOS
- Ion acceleration + injection
- Relativistic laser-matter interaction
- X-ray source generation

Facility for Antiproton & Ion Research



- 100x intensity of primary beams
- 10000x intensity for rare isotopes
- energies from rest up to 35 GeV/u
- antiprotons



4 experiment pillars

- Nuclear Astrophysics
- Compressed Baryonic Matter
- Anti-Proton Research
- Atomic, Material, Radiation Biology, **HED-Plasmas**

CN



DE



ES



FI



FR



GB



GR



IN



IT



PL



RO



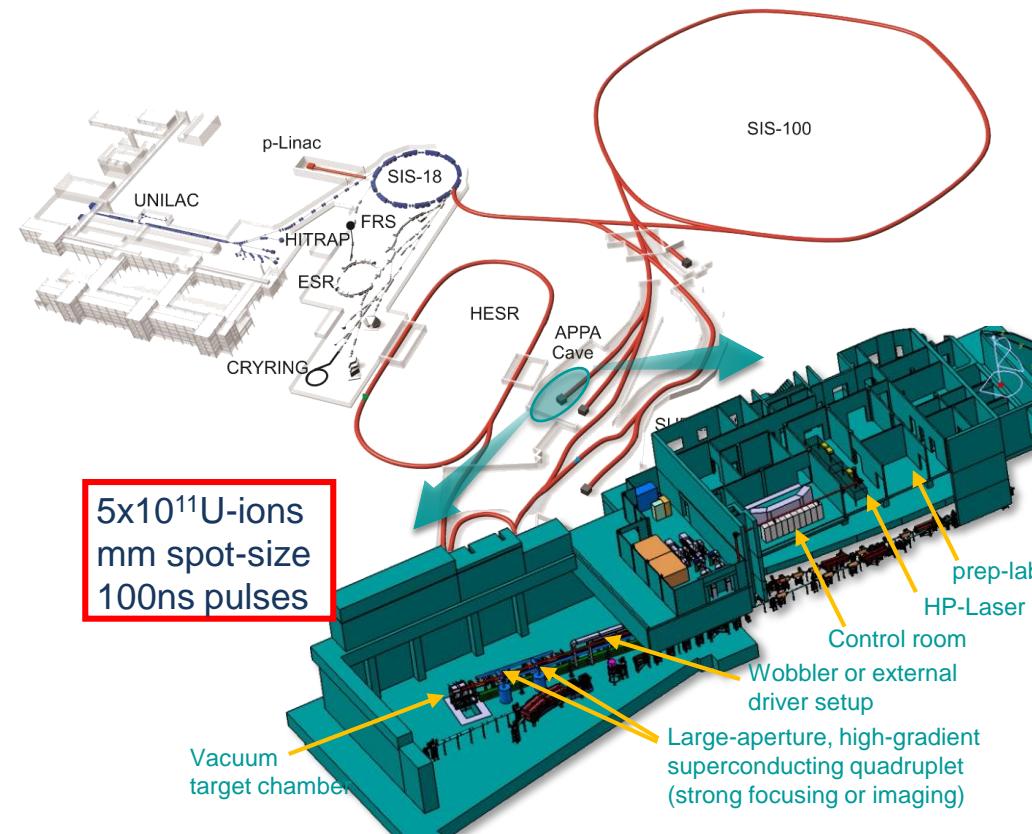
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Extension of the GSI accelerator complex: FAIR (Facility for Antiproton and Ion Research)

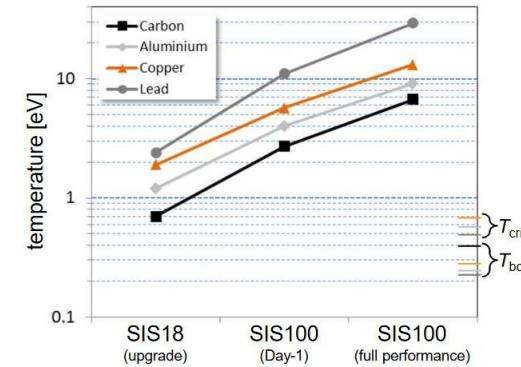


FAIR will offer exciting new possibilities for research in high-energy density matter science

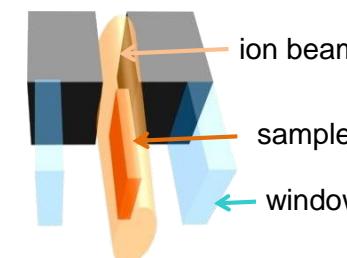


Ion beam driven plasmas:

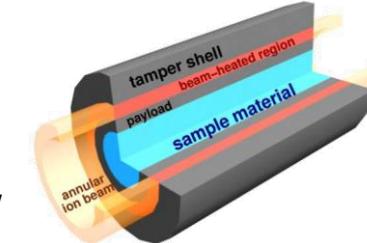
- large mm-size samples
- homogenous energy deposition
- equilibrium conditions



Heating + expansion



Isentropic compression



The HED@FAIR collaboration

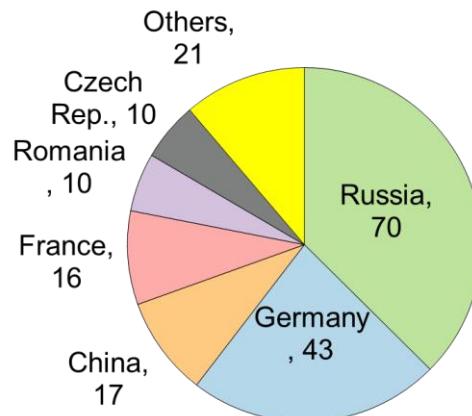


HED@FAIR

Spokesperson	Alexander Golubev (ITEP)
Deputy Spokesperson	Kurt Schoenberg (LANL)
Chair Collaboration Board	Vincent Bagnoud (GSI)
Technical Coordinator	Abel Blazevic (GSI)
Resource Coordinator	Stephan Neff (FAIR)



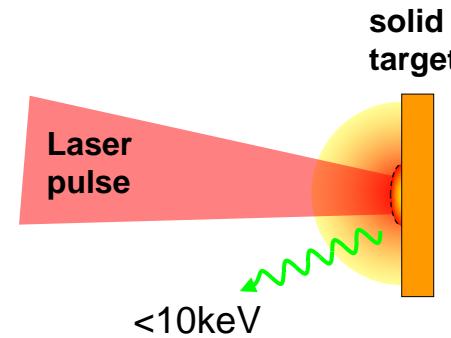
187 members from 12 countries
(Russia, Germany, China, France,
Romania, Czech Republic, USA,
S. Korea, Spain, Norway, Israel, UK)



Intense x-ray sources based on laser-produced hot plasmas

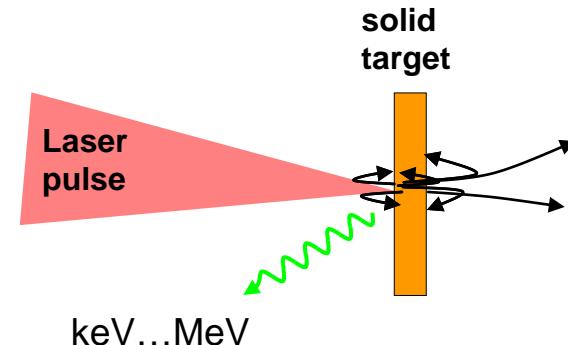
Long (ns) laser pulses at $\sim 10^{14}\dots 10^{16} \text{W/cm}^2$

- Hot (keV) expanding plasma
- Line + continuum emission from highly-charged ions
- $E_{\text{photon}} < 10 \text{keV}$
- Duration \sim nanosecond



Short (ps) intense laser pulses ($> 10^{17} \text{W/cm}^2$)

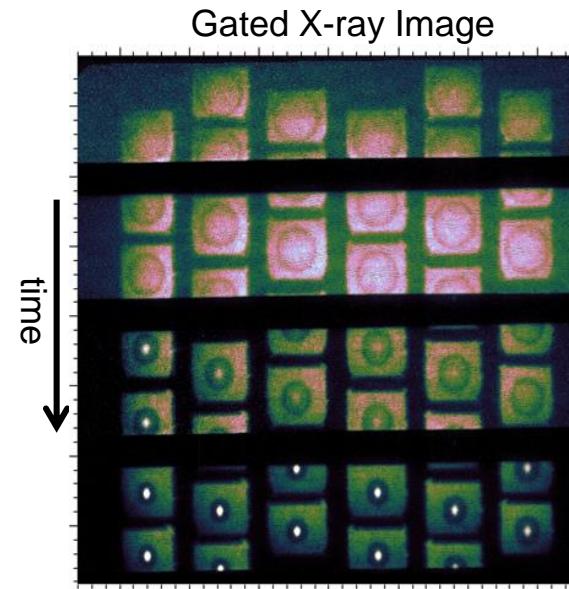
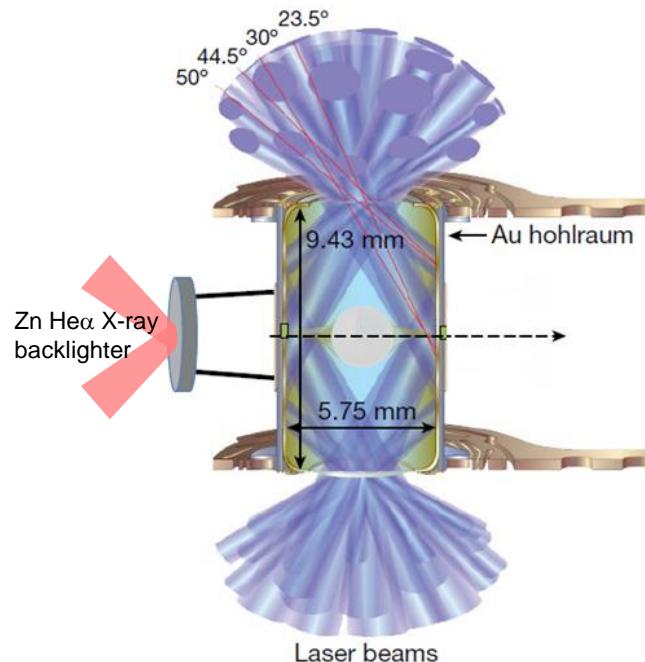
- „hot“ (MeV) electrons
- K-shell + bremsstrahlung
- $E_{\text{photon}} \sim \text{keV\dots MeV}$
- Duration $\sim 10 \text{ picoseconds}$
- Emission confined to initial target dimensions
- small source sizes ($10 \mu\text{m}$ demonstrated)



X-ray radiography is a crucial diagnostic at NIF



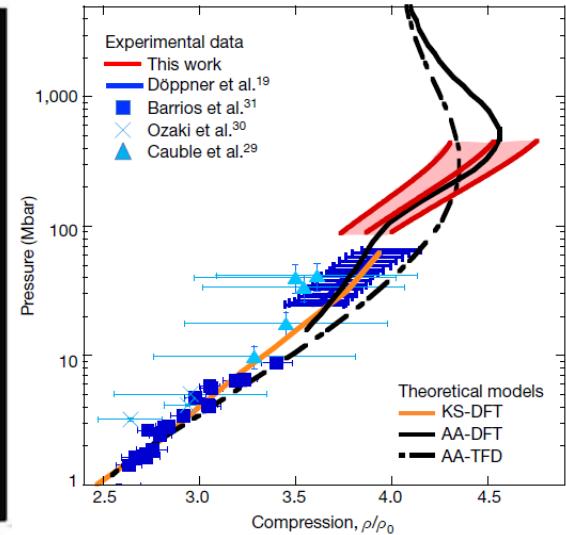
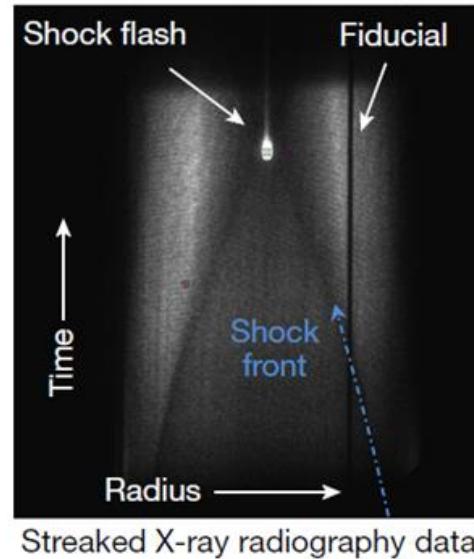
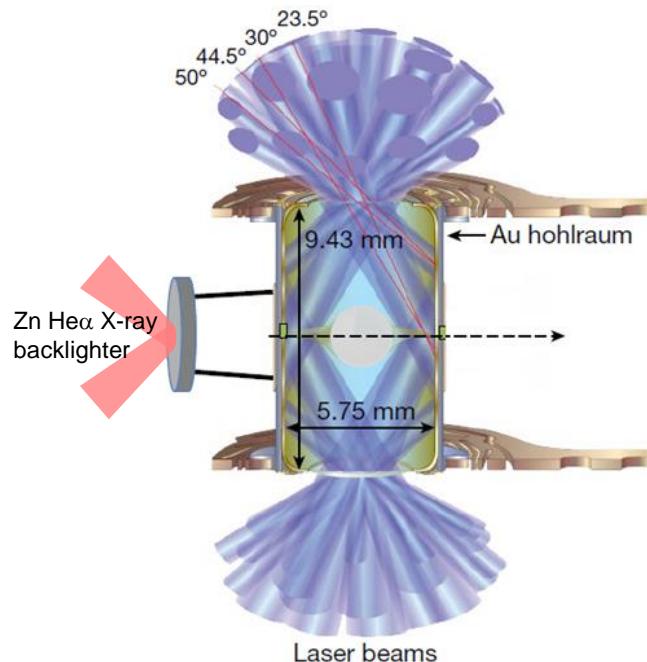
ICF campaign: symmetry, implosion velocity, remaining mass



X-ray radiography is a crucial diagnostic at NIF



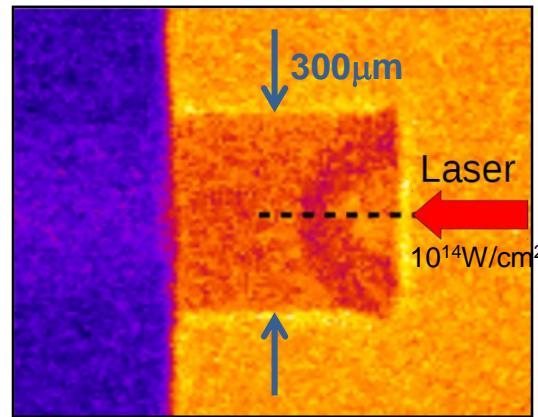
Fundamental science program: EOS at extreme pressures



T. Döppner et al., PRL **121**, 025001 (2018)
A. L. Kritcher et al., Nature **584**, 51 (2020)

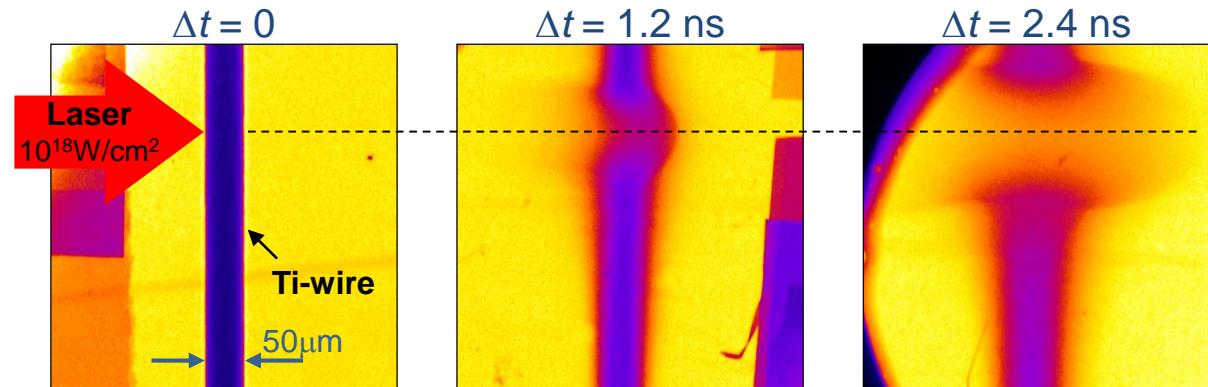
Some examples of high-resolution x-ray radiography

Spherical shock propagation
in polystyrol-cylinder



L. Antonelli et al., EPL 125, 3 (2019)

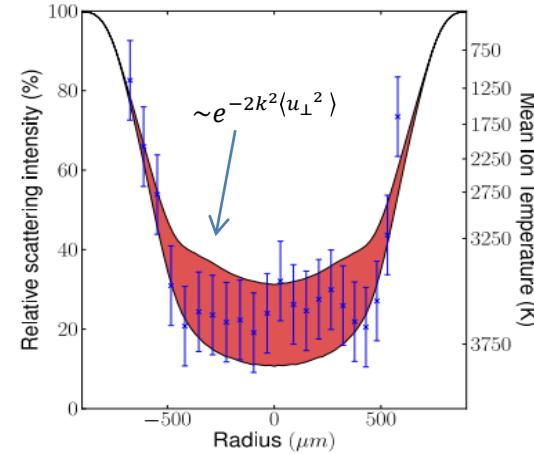
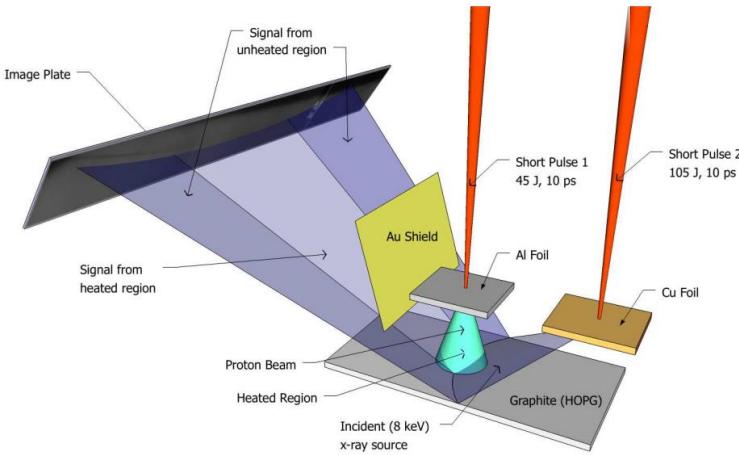
Hydro-evolution of
„isochorically heated“ wires



X-ray diffraction from proton heated carbon

Experiment at the Titan laser

- Ultra-fast heating of graphite by laser-generated protons
- Diffraction of Cu-K α photons (8keV)



- Reduction of diffraction due to heating of ion lattice
- Comparison to deposited energy suggests strongly inhibited electron-phonon coupling

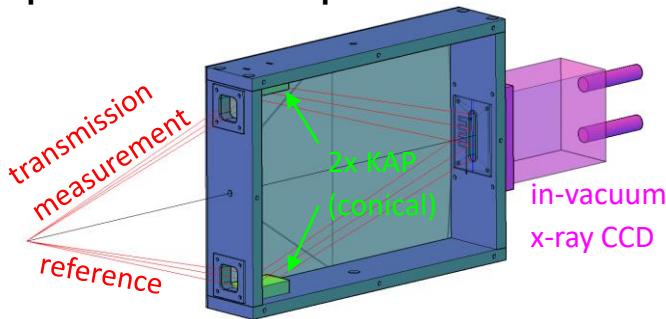
T. White, et al.,
Sci. Rep. **2**, 889 (2012)



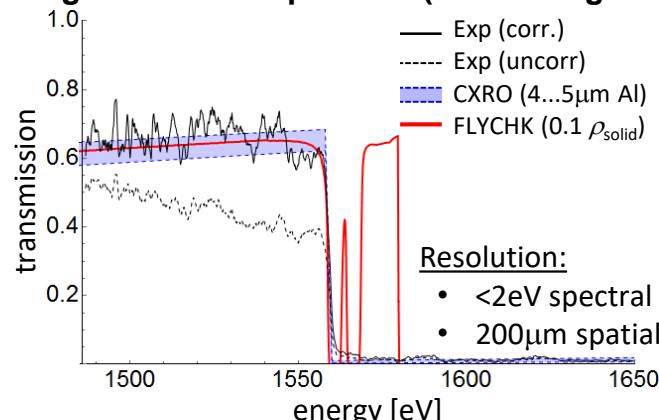
Development of XANES for HI heated samples



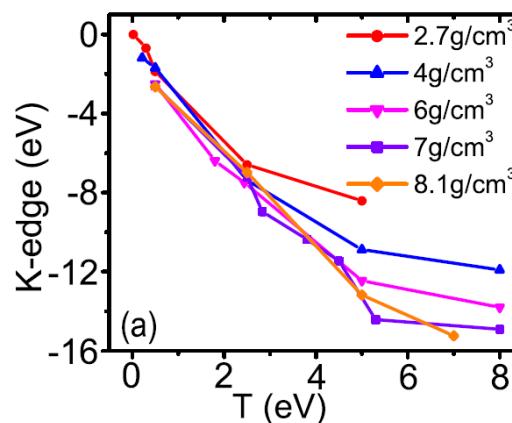
Spectrometer development at GSI/Jena



Single-shot XAS spectrum (Sm-backlighter)



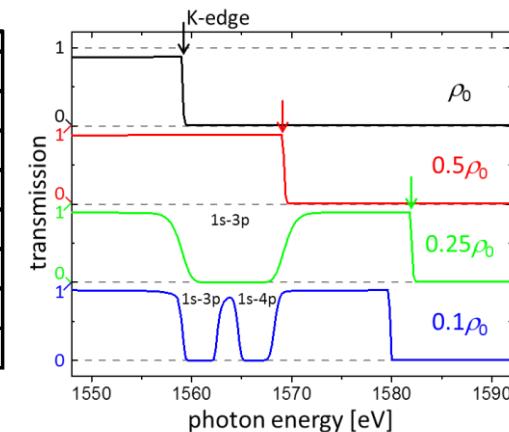
K-edge shift vs. temperature



→ Exploit as temperature diagnostic?

(S. Zhang et al.,
PRB 93, 115114 (2016))

Continuum lowering in strongly-coupled Al-plasma

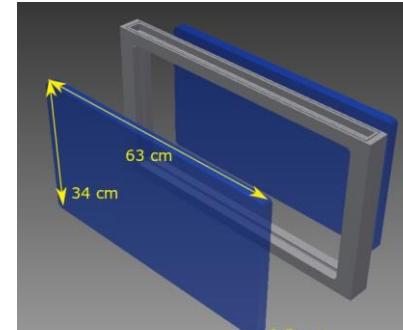


- K-edge shift
- M-shell rebinding (metal-to-insulator transition)

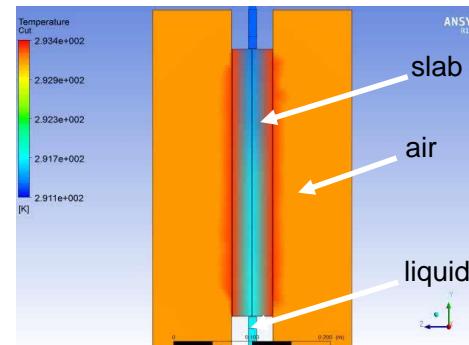
(FLYCHK w/ S&P-IPD)

Progress on active amplifier cooling

- Goal: develop a liquid-cooled slab module for PHELIX-type lasers (30 cm aperture)
- Simulations show that a complete cooling cycle (no thermal loading) is possible with a simple geometry within a few minutes
 - 3-D simulations performed with CADFEM ANSYS: FEM with heat transport and fluid dynamics
 - Further analysis of the distorted optical wavefront
 - 2 x 2.5 cm slabs
 - minimized volume of liquid
 - temperature cycle within minutes (4-6)
 - temperature homogeneity < 0.1K over the whole 60 x 30 cm² slab.



split-slab design



Temperature map with ANSYS simulation

Progress on active amplifier cooling

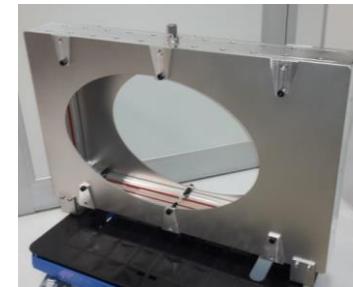
- Current design decision

- work with index matched fluids: $n = 1.51$
- temperature cycle of cooling liquid (cooling with colder liquid for 1 to 2 min.)
- cooling liquid flow stopped during the shot

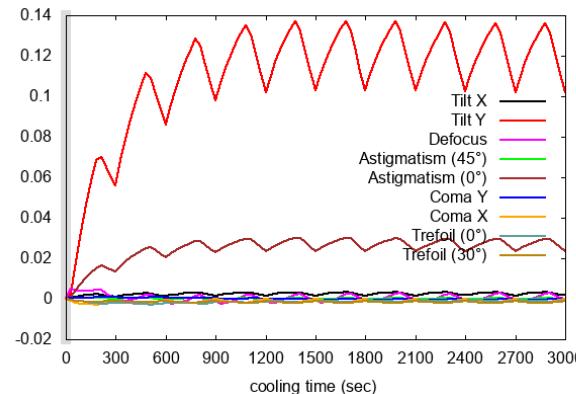
laser glass at SIOM



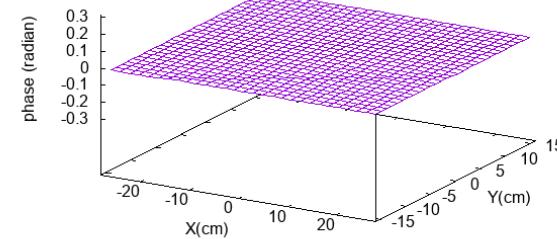
laser glass module



aberrations vs. time



wavefront distortion

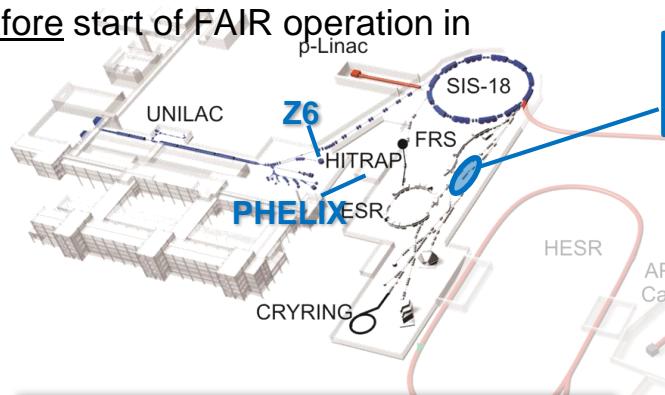


Facilities for Plasma Physics Experiments at GSI



FAIR „Phase-0“:

Research activities related to or relevant for FAIR, before start of FAIR operation in 2025.

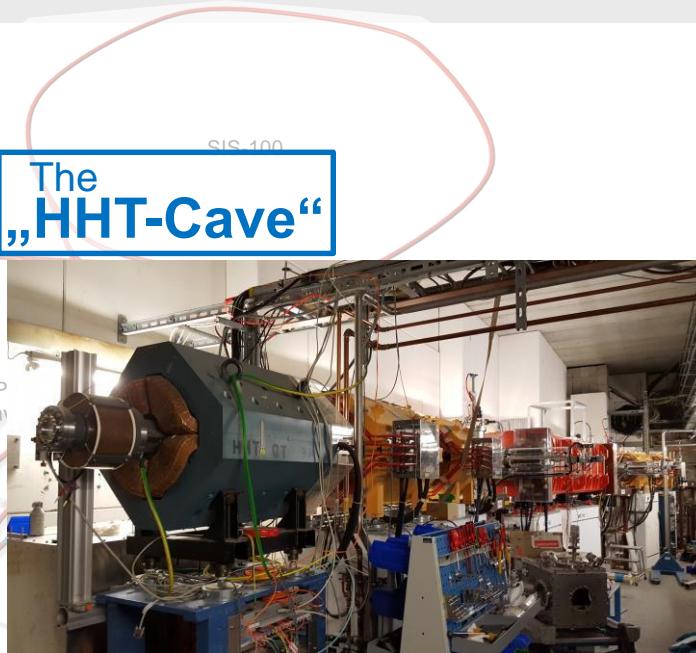


Stage Ia: SIS-18 beams @ HHT-cave

- conditions: civil construction is finished, the "bypass" beam line from SIS-18, the HHT-cave and HHT-beam line including the FFS are ready
- may be expected in 2019 – 2021

Ion	Max. energy, AGeV	Max. intensity, per pulse	Focal spot size, (1/e) mm	Pulse duration, ns	Comments
1 U28+	0.2	3e10	1.3	100	
2 U39+	0.35	3e10	1.2	100	exclusive mode with a stripper foil in the UNILAC
3 U73+	1.0	3 – 5e9	0.9	100	intensity can be up to 5e9 if not cooled in SIS-100 beam line; may also be used with other ions

>10kJ/g in Al



New capabilities enabled by high-energy laser pulses at the HHT-cave



200J/ns laser pulses, focused to 10^{12} - 10^{15} W/cm² can drive:

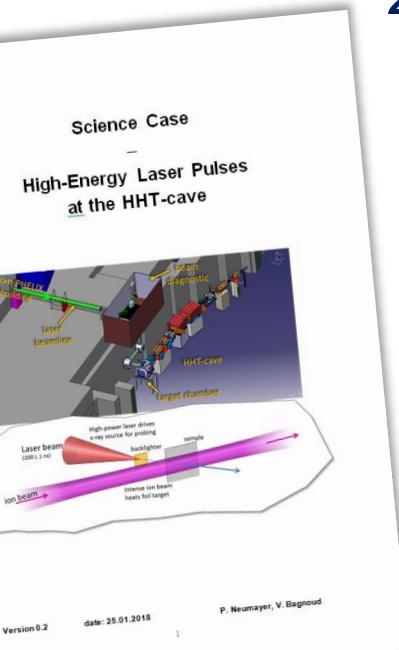
- Intense He- α line-radiation sources (<10keV) from mid-Z plasmas, few keV quasi-continuous radiation from high-Z plasmas
⇒ **Diagnostic capabilities enabled by laser-driven x-rays:**
 - Radiography
 - low-Z targets: (isentropic) expansion/compression, ablation/fracture/spallation/explosion
 - high-Z targets: expansion into low-Z tamper
 - X-ray diffraction
 - lattice constant + strength, structural phase transitions (e.g. diamond-graphite), melting
 - X-ray scattering
 - liquid structure (ion-ion distance, coupling strength, ion temperature, compressibility)
 - Absorption spectroscopy
 - XANES (electron temperature), VUV-opacity (e.g. Bi, Pb), continuum lowering
- few Mbar shocks into solids
 - Shock-induced ablation/spallation
 - Laser-accelerated flyer plates



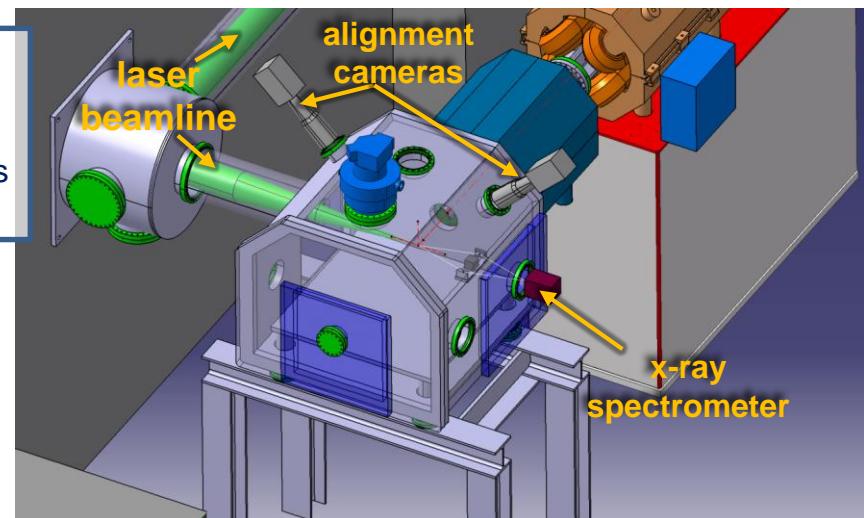
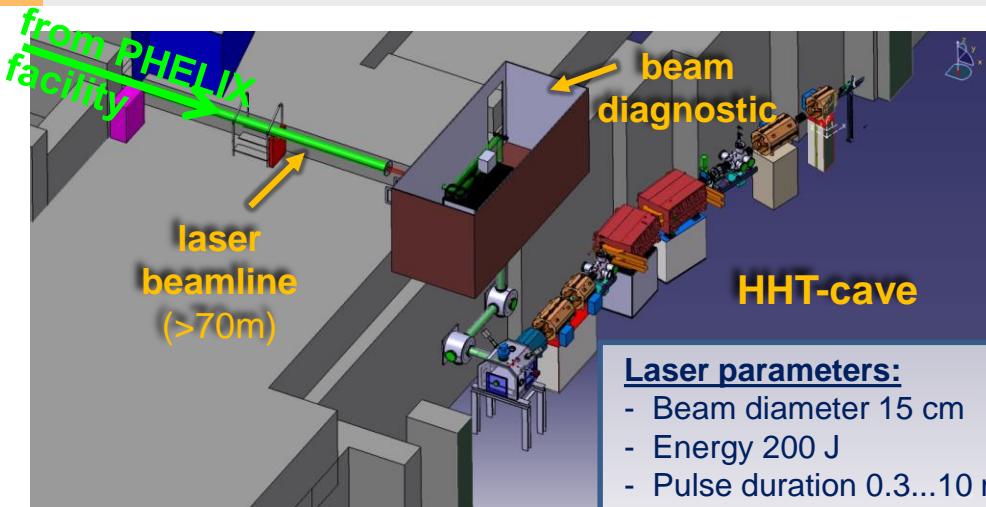
→ Proton microscopy with **PRIOR**

International panel discussion (HED@FAIR2017 workshop):

The unique combination of the intense heavy ion beams at HHT with a high-energy laser pulse significantly enhances the experimental possibilities and has a large scientific discovery potential



Laser transport beamline to HHT is nearing completion



- Commissioning (beamline + new target chamber) until June 2021
- First user-experiments in March 2022

- Intense pulses of heavy ions at GSI (and later FAIR) will enable volumetric heating to eV temperatures → alternative route to generate WDM
- X-ray probing (XRI, XRD, XANES, XRTS) based on laser-driven x-ray sources will be available
- First combined experiments will take place in early 2022

Thanks for your attention!