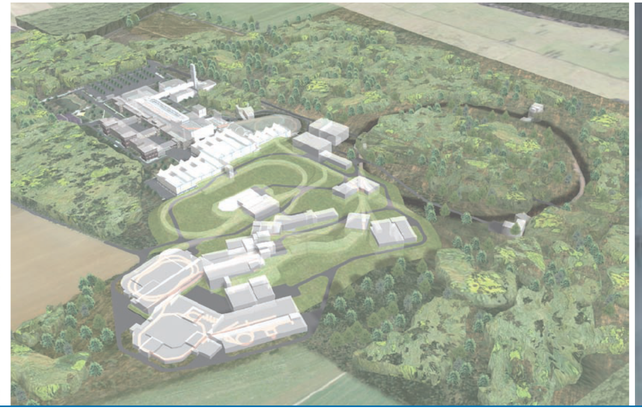
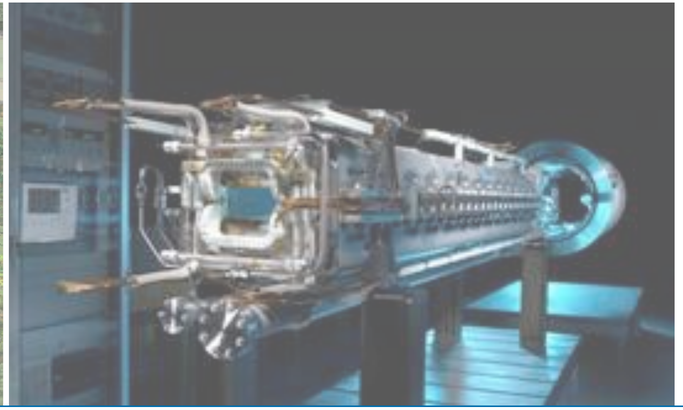




HEDP Infrastructure at the APPA cave

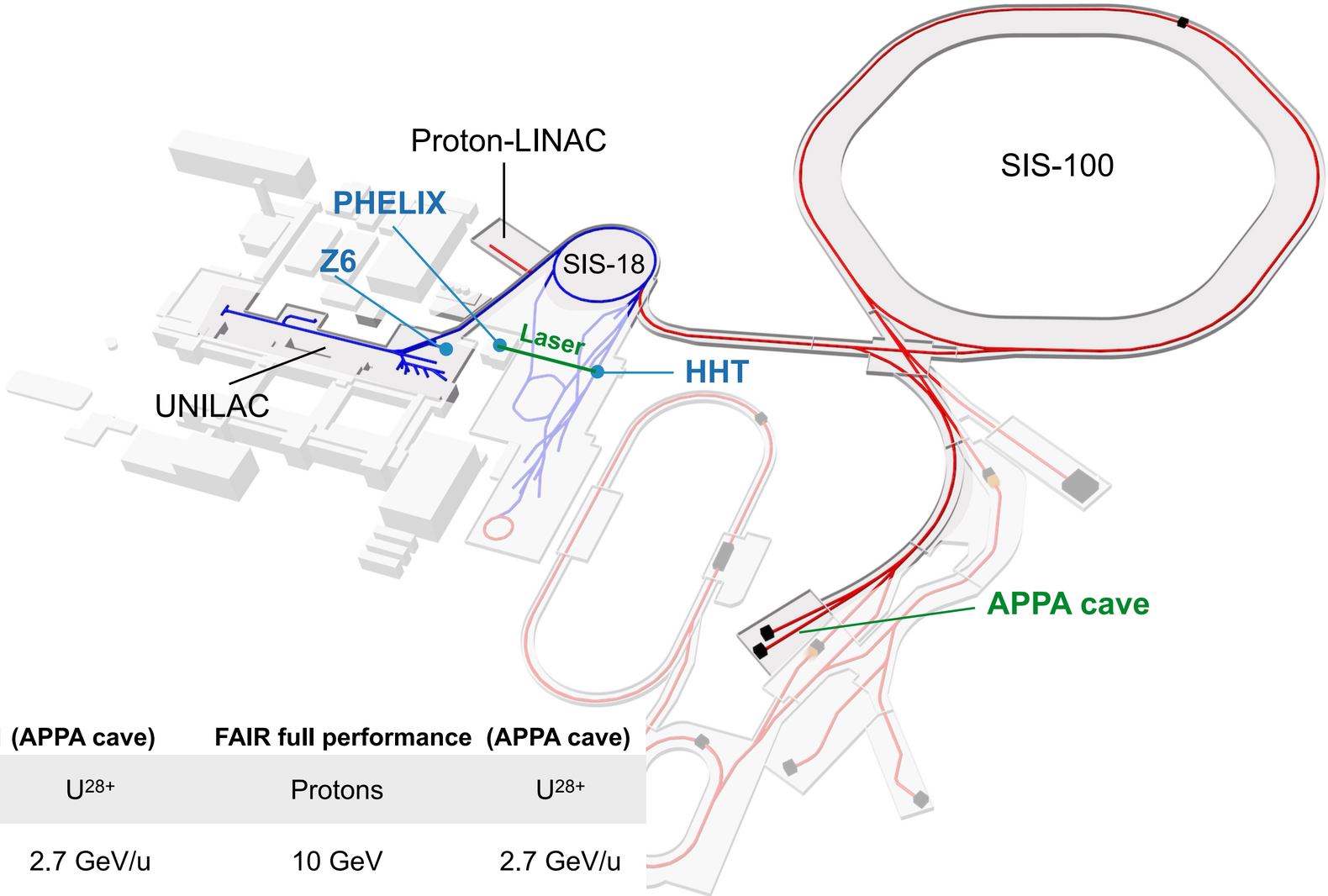
Workshop on High Energy Density Physics Opportunities at FAIR
Madrid, November 18, 2022

Stephan Neff
Facility for Antiproton and Ion Research

FAIR will offer much higher beam intensities than are available at GSI

Phase 0: Experiments using existing GSI accelerators in preparation for FAIR, e.g. for detector commissioning
PHELIX: High energy laser for coupled or standalone experiments
Z6: UNILAC beam and PHELIX long-pulse
HHT: High energy protons and ions from SIS-18 and PHELIX long-pulse

Day-1: First experiments using the new FAIR accelerators, with reduced beam parameters at the beginning
APPA cave: High energy beams from SIS-100, FLAX diagnostic laser



	GSI (HHT)		FAIR Day-1 (APPA cave)		FAIR full performance (APPA cave)	
	Protons	U^{73+}	Protons	U^{28+}	Protons	U^{28+}
Max. Energy	4.7 GeV	400 MeV/u	4.7 GeV	2.7 GeV/u	10 GeV	2.7 GeV/u
Particles/Bunch	$7 \cdot 10^{10}$	$4 \cdot 10^{9}$	$1 \cdot 10^{11}$	$1 \cdot 10^{11}$	$2.5 \cdot 10^{13}$	$5 \cdot 10^{11}$

The APPA cave will house the experimental setup for HED@FAIR

FAIR South Area Construction Site, October 2022

optional connection to short-pulse laser

Klystrons & Cryogenics

Laser laboratory

Control room

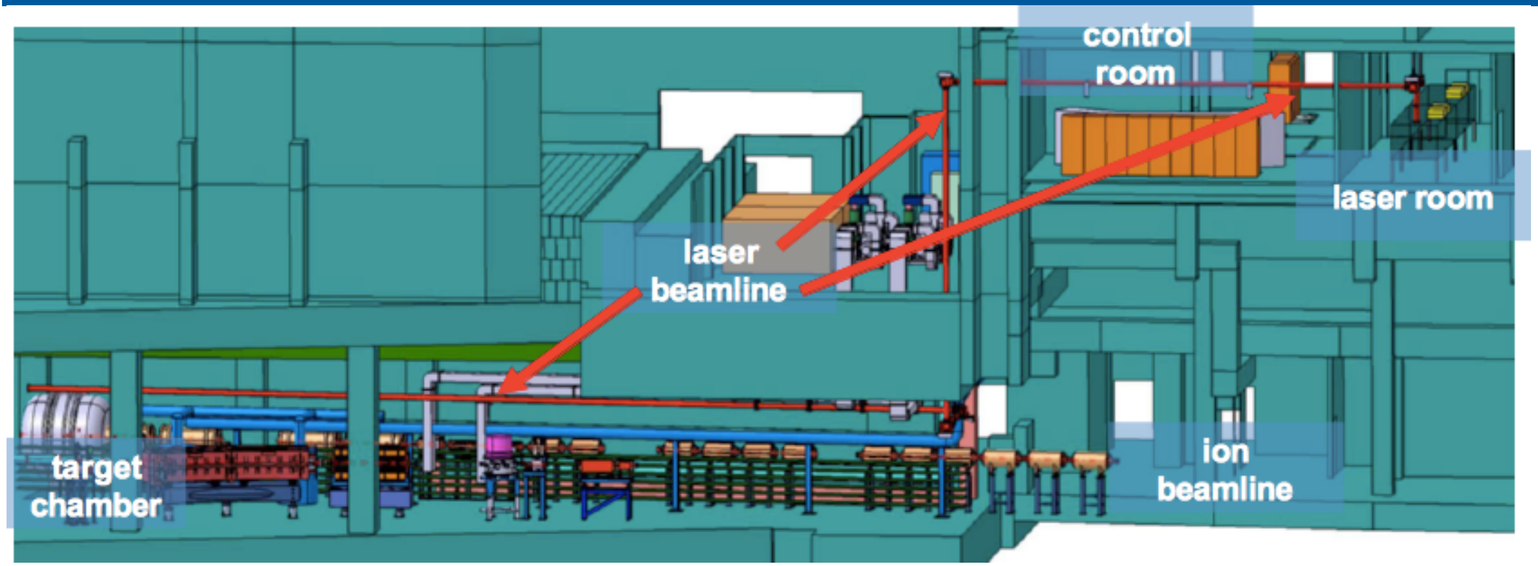
Plasma physics

BioMat

Atomic physics

The civil construction of the APPA cave is progressing as planned.

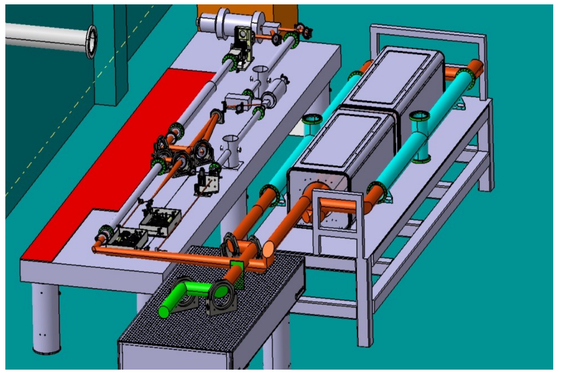
FLAX: First Laser for APPA eXperiments



Flash lamp module prototype, TU Darmstadt

Energy	Repetition rate	Pulse length	Pulse shaping	Wavelength
100 J	up to 1 shot/minute	0.1 - 20 ns	Yes	532 nm

- FLAX under construction by PHELIX laser team (GSI)
- Supported by German university projects (BMBF VBF):
  Laser frontend (U Jena)
  Prototype main amplifier (TU Darmstadt)
- Option to later on install a short-pulse laser (Helmholtz Beamlines) if funding becomes available.

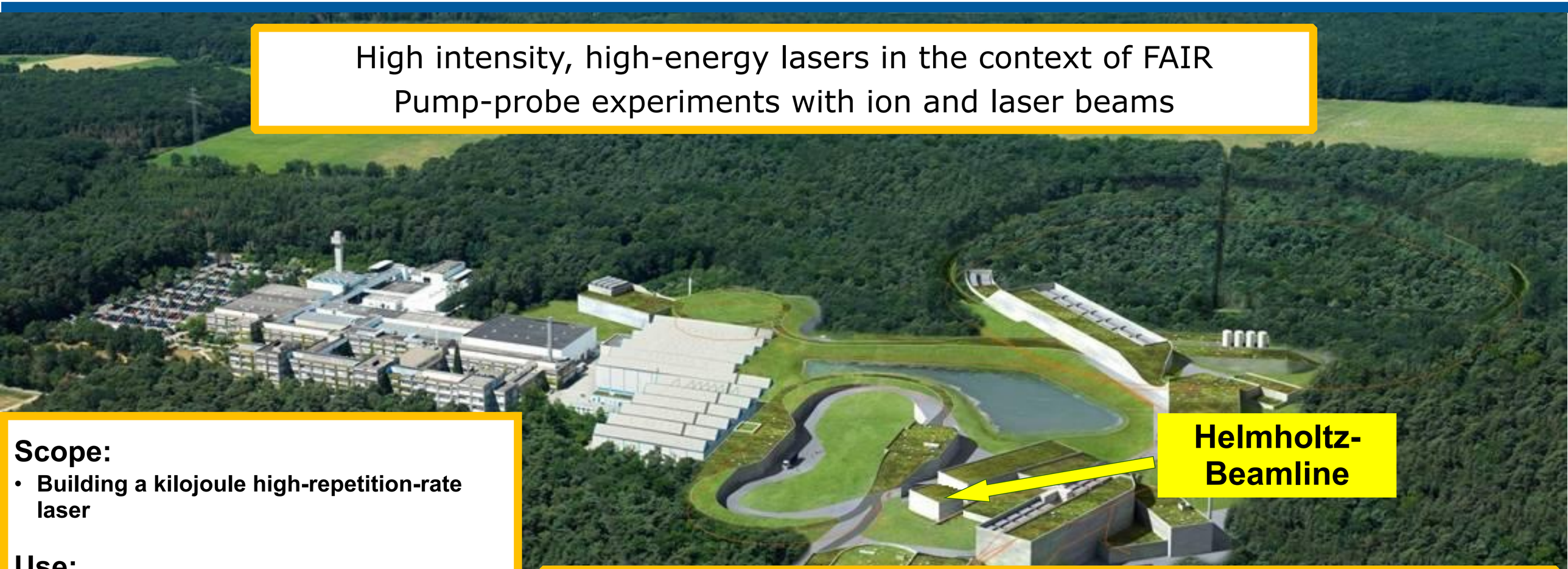


Laser frontend, U Jena

Amplifier prototype, TU Darmstadt

The Helmholtz Beamline project would provide a high-intensity short-pulse laser

High intensity, high-energy lasers in the context of FAIR
Pump-probe experiments with ion and laser beams



Scope:

- **Building a kilojoule high-repetition-rate laser**

Use:

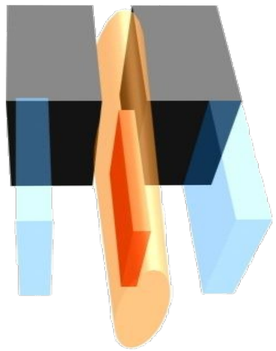
- **Advanced diagnostics for HED targets at the APPA cave (backlighting with X-rays, ions, neutrons, electrons)**
- **Relativistic laser-ion interactions for atomic physics experiments**

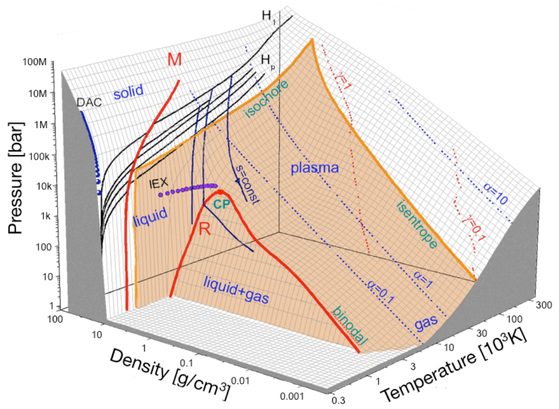
Initiative of the Helmholtz Center HZDR in close collaboration with HI-Jena.
Already part of the Helmholtz roadmap for new research infrastructures.

Design study to be carried out as part of European THRILL project.

Three main experimental schemes will be used: HIHEX, PRIOR & LAPLAS

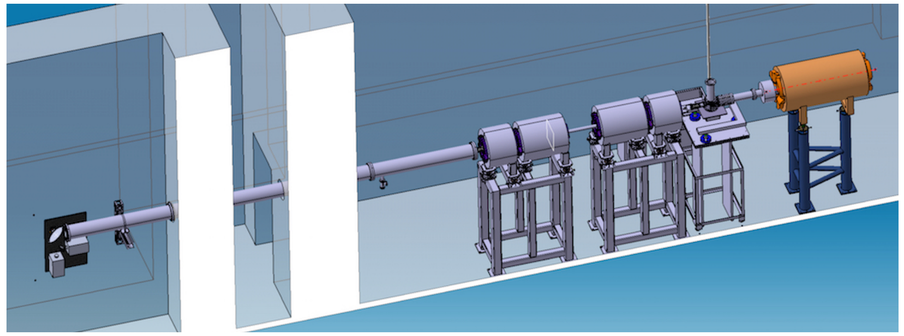
HIHEX
Heavy Ion Heating and Expansion

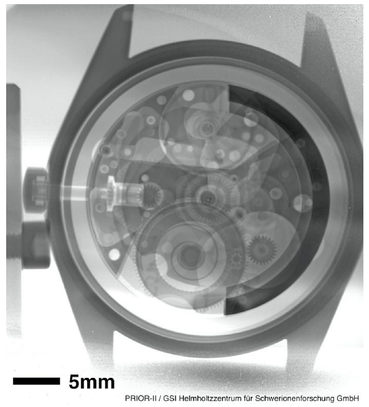




Create mm-sized samples
of warm dense matter

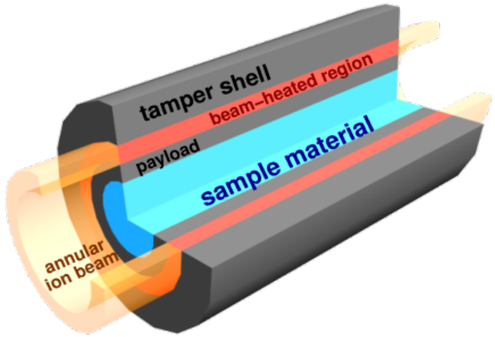
PRIOR
Proton Microscopy

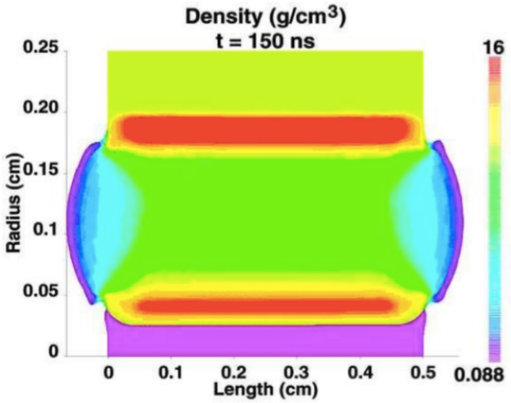




Use protons for precise
density measurements

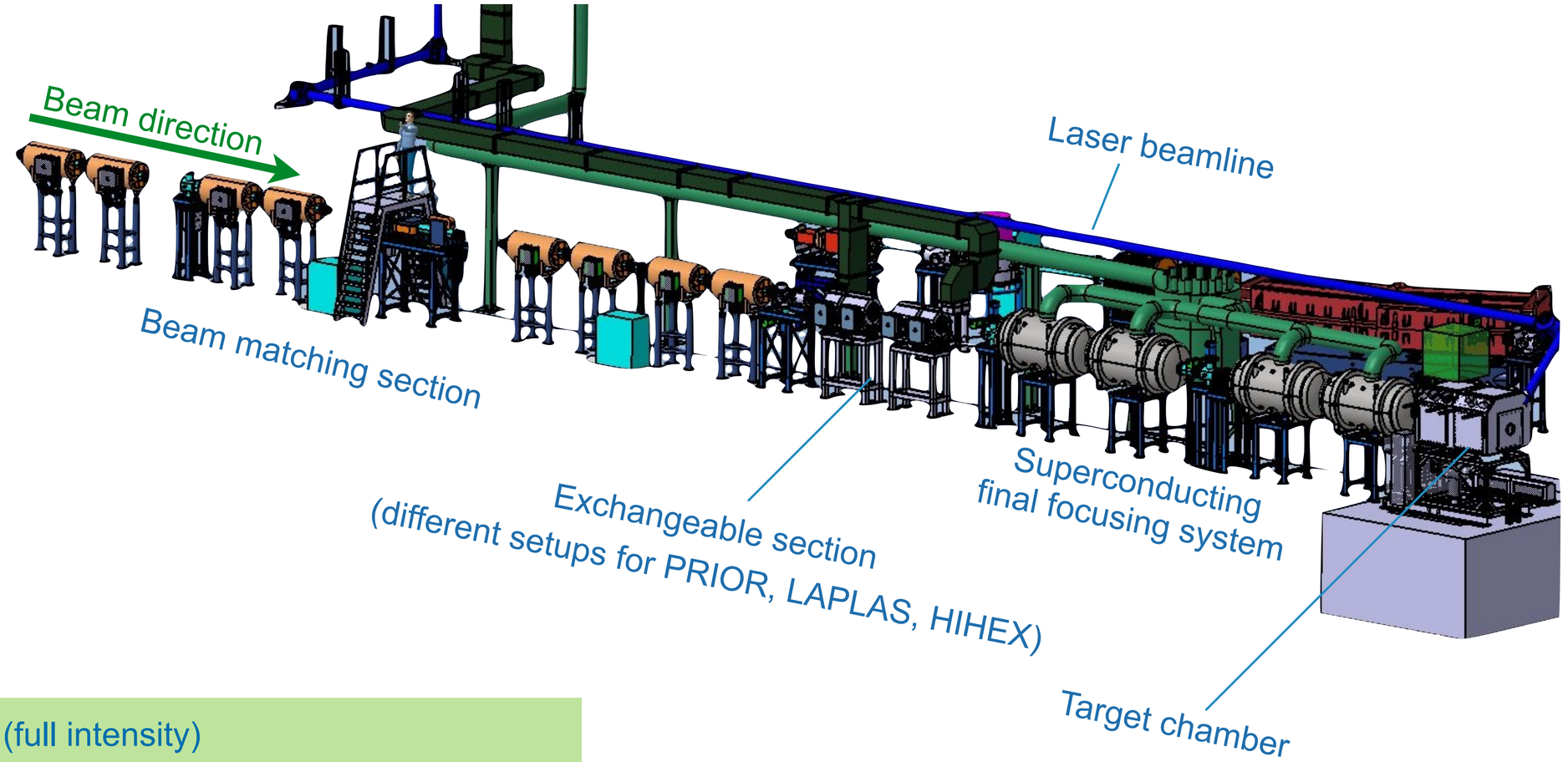
LAPLAS
Laboratory Planetary Science





Compress mm-sized samples
to Mbar pressures

The modular design of the HED@FAIR beamline accommodates all experimental setups

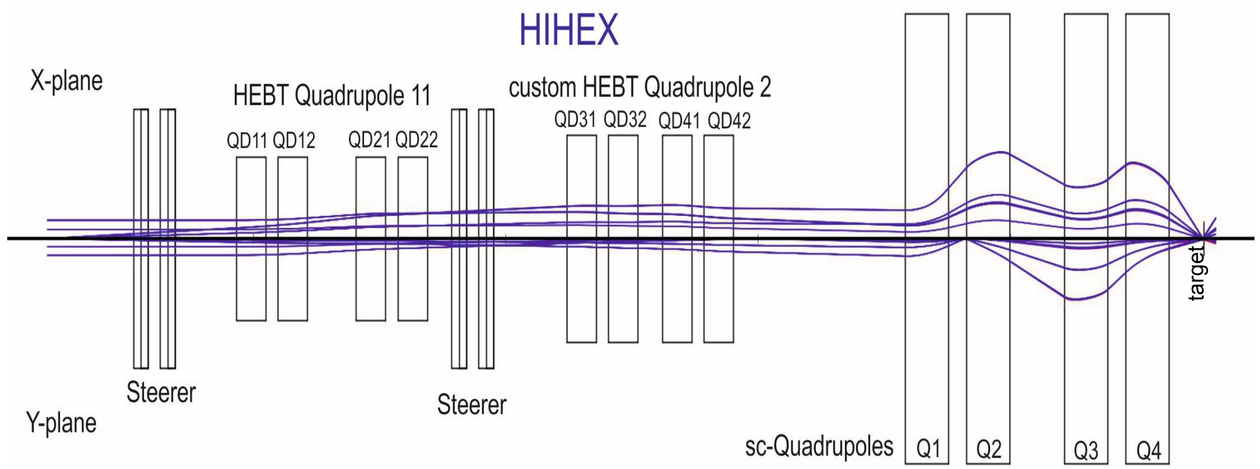


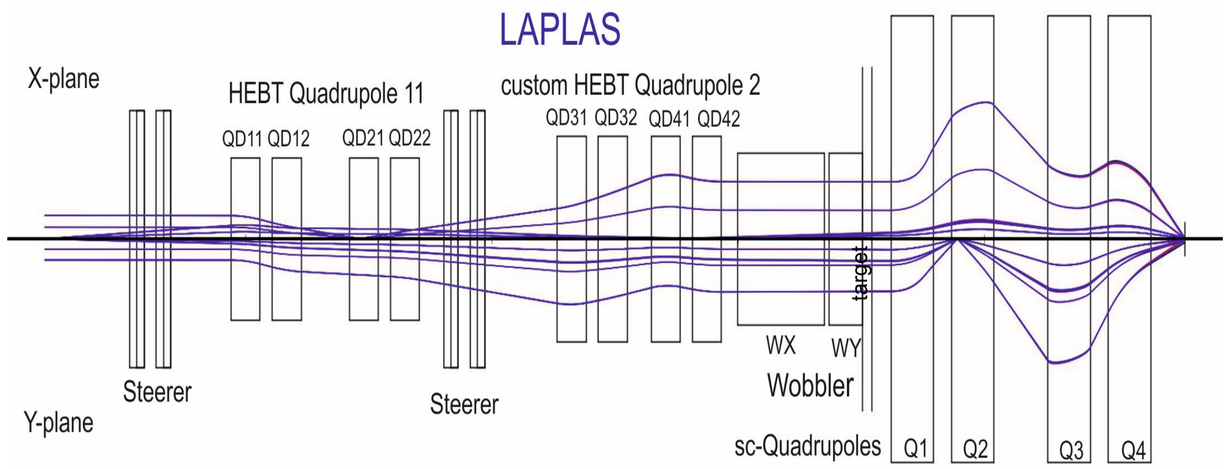
Maximum shot rate for heavy ions (full intensity)

Every 3 minutes for thin targets / every 15 minutes for massive targets

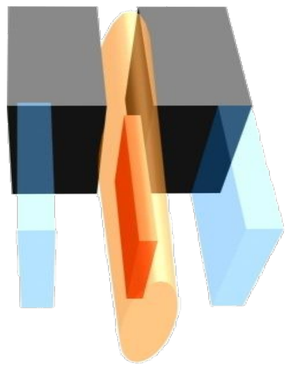
Limited by radiation safety constraints and target debris

Beam line setups used for HIHEX and LAPLAS





HIHEX setup

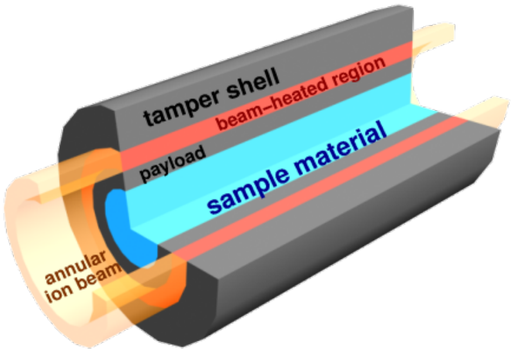


focused beam
on target

Beam parameters on target for HIHEX and LAPLAS

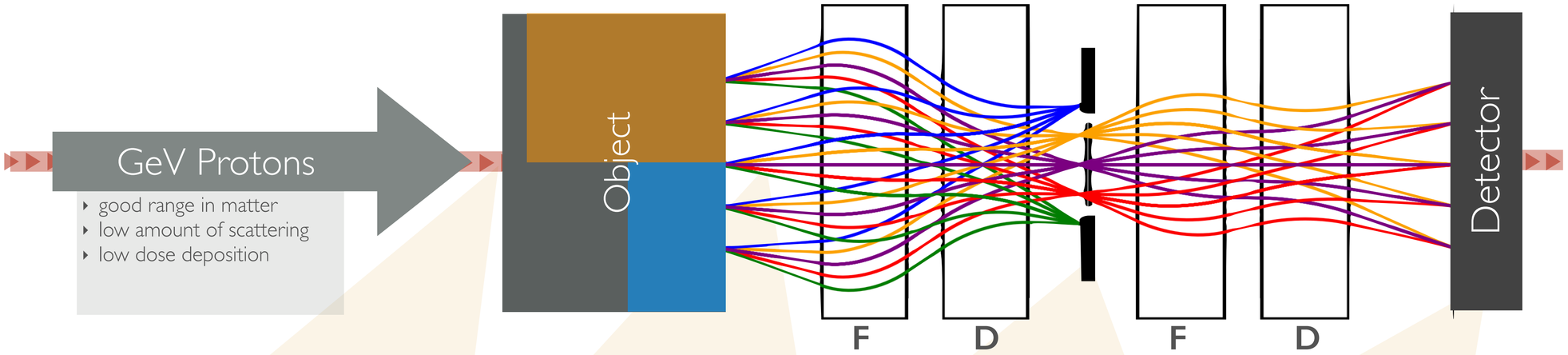
Beam ion (reference)	U^{28+}
Energy	0.4 - 2.7 GeV/u
Ions / bunch	up to $5 \cdot 10^{11}$
Focal spot size	1 mm
Duration	50 ns
Beam power	160 GW - 1 TW
Beam energy	8 - 50 kJ

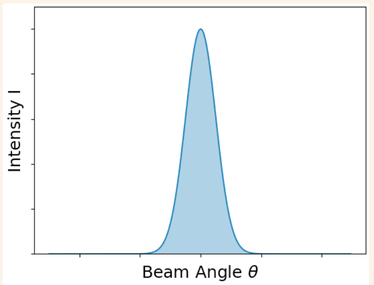
LAPLAS target



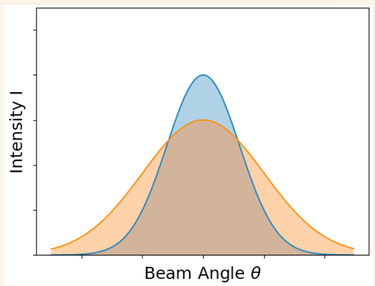
beam spot is rotated
to create annular profile

The *Proton Microscopy at FAIR* (PRIOR) setup will be used to image dense samples generated with secondary drivers

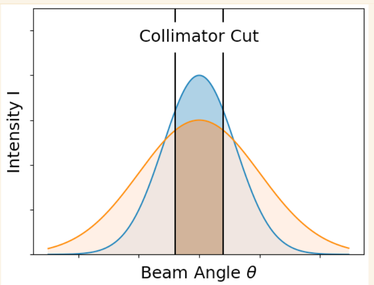




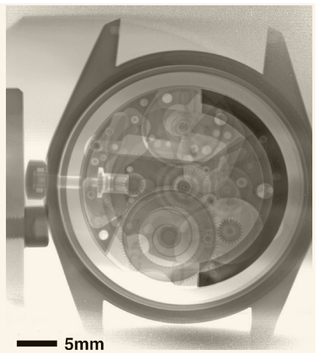
incident beam



after object



after collimator



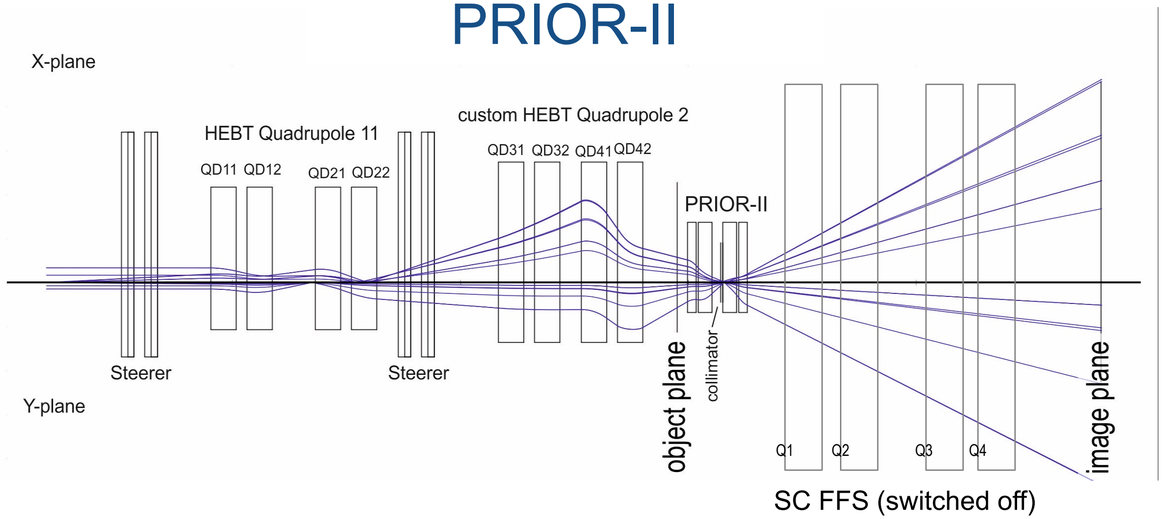
transmission (intensity) provides information about the object density

D.Varentsov et al., *Review of Scientific Instruments* **87/2**, 023303 (2016)

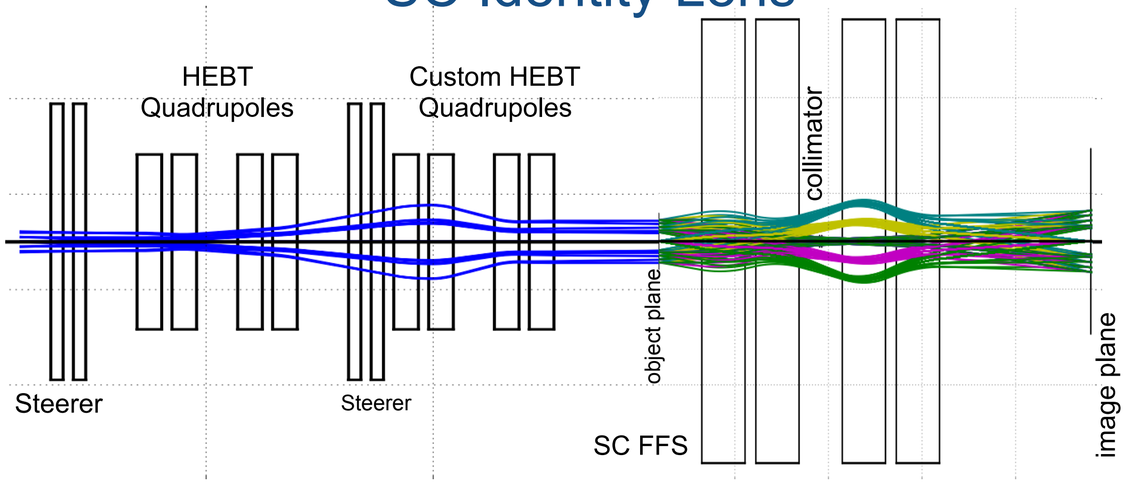
By courtesy of M. Schanz

It is also possible to use the superconducting magnets for 1:1 imaging

PRIOR-II



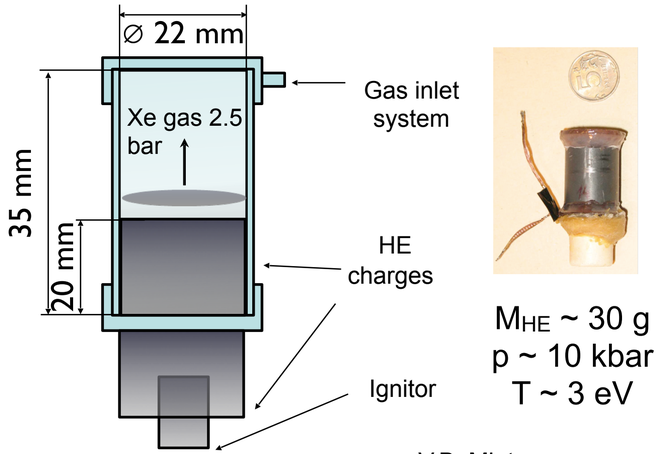
SC Identity Lens



Design parameters	PRIOR-II @ FAIR		SC Identity Lens
Reference energy (MeV)	5000		5000
Protons/bunch (maximum)	2.5×10^{13}		2.5×10^{13}
Magnification	8.03		1.00
Collimator acceptance (mrad)	2.0	5.0	5.0
Field of view, $FOV_x \times FOV_y$ (mm)	30 × 52	29 × 48	82 × 82
Chromatics RMS resolution $Cr_x \times Cr_y$ (μm)	1.8 × 3.4	4.5 × 8.5	23.6 × 23.6
Off-axis RMS resolution $Or_x \times Or_y$ (μm)	2.0 × 3.9	5.1 × 9.7	63.0 × 63.0

A wide variety of external drivers can be used for the proton radiography of shocks and other phenomena

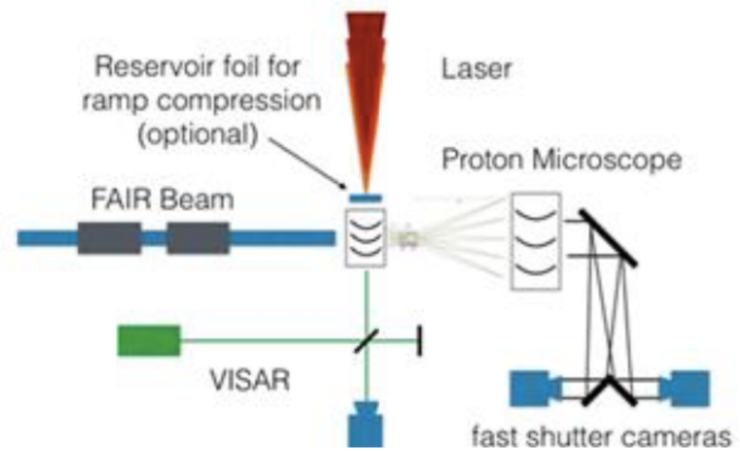
Explosively driven shocks



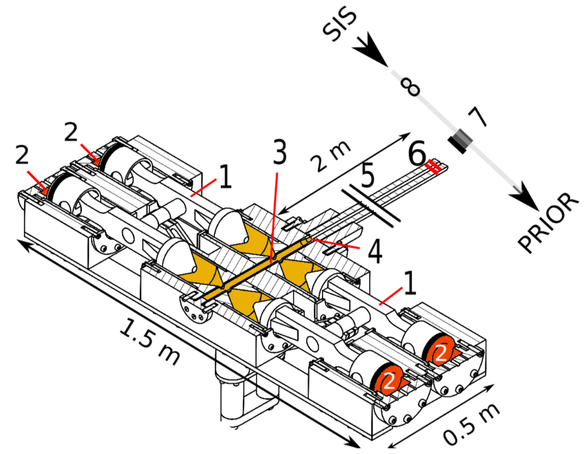
M_{HE} ~ 30 g
p ~ 10 kbar
T ~ 3 eV

V.B. Mintsev,
IPCP Chernogolovka

Laser driven shocks

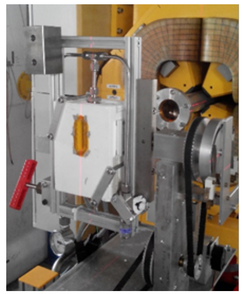


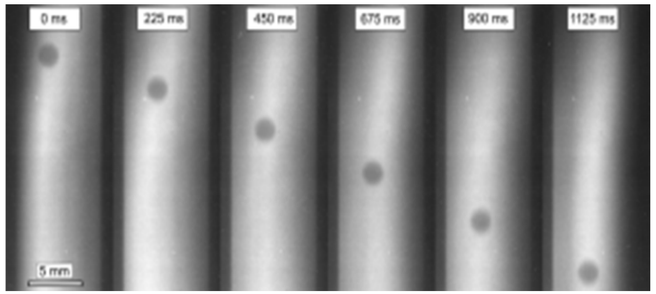
Shocks driven with a light gas gun



M. Endres, TU Darmstadt

Viscosity measurements with falling spheres in high-pressure liquids

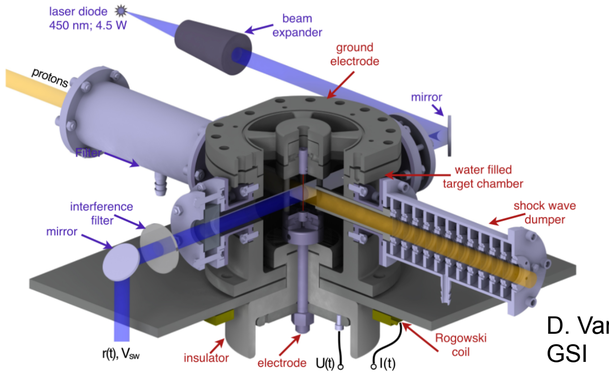




2-mm-diameter ball falling inside a thick Ti high-pressure vessel filled with liquid sulfur

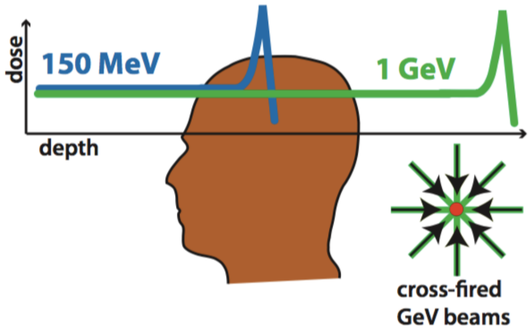
B. Winkler,
GU Frankfurt

Exploding wire setup for EOS measurements



D. Varentsov,
GSI

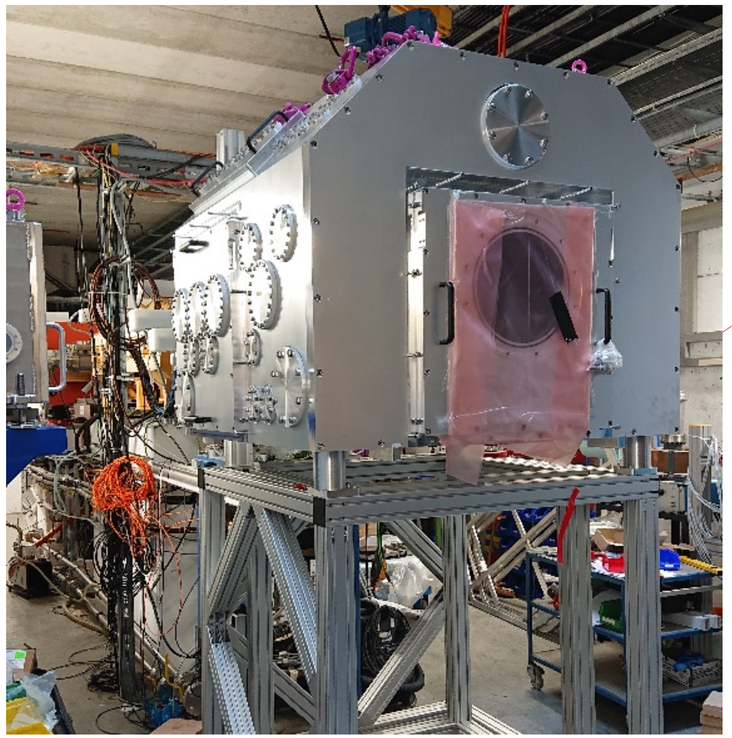
Proton imaging and therapy



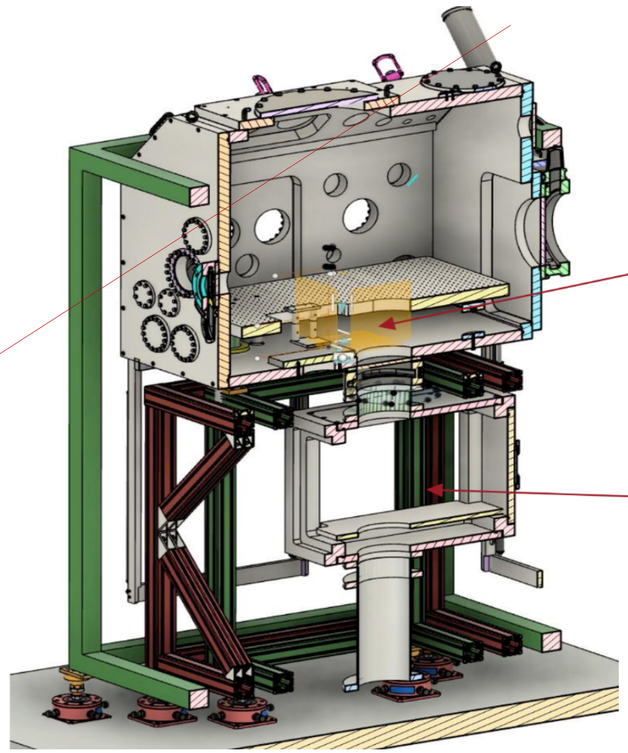
R&D project in collaboration with the GSI biophysics department

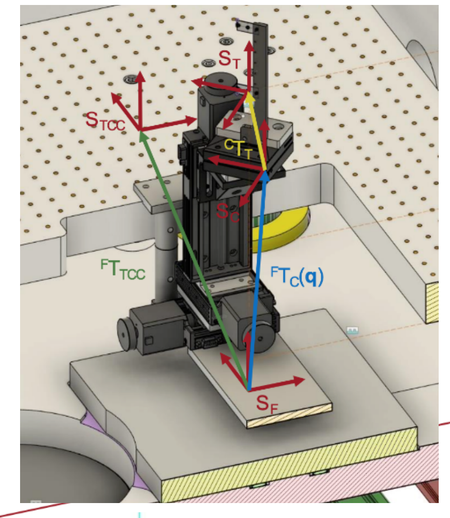
The target chamber for HIHEX and LAPLAS experiments has been commissioned and the target supply system is under development at the TU Darmstadt

- First target chamber successfully commissioned
- Second target chamber is used to test target supply system
- Hardware has been purchased
- Control software is under development

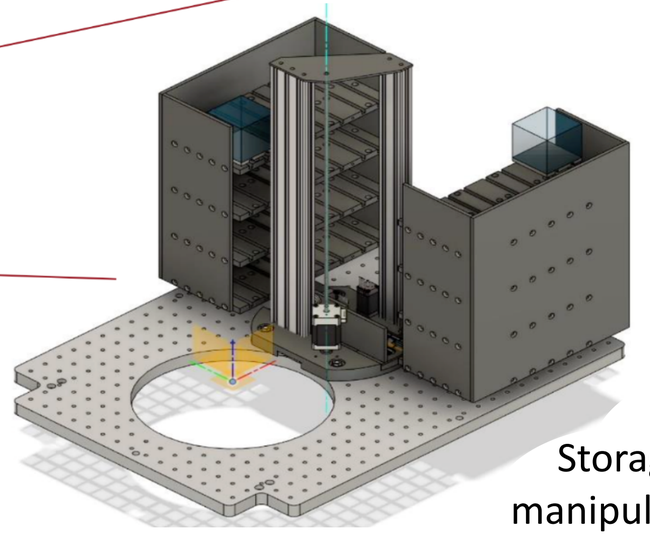


Target chamber installed at HHT





Target positioning robot: 4 axes



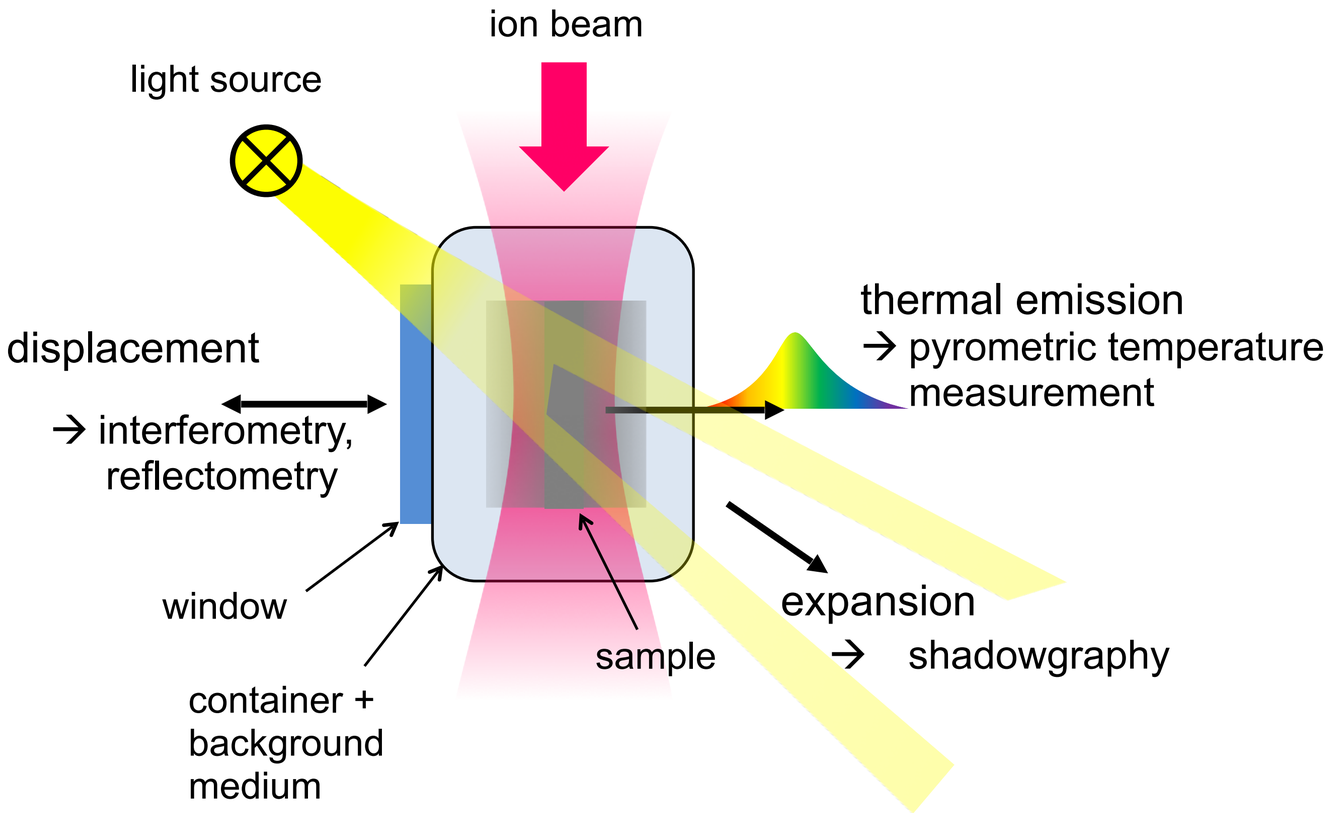
Storage manipulator: 2x32 target storage slots

Lift manipulator
Two grippers

M. Roth, G. Schaumann
TU Darmstadt

A set of optical and x-ray diagnostics will be used in the experiments and are tested in experiments at GSI

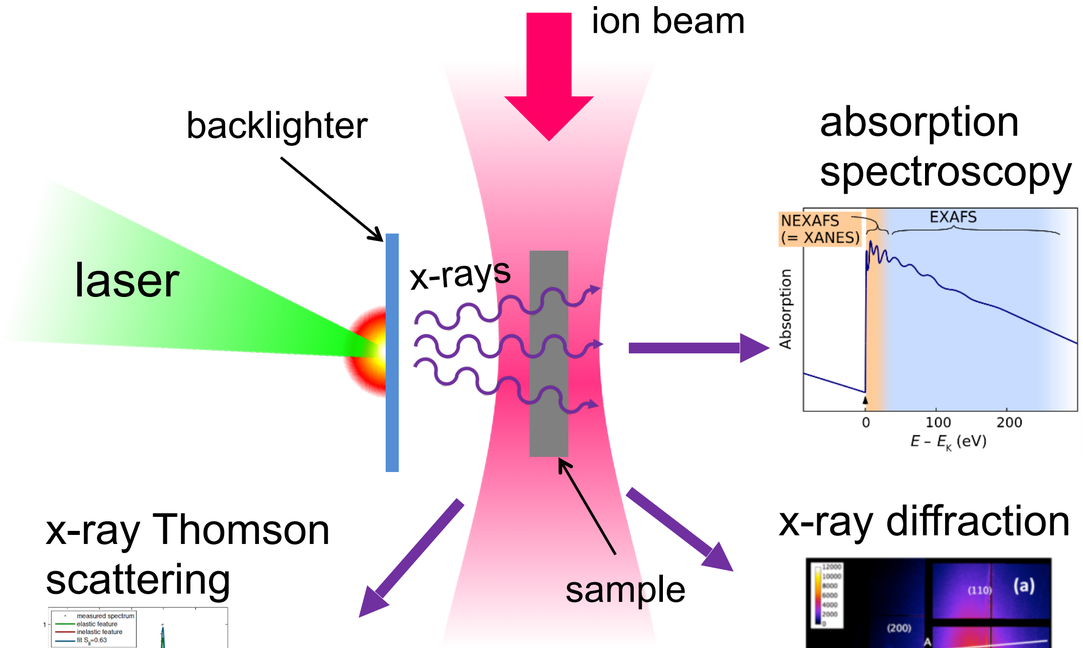
Optical probes look at the outside → macroscopic observables (p,T,V)



Topics

- Equation-of-state, thermo-physical properties
- Coexistence regime, critical points

X-rays penetrate sample (volumetric probe) → microscopic structure (ionic/atomic, electronic)



Topics

- Ionization-potential depression
- Insulator-Metal transition
- Graphitization, s-s phase changes
- Melting, super-heating

Conclusions

A selection of planned physics experiments

Physics examples / Project phases	HED platform	GSI SIS-18 / HHT	First experiments @FAIR	Full performance
Multiple-shock compression of Earth crust minerals[1]	PRIOR			
Ionization Potential Depression (IPD)[2]	HIHEX			
Critical point in lead[3]	HIHEX			
Phase transitions in carbon[4]	LAPLAS			
Iron in Earth and Super Earths[5]	LAPLAS			
Warm dense water[6]	LAPLAS			
H/He demixing[7]	LAPLAS			

1 - Letter of Intent for PRIOR (2021) – collection of proposed experiments
2 - White paper for Day-1 experiments (2014); D. Kraus et al., Phys Rev. E 94, 011202 (2016)
3 - V. Mintsev et al., Contrib. Plasma Phys. **56**, 281 (2016)
4 - GSI experiment S489; D. Kraus et al., Nature Astronomy **1**, 606 (2017)
5 - N. Tahir et al., The Astrophysical Journal Supplement Series **232**,1 (2017)
6 - N. Tahir et al., Phys. Plasmas **28**, 032712 (2021); doi: 10.1063/5.0037943
7 - W. Lorenzen et al. PRB **84**, 235109 (2011)

Color codes

Preparation/ commissioning

Partially feasible

Feasible

Backup slides

The civil construction of the buildings for the first experiments is nearly finished

FAIR Construction Site, October 2020

FAIR Construction Site, October 2022

HED@FAIR - plans for first FAIR experiments in 2025

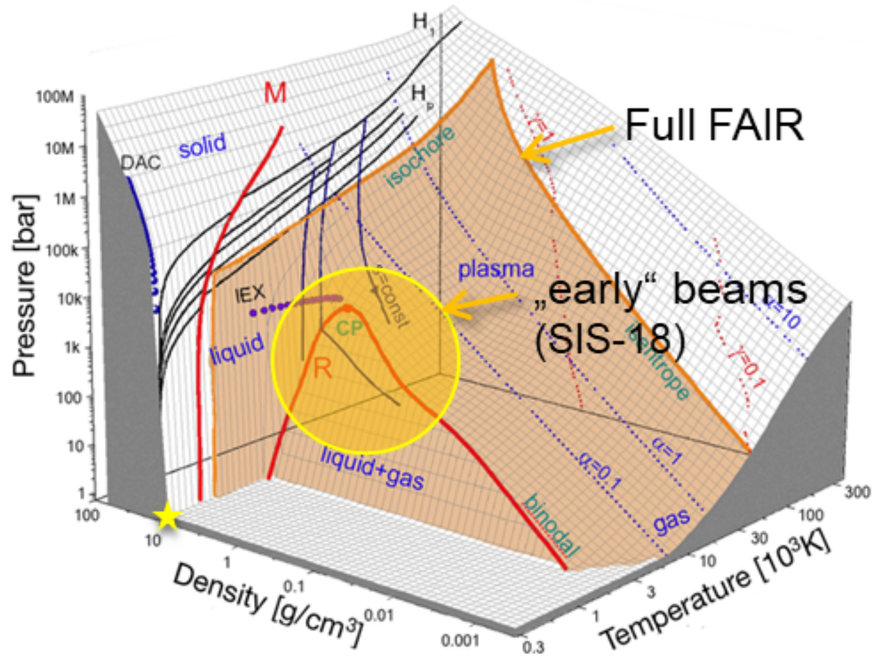
- Commissioning of superconducting final focusing system can be done at 10^9 ions/bunch
- Experiments near critical point or in strongly-coupled regime will need >10^{10} ions/bunch

Two flagship ion beam heating experiments are in preparation for day-1

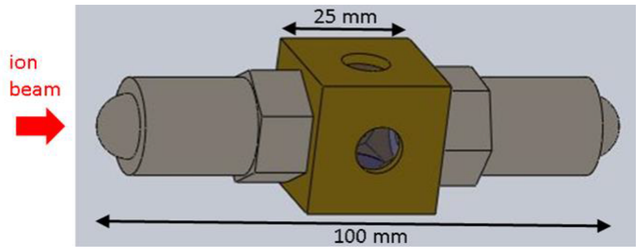
1) Equation-of-state of metals near the critical point

- liquid-gas phase transition and coexistence regime is of fundamental interest and high technical relevance
- Regime at 10kK-kbar experimentally challenging
- Advanced theoretical models differ by up to 100%
  → measurements will strongly constrain models

Pb phase diagram



High-pressure cell

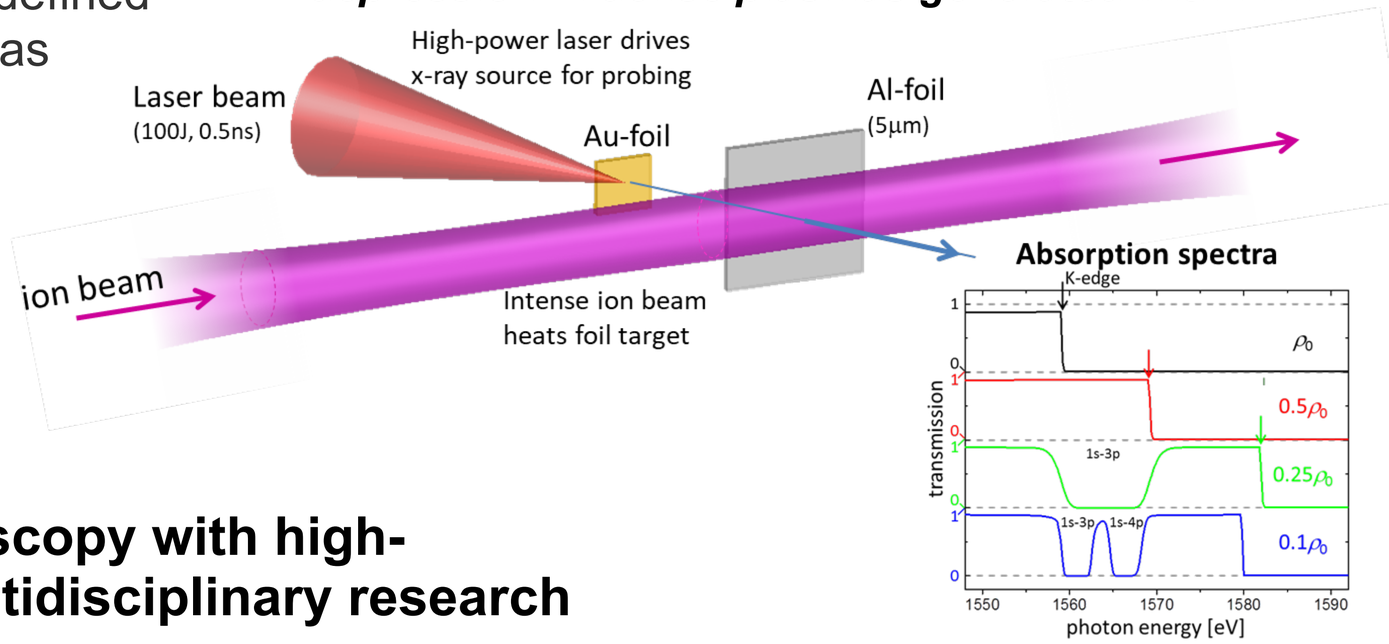


HED@FAIR - plans for first FAIR experiments

2) Ionization potential depression in dense plasmas

- Screening in plasmas causes lowering of the continuum, affecting charge state, transport properties, EOS
- Widely used models fail in strongly-coupled regime
- Current benchmarking experiments often with strong gradients, small sample sizes
  → with FAIR-beams we can produce large, well-defined homogenous samples of strongly-coupled plasmas

Experimental setup to measure ionization potential depression in dense plasmas generated with FAIR



In addition, PRIOR-II will offer proton microscopy with high-energy, high-intensity proton beams for multidisciplinary research