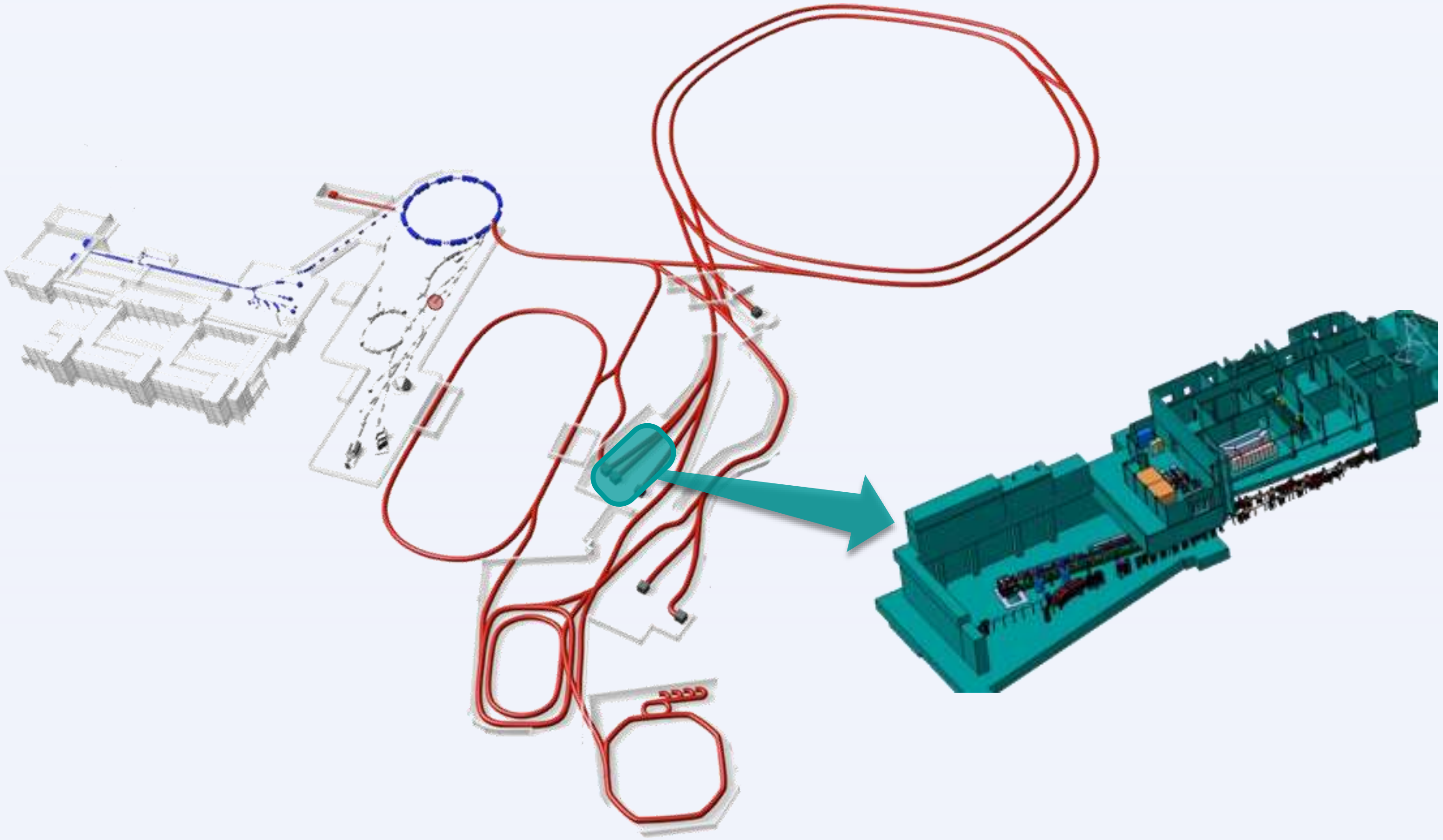
First plasma physics experiments at FAIR

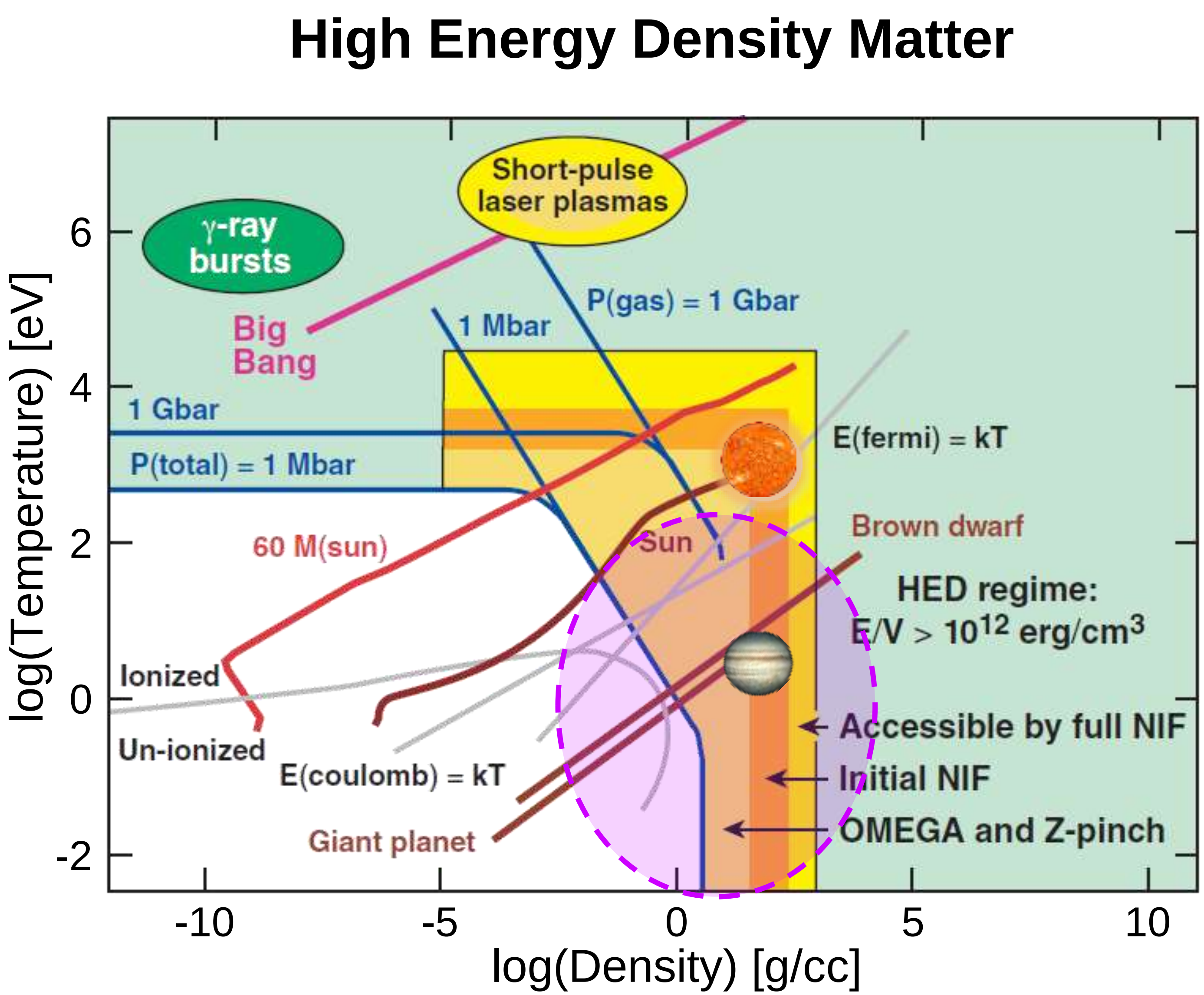
P. Neumayer (GSI) for the collaborations **HEDgeHOB** and **WDM**

International Conference on Science and Technology for FAIR in Europe 2014

Worms, October 13-17, 2014



Warm dense matter – strong coupling and degeneracy



Warm-dense matter occurs in**:**

- Transition solid-to-plasma
- Matter in extreme conditions
- Planetary interiors
- Fusion reactors

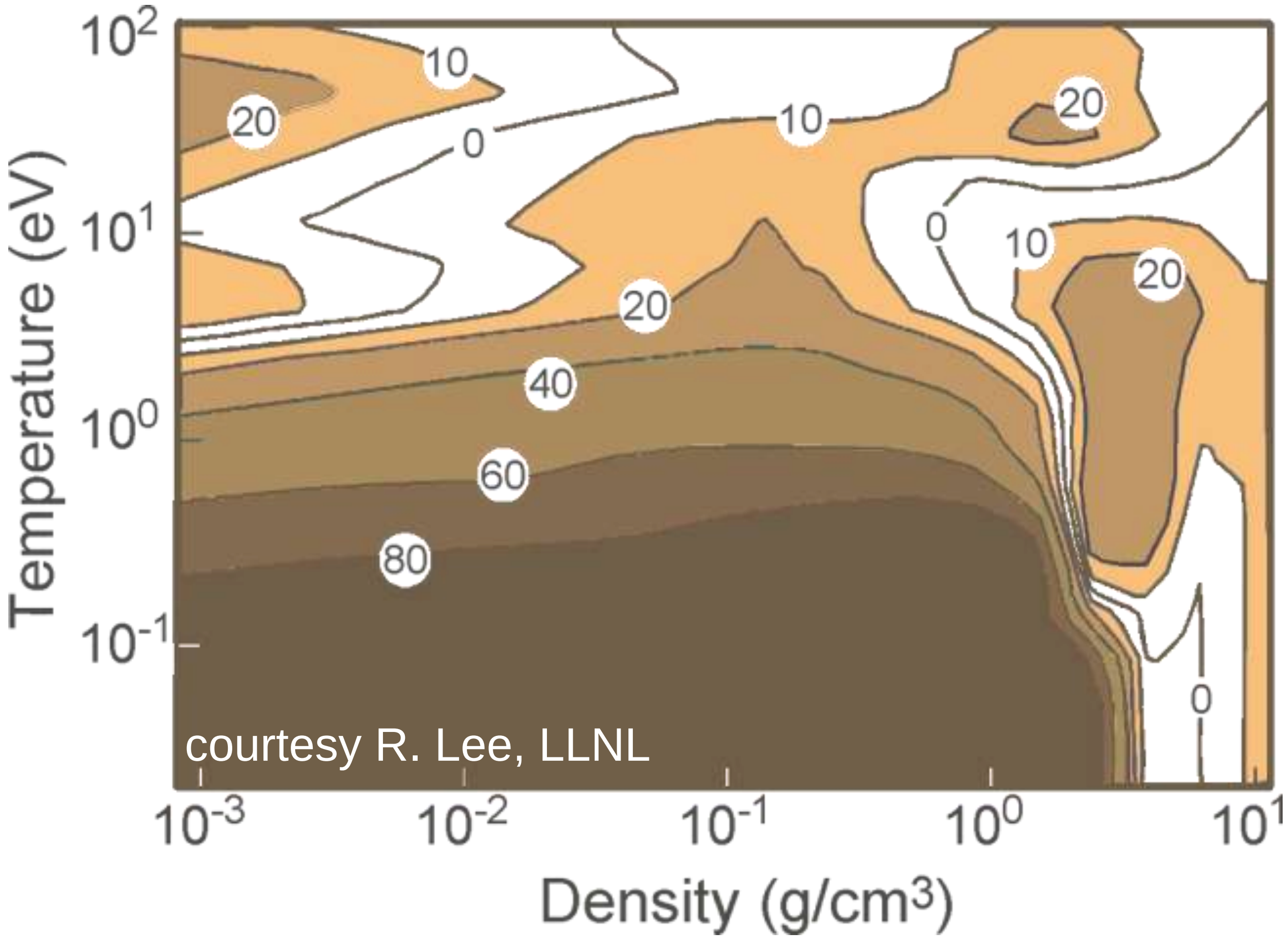
Warm-dense matter is complex**:**

- Strong coupling: $E_{pot} \geq k_B T$ ($\Gamma \geq 1$, „non-ideal“)
- Quantum effects: $E_F \sim k_B T$ ($\theta<1$, partly degenerate)
- Collisions (conductivity, heat transport): $\Lambda_C<0$
- Partial ionization
- Continuum lowering (→pressure ionization)
- Radiation transport
- Chemical bonding
- Phase transitions, phase coexistence, critical points

Warm dense matter – strong coupling and degeneracy

Example: Aluminium Equation-of-State

Contours of % pressure difference between two most advanced wide-range semi-empiric EOS models



- Theories are in a good agreement in the regions where experimental data exists
- Lack of experimental data in the WDM region

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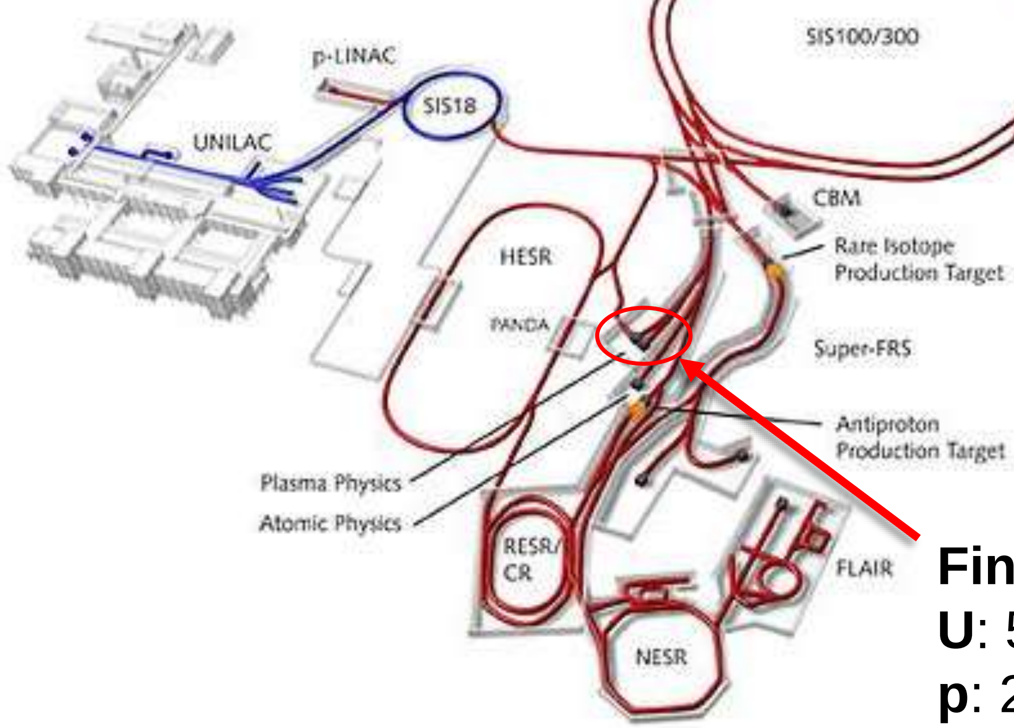
- Chemical bonding
- Phase transitions, phase coexistence, critical points

WDM experiments are typically:

- Transient, large gradients
- Require high spatial/temporal resolution diagnostics or large samples
- Difficult to diagnose (low self emission and high absorption)

Opportunities for HED science with FAIR ions

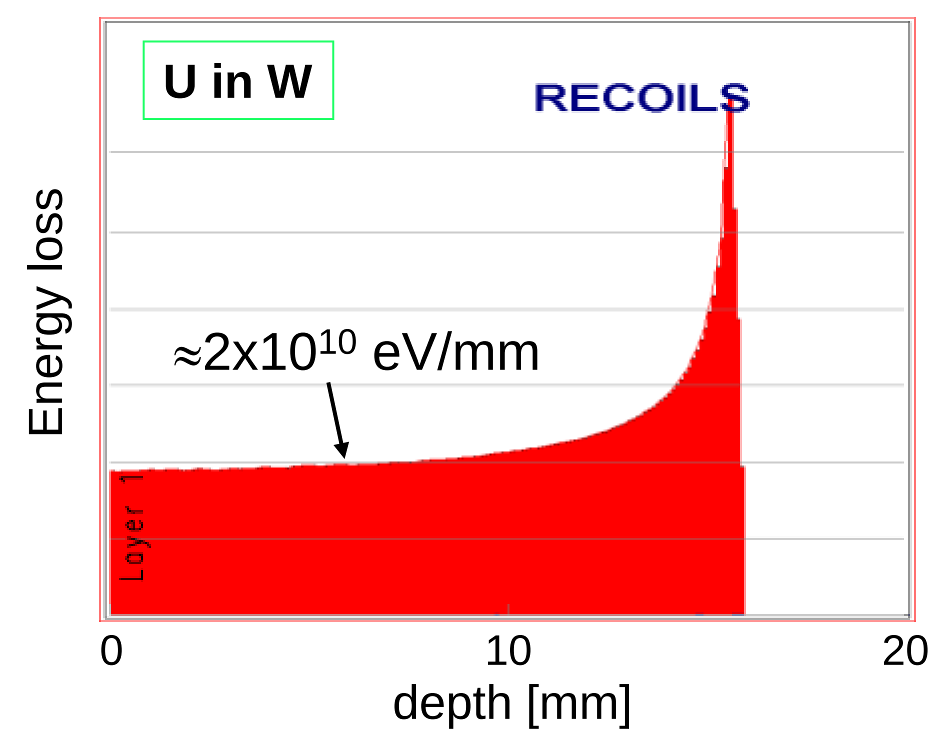


Final design goal
U: 5e11 (2GeV/u)
p: 2.5e13 (10GeV)
<100ns pulses

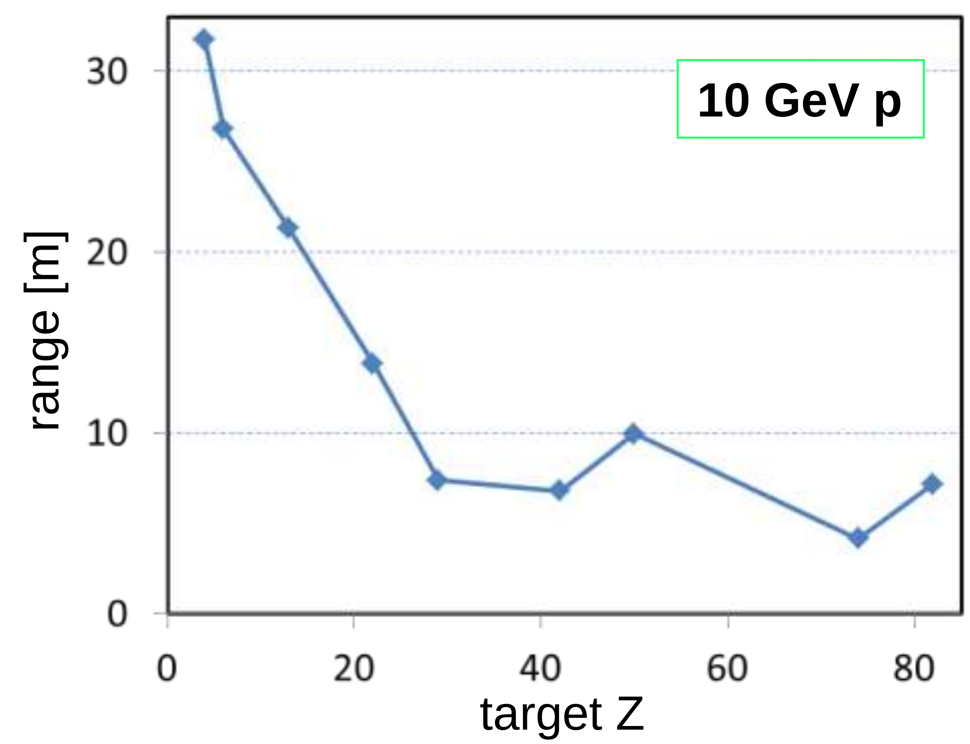
Expected for first beams:

	U	p
SIS-18 (upgraded)	4e10	1e11
SIS-100 „early“ beams	1e11	5e12

Homogenous energy deposition



Long stopping range

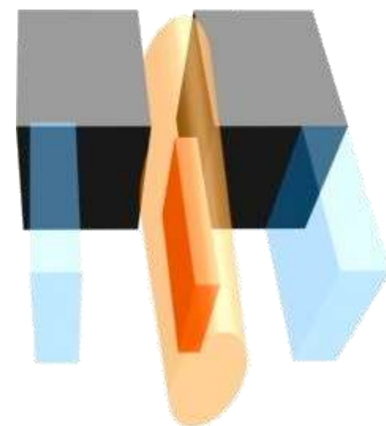


HEDgeHOB experimental frameworks

HIHEX

Heavy Ion Heating and Expansion

U^{28+}, 2 AGeV, $5 \cdot 10^{11}$, SC FFS

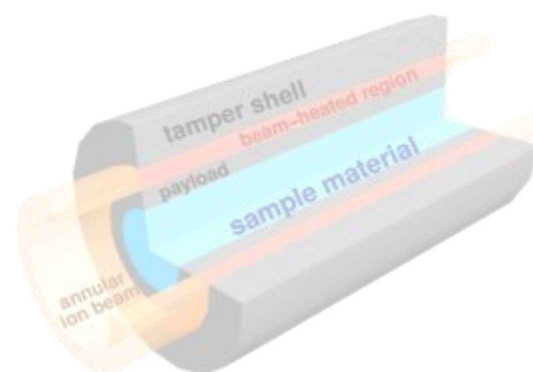


- uniform quasi-isochoric heating of a large-volume dense target and isentropic expansion
- numerous high-entropy HED states: EOS and transport properties of non-ideal plasmas / WDM for various materials

LAPLAS

Laboratory Planetary Sciences

U^{28+}, 1 AGeV, $5 \cdot 10^{11}$, Wobbler

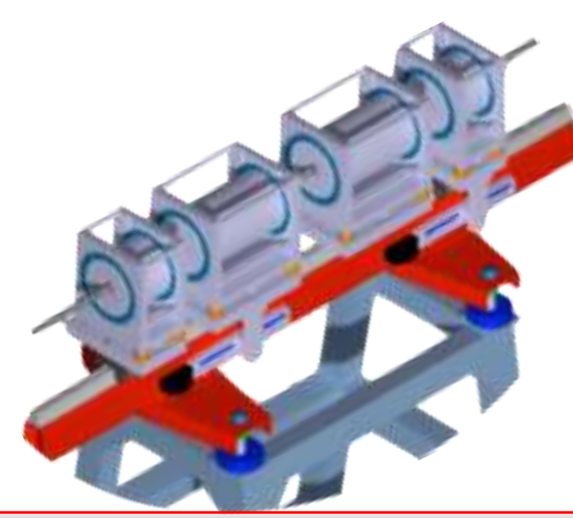


- ring-shaped beam implodes a heavy tamper shell, low-entropy compression of hydrogen
- Mbar pressures @ moderate temperatures: hydrogen metallization, interior of Jupiter, Saturn or Earth

PRIOR

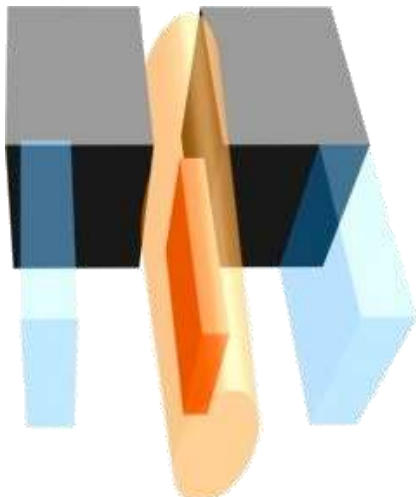
Proton Microscope for FAIR

p, 5–10 GeV, $2 \cdot 10^{13}$, PRIOR



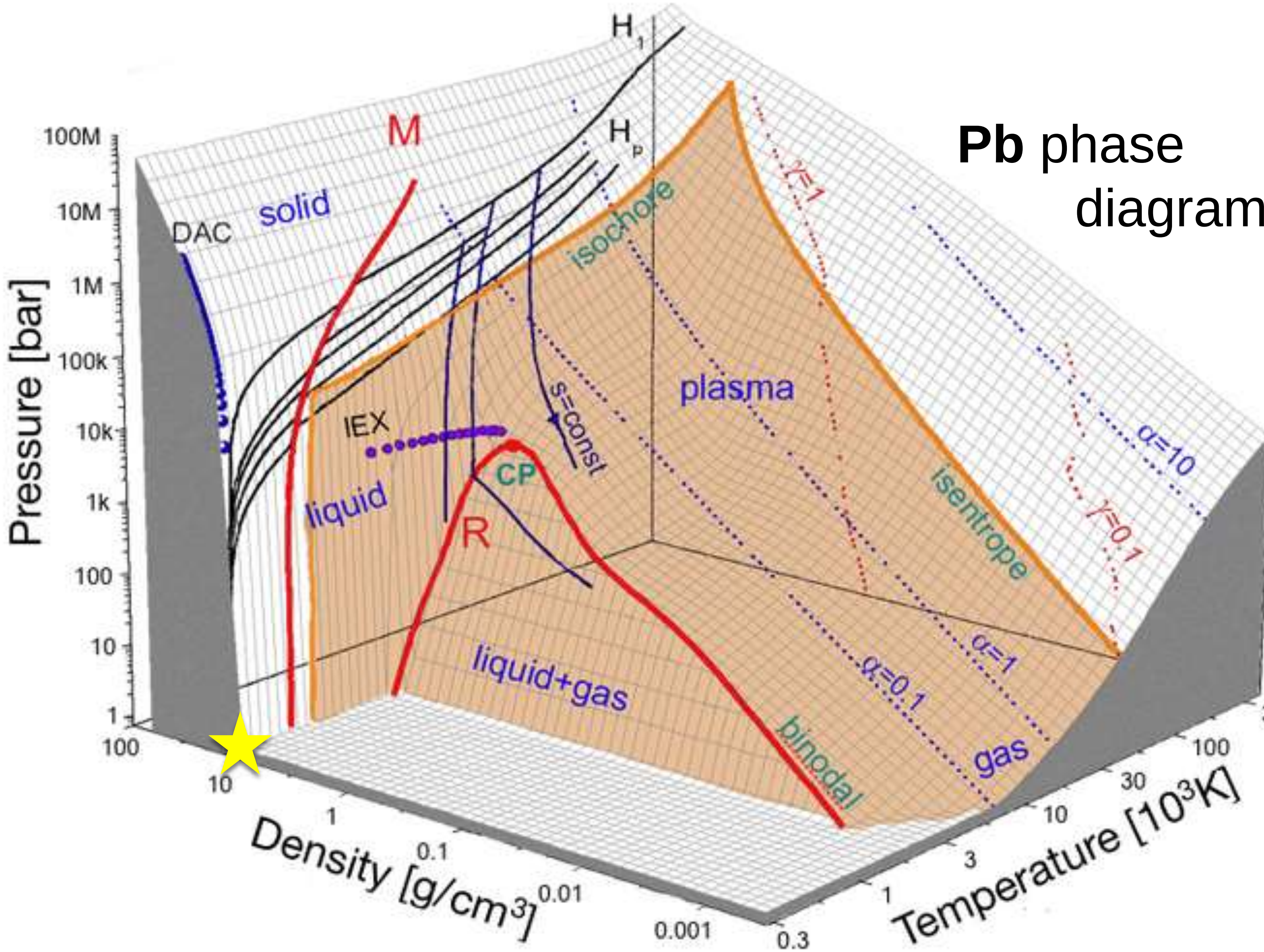
- worldwide unique high-energy proton microscopy setup with SIS-100 proton beam
- dynamic HEDP experiments and PaNTERA: unparalleled dynamic density distribution measurements and Proton Therapy and Radiography project (with BIOMAT)

HIHEX: EOS and transport properties of various elements and materials in HEDP and WDM states



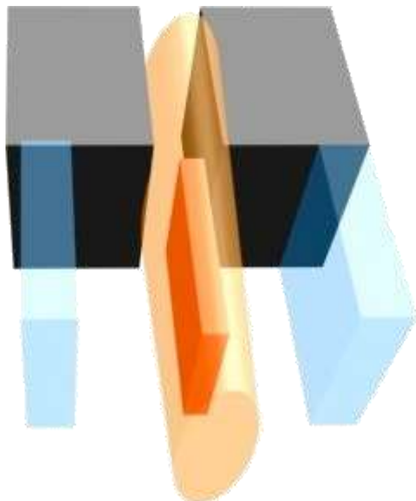
HIHEX: ***H****eavy* ***I****on* ***H****eating and* ***Ex****pansion*

Pb phase diagram



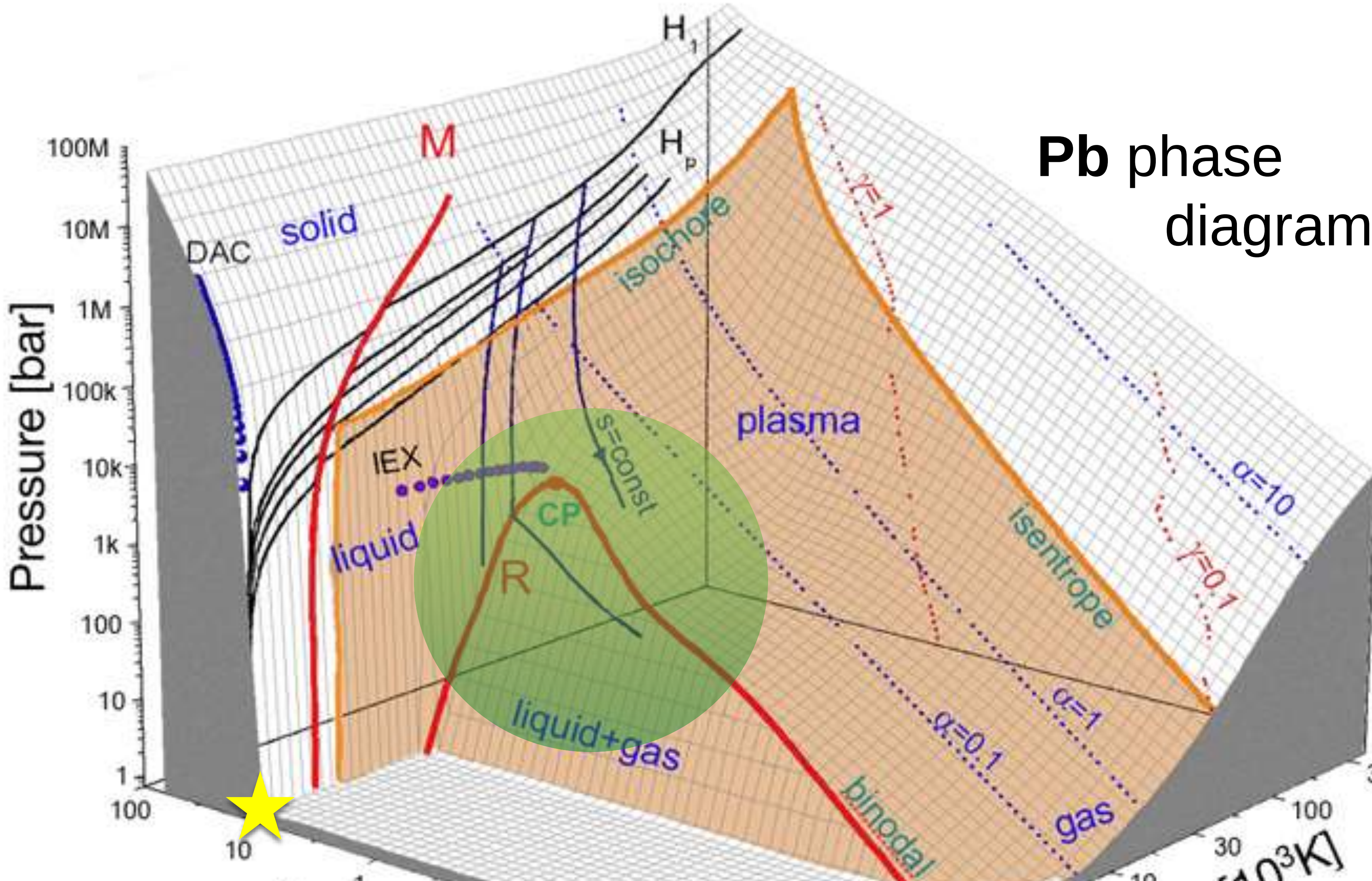
EOS and transport properties of various elements and materials in HEDP and WDM states

“Early” HIHEX: critical points of various materials



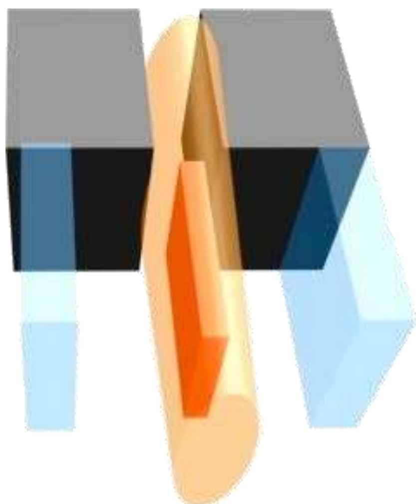
HIHEX: ***H**eavy **I**on **H**eating and **Ex**pansion*

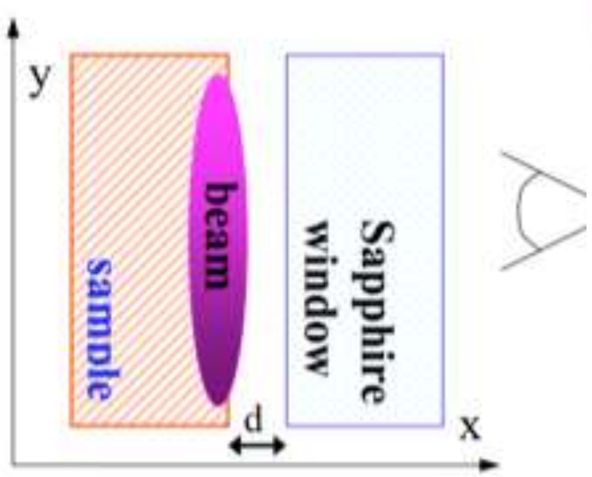
Pb phase diagram

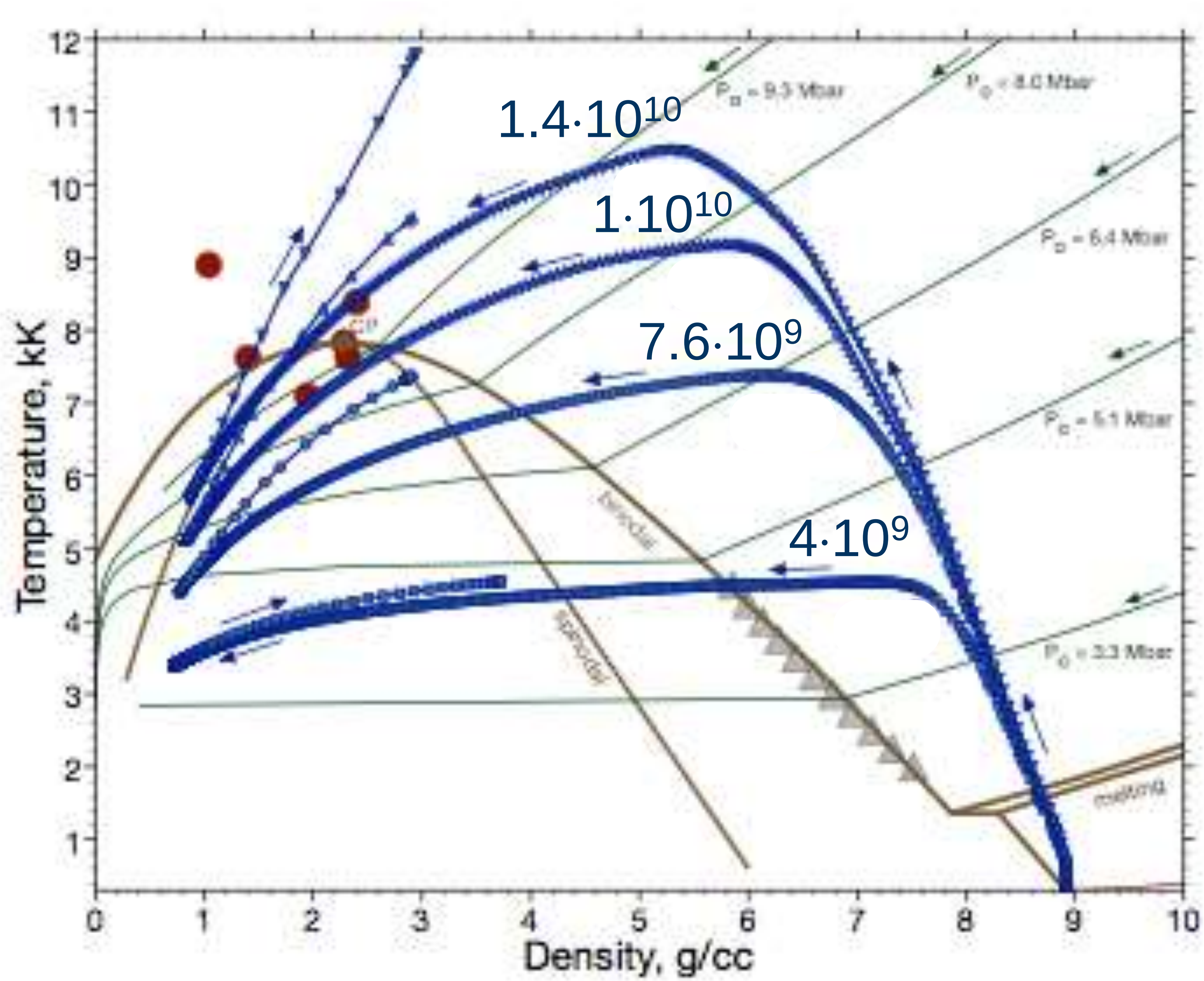


- For most of the metals in the periodic system the locations of the critical points are still unknown!
- Theoretical estimates of the critical point location differ by up to 100–200% in T and P

Early HIHEX: the critical point of copper



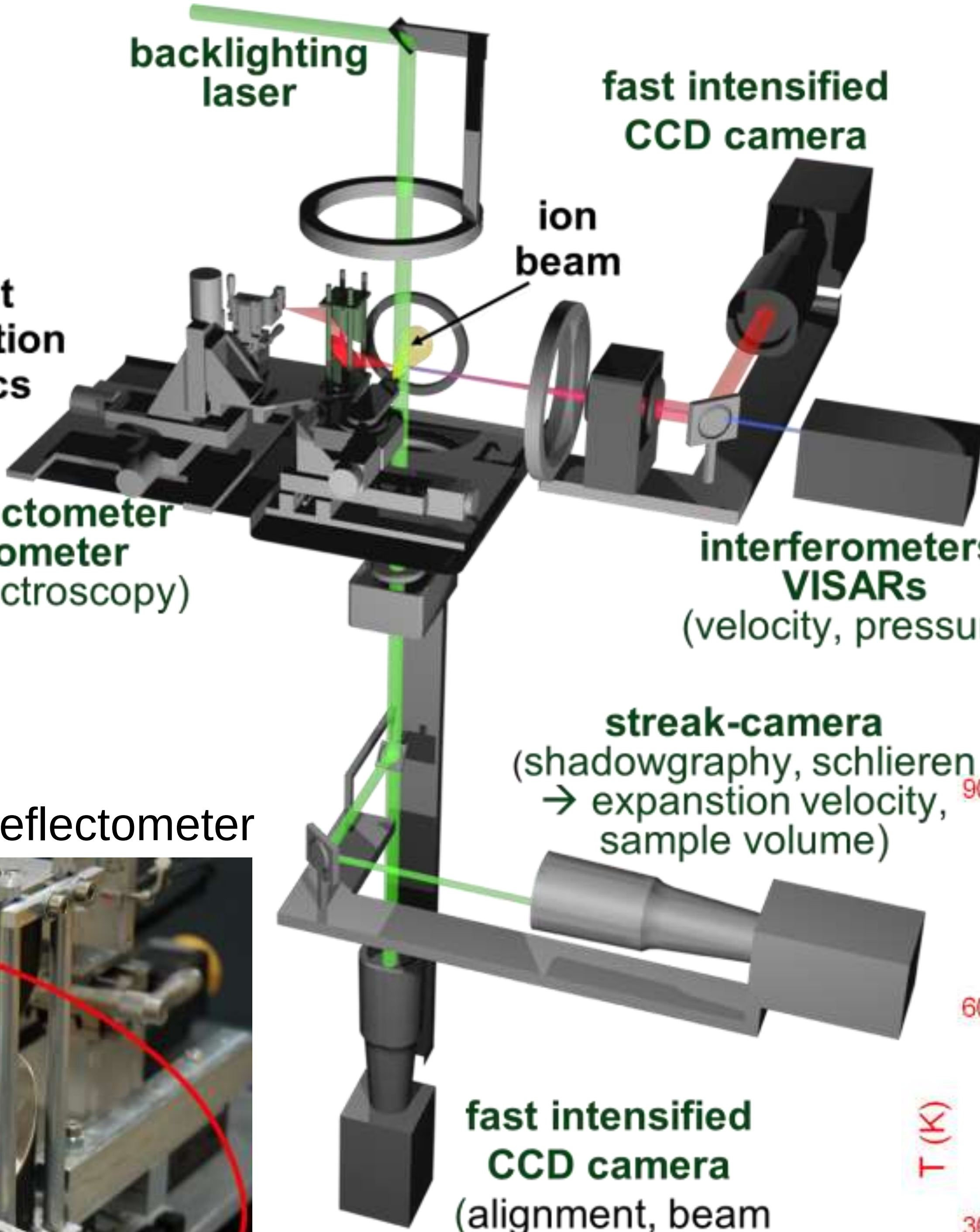




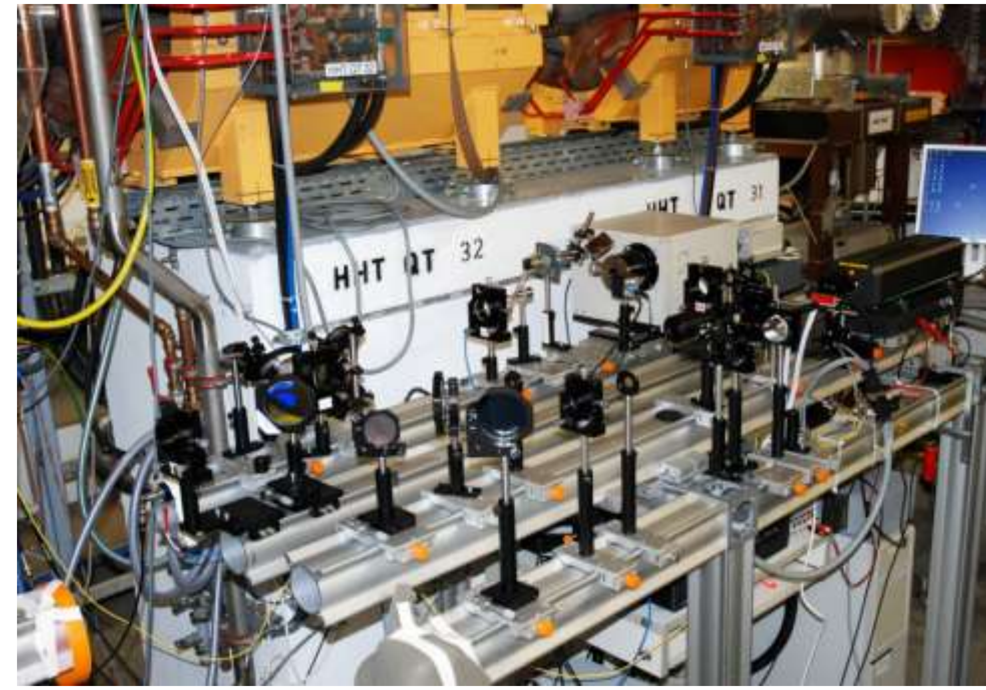
Courtesy: IPCP, Chernogolovka

Three proposals for early HIHEX experiments are being evaluated by HEDgeHOB

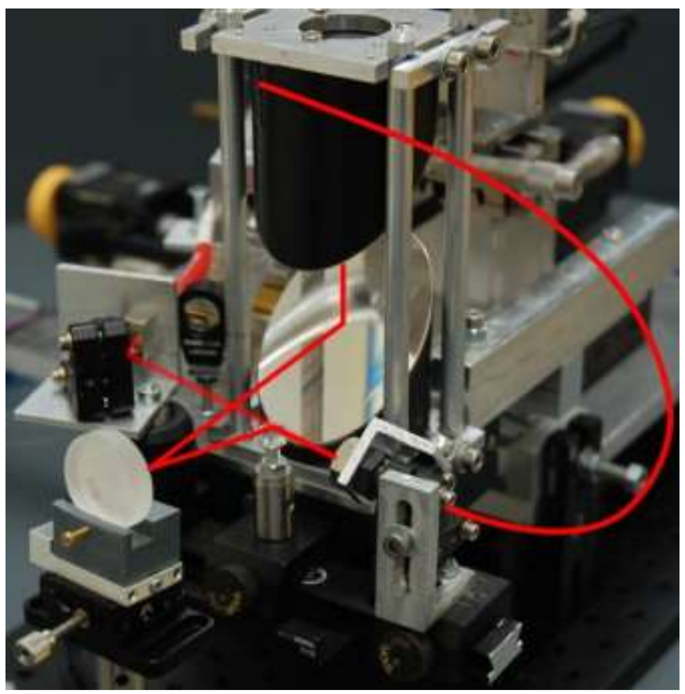
Diagnostics tests with SIS-18 U^{73+} beams at GSI



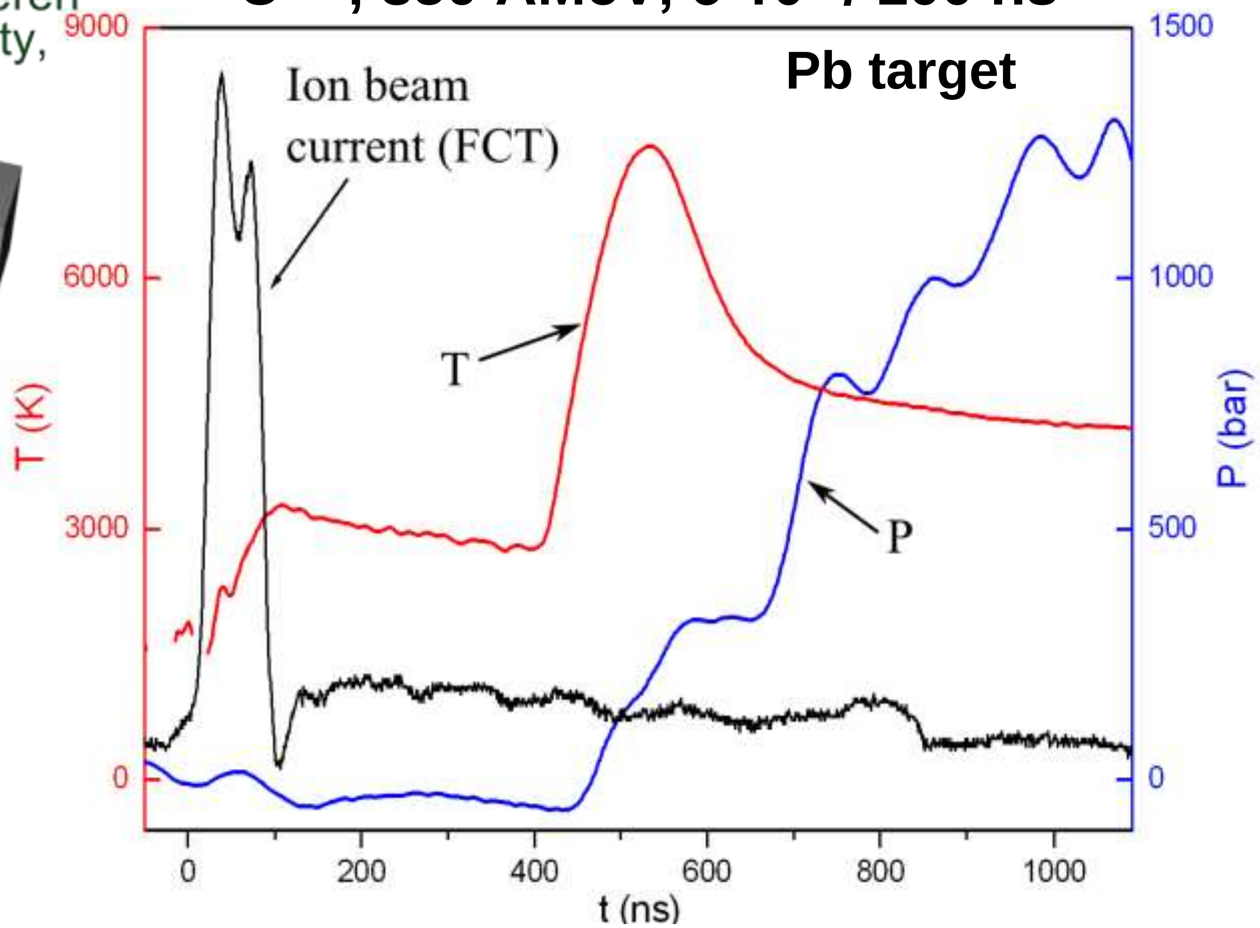
laser interferometer



fast pyrometer-reflectometer



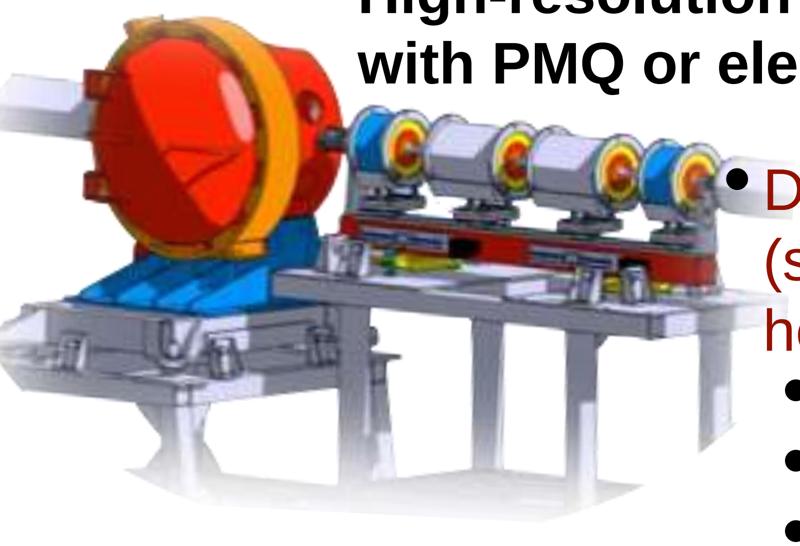
U^{73+}, 350 AMeV, $3 \cdot 10^9$ / 100 ns



PRIOR – Proton Microscope for FAIR

- worldwide unique high energy proton radiography facility
- early SIS-100 or SIS-18 proton beams:
  3 – 10 GeV, moderate (>10^{10}) to high (10^{13}) intensity
  - materials at extreme dynamic environments generated by external drivers (HEDP, plasma physics and materials research)
  - PaNTERA (Proton therapy and radiography) project (jointly with BIOMAT)

GSI, 2014



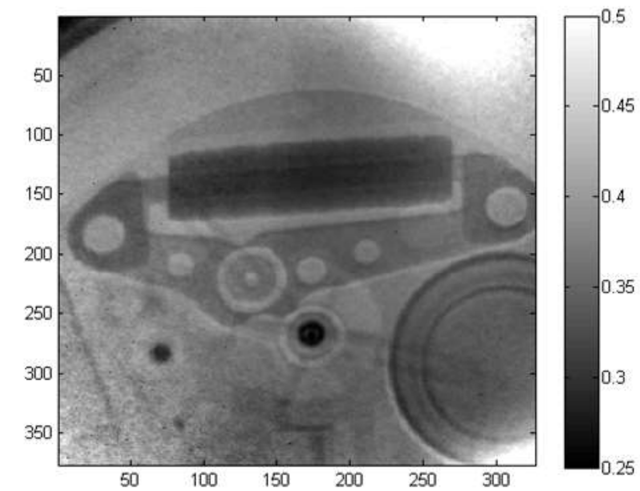
High-resolution (10 µm) magnifier with PMQ or electromagnets

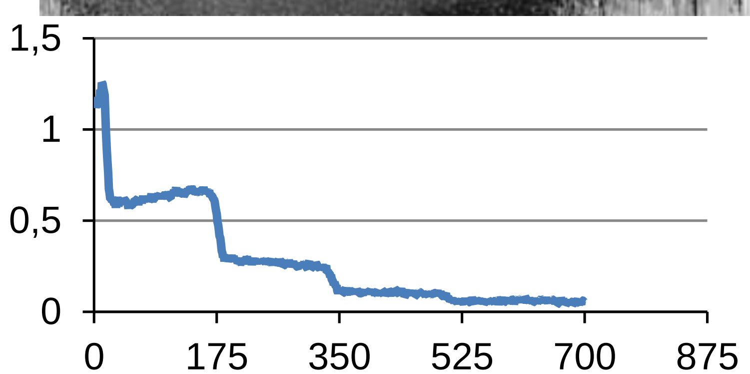
- Dynamic compression (shocks, ramp) or fast heating by external drivers:
  - pulsed power generator
  - high energy laser
  - light gas gun
  - HE generators

Superconducting imager with high-gradient quadrupoles

- Large FOV (15 cm) for static and dynamic experiments:
  - applied studies
  - PaNTERA

PRIOR prototype: static commissioning, April 2014





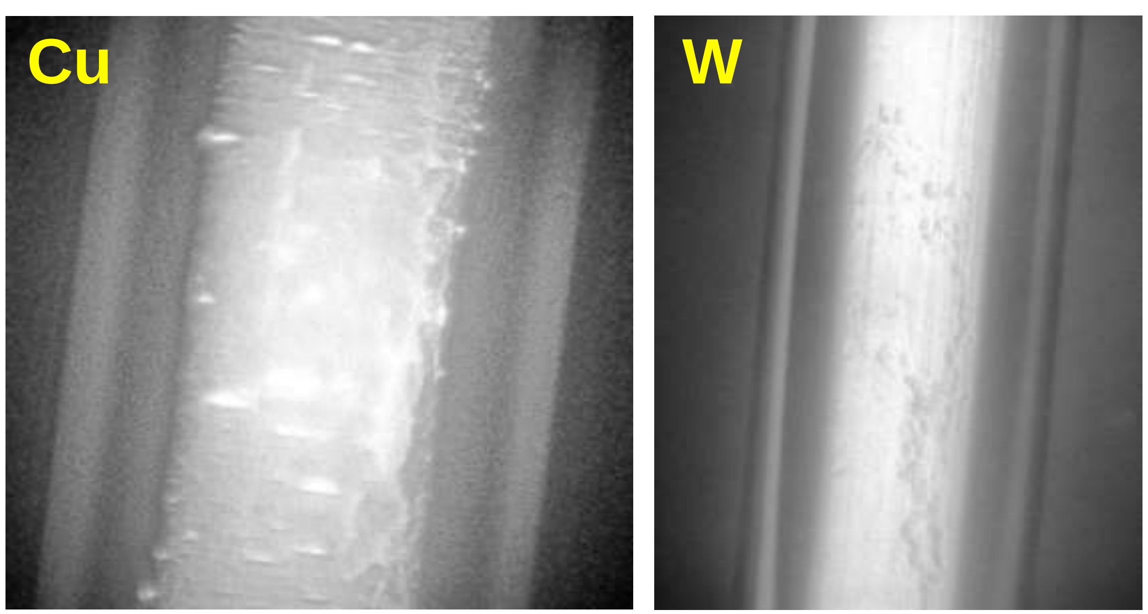
Ta calibration steps

- 25 – 40 µm spatial resolution
- remarkable density sensitivity

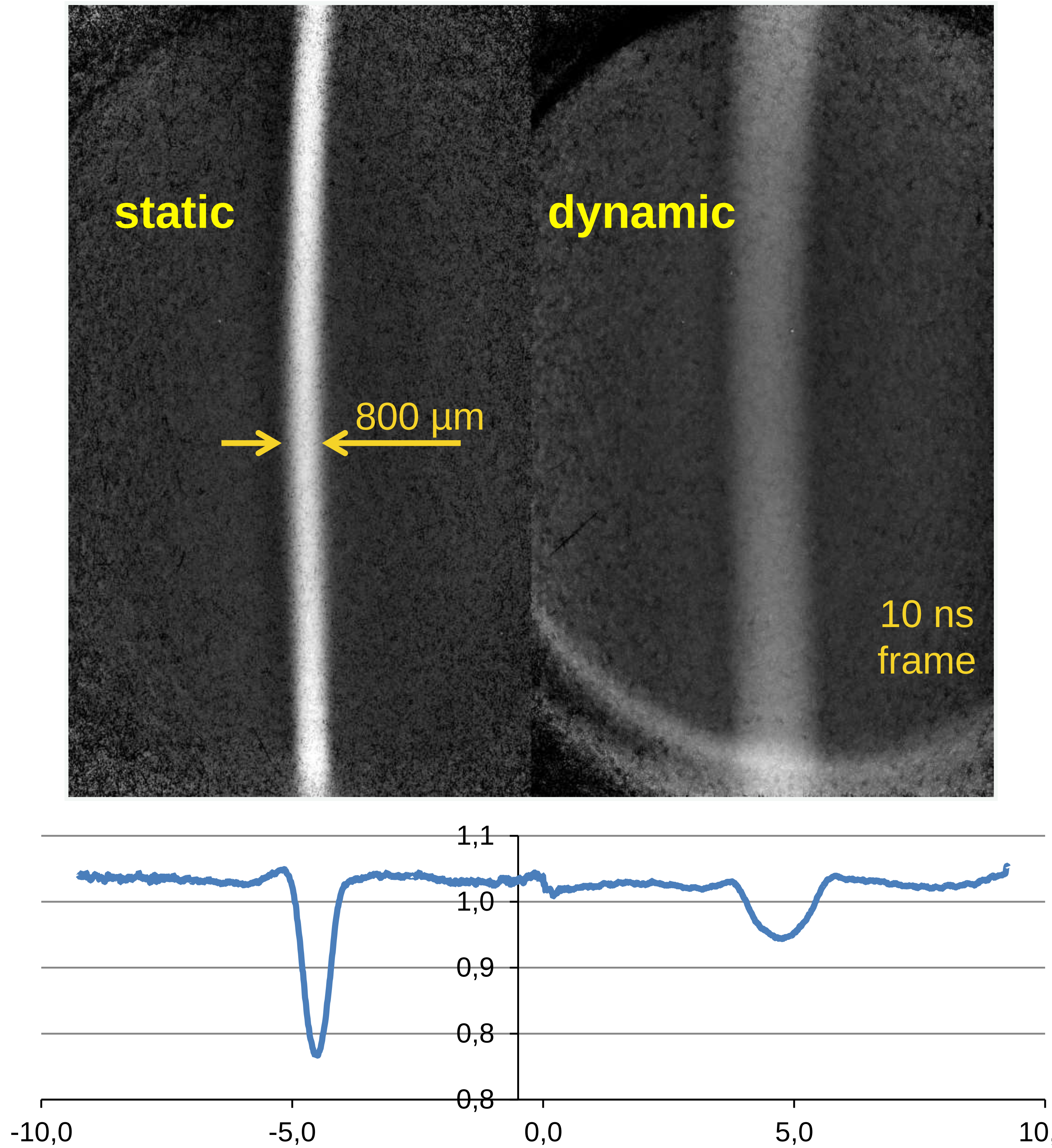
- installed at HHT area of GSI
- NdCo Ø30mm PMQ lenses
- CsI and plastic detectors
- 3.5 – 4.5 GeV protons from SIS-18

PRIOR prototype: dynamic experiments, July 2014

- Underwater electrical wire explosions (0.8 mm Ta wire in 2 cm of water).
- 35 kV, 40 MA/cm^2, 5 GW deposited
- WDM states in Ta: 10 kJ/g specific energy, ~2 eV temperature, ~km/s expansion velocity.
- Several dynamic experiments were performed to build a time history of the wire expansion.
- Main goal: to measure internal structure (density distribution) of expanding hot Ta for EoS studies.



Self-emission images



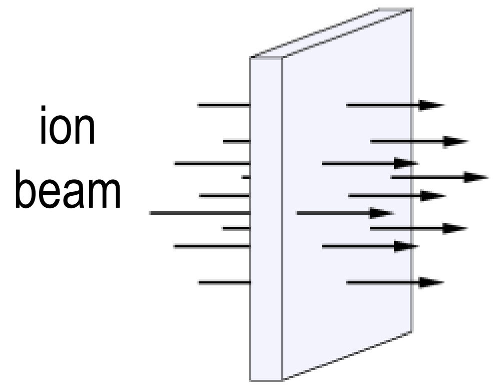
Proton radiographs

Five proposals for early PRIOR experiments are being evaluated by HEDgeHOB

WDM Proposes Different Target Schemes

EOS measurements at constant pressure

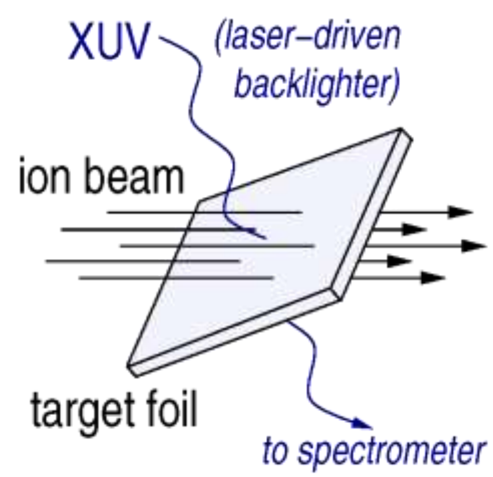
Quasi-static heating of thin targets



0.5 – 1·10^{10} U ions
0.4 GeV/u
0.1 – 1 μs bunch
„first“ beams SIS18 or SIS100

Opacity measurements at constant temperature

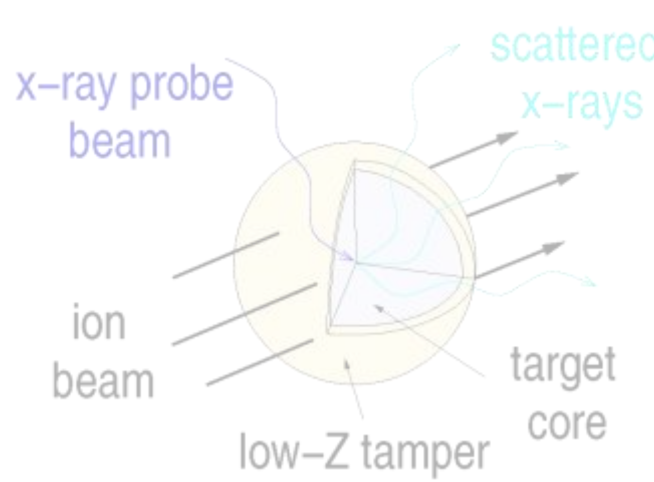
Isothermal expansion of thin foil targets



1·10^{10} U ions
0.4 GeV/u
100 ns bunch
10 – 100 J backlighter laser
„early“ beams SIS18 or SIS100

Optical diagnostics at constant volume

Dynamic confinement of low-Z targets



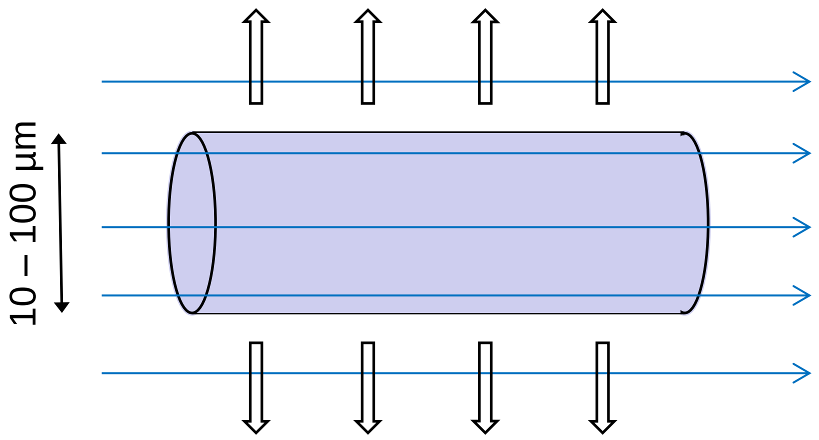
1·10^{11} U ions
0.4 GeV/u
100 ns bunch
100 J backlighter laser
optimized SIS beam

Dynamics of Metastable States in the Two-Phase Region Measurement of EOS at the Binodal

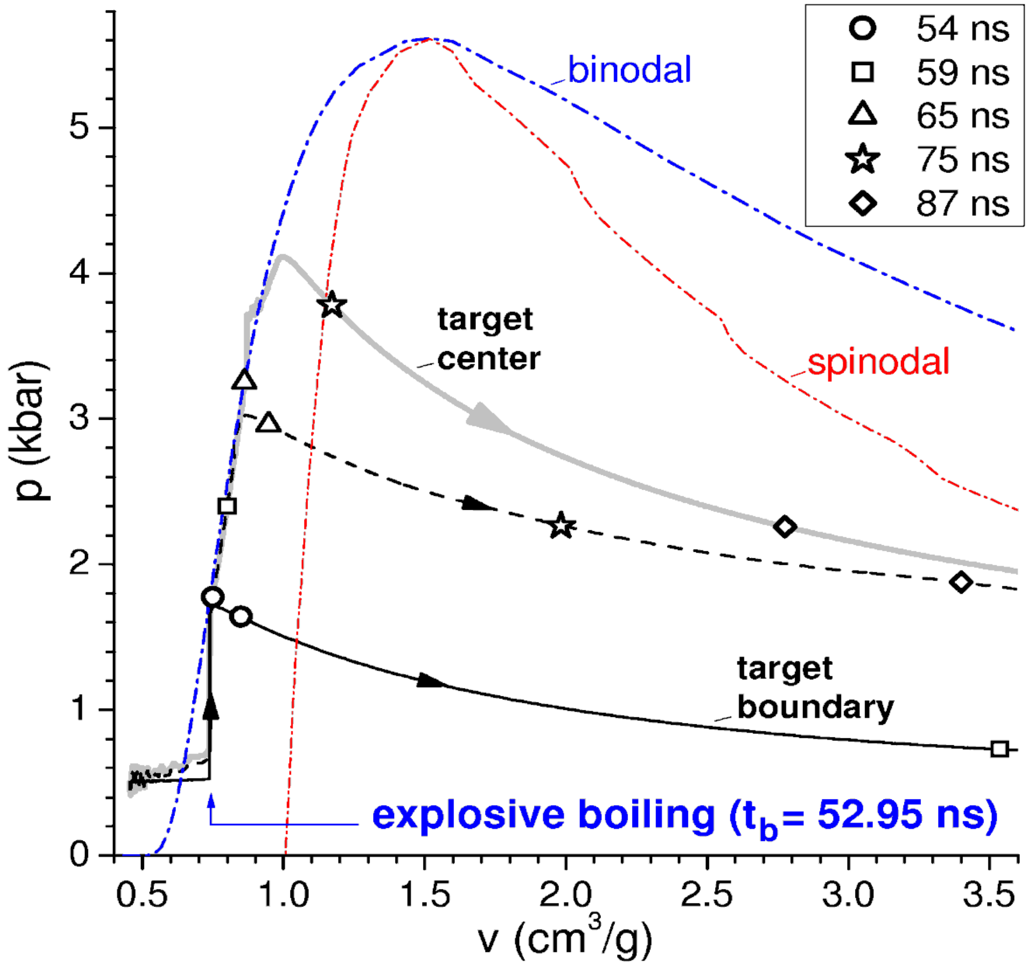
- Test hydro-calculations in 2-phase regime (explosive boiling)
- Measurements at the binodal (liquid-vapor coexistence curve) can validate critical point predictions

Heating of cylindrical or planar targets in three steps:

1. quasi-static heating (thermal expansion)
2. explosive boiling at t_b
3. hydrodynamic expansion



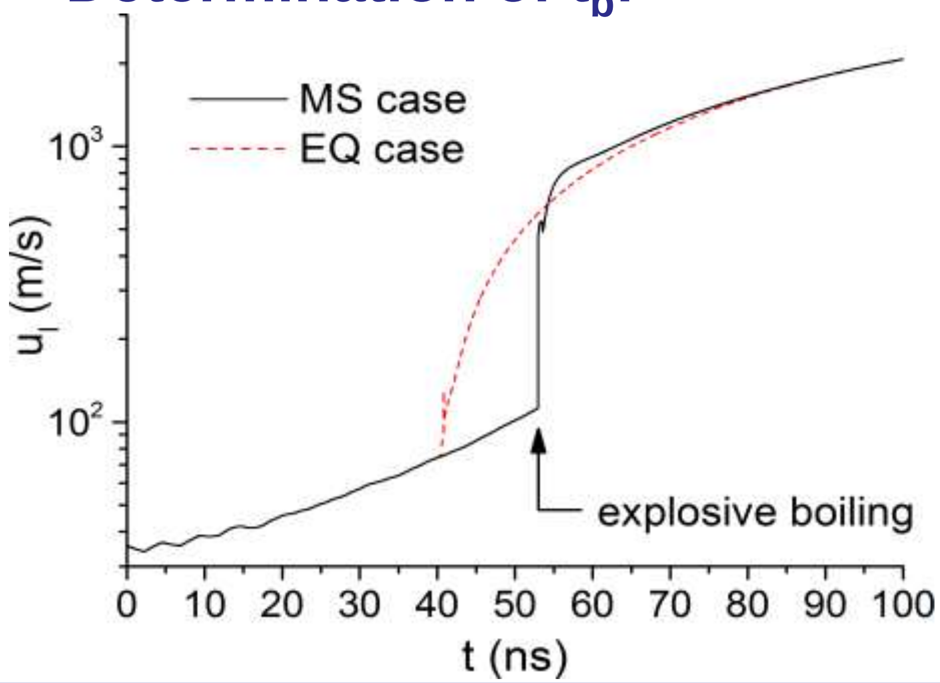
early beam:
10^{10} U ions
1 GeV/u
0.1 – 1 µs bunch



- The transition from metastable to equilibrium state occurs by explosive boiling and is clearly characterized by a large jump in expansion velocity
- Complete EOS information of a point on the binodal at t_b: measurement of the homogeneous target density and deposited ion beam energy (= internal energy)
- After the phase transition inner foil elements remain on the binodal until the rarefaction wave has reached the target center and can extend the measurement to higher pressures

Measurement of EOS at the Binodal: Diagnostics

Determination of t_b:



Internal Energy:

energy loss is well known:
→ measurement of beam profile

classical ion beam diagnostics

beam induced k_α-diagnosics

Temperature:

up to t_b: pyrometry

after t_b: penetrating diagnostics
sensitive to highest temp.
→ XANES

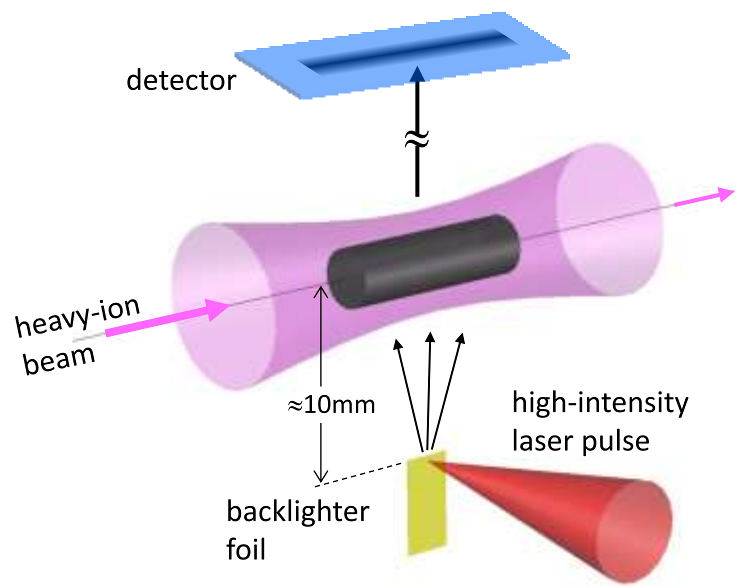
Density:

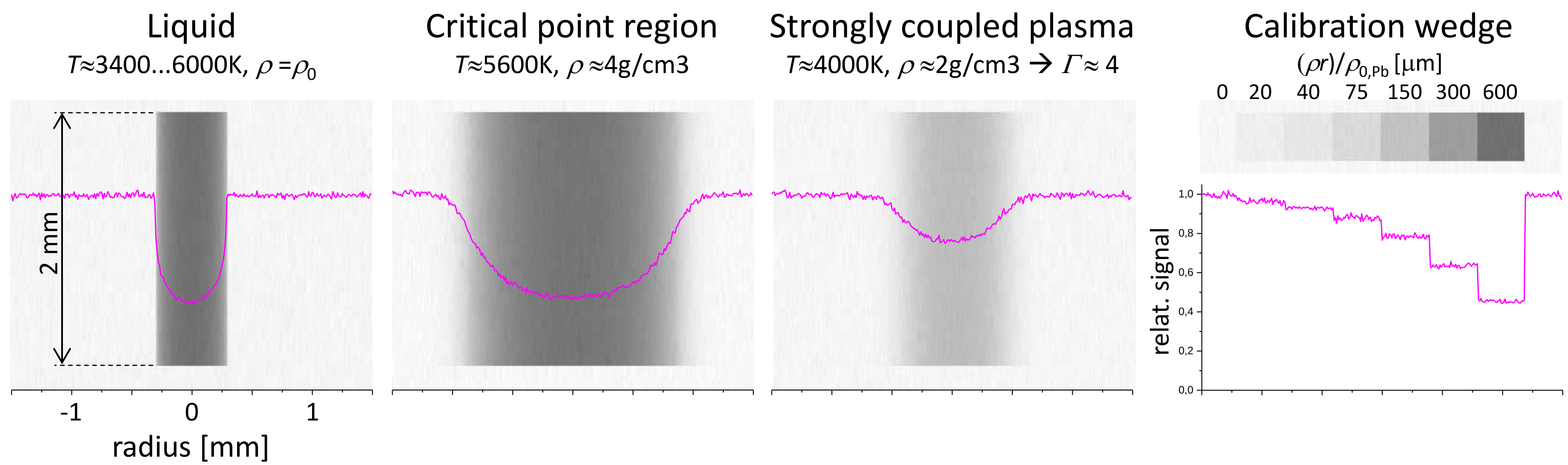
up to t_b: visible shadowgraphy

after t_b: x-ray radiography

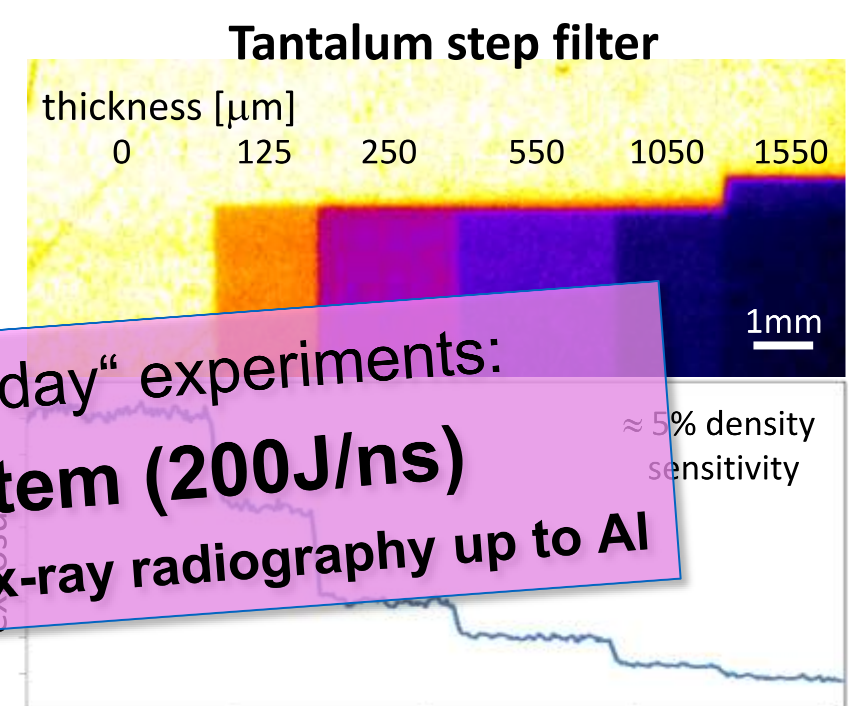
Laser-driven x-ray radiography

Simulated radiographs of expanding lead cylinder





Demonstration at GSI‘s high-intensity laser



E_L=120 J

τ_p = 0.6 ps

Application (BMBF) for „first day“ experiments:

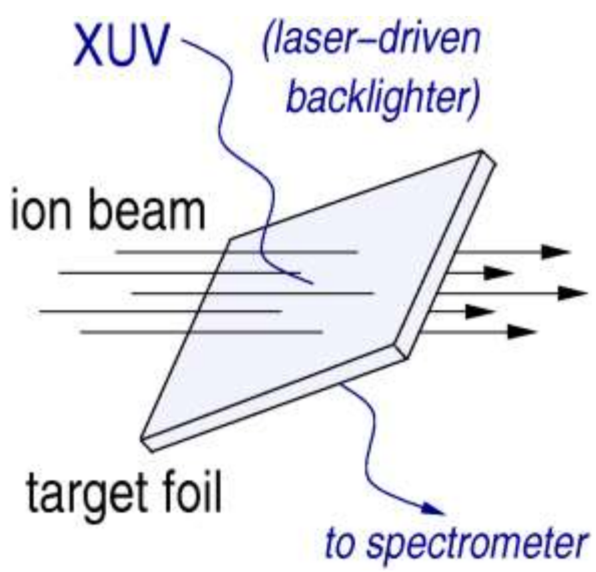
Long-pulse laser system (200J/ns)

drive intense He_α-source (~5keV) → x-ray radiography up to Al

Tests of Fundamental Atomic Physics in Warm Dense Matter
Opacity Measurements in the XUV Range

- Strong coupling and eV temperatures significantly affect atomic population kinetics
- Predictions by state-of-the-art opacity models vary significantly
- Spectrally resolved opacity measurements can benchmark theoretical approaches

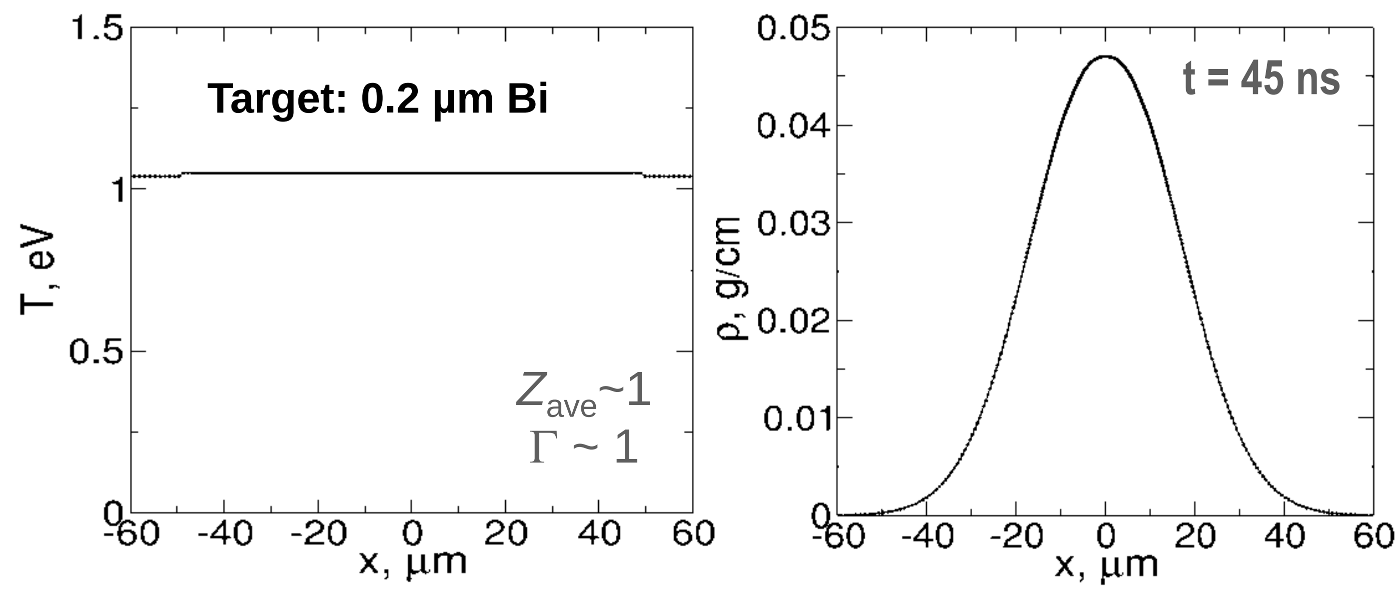
Experimental scheme: XUV transmission measurement in HI heated think foil



early beam:
10^{10} U ions
0.4 GeV/u
100 ns bunch

>10J laser energy necessary to overcome beam generated background

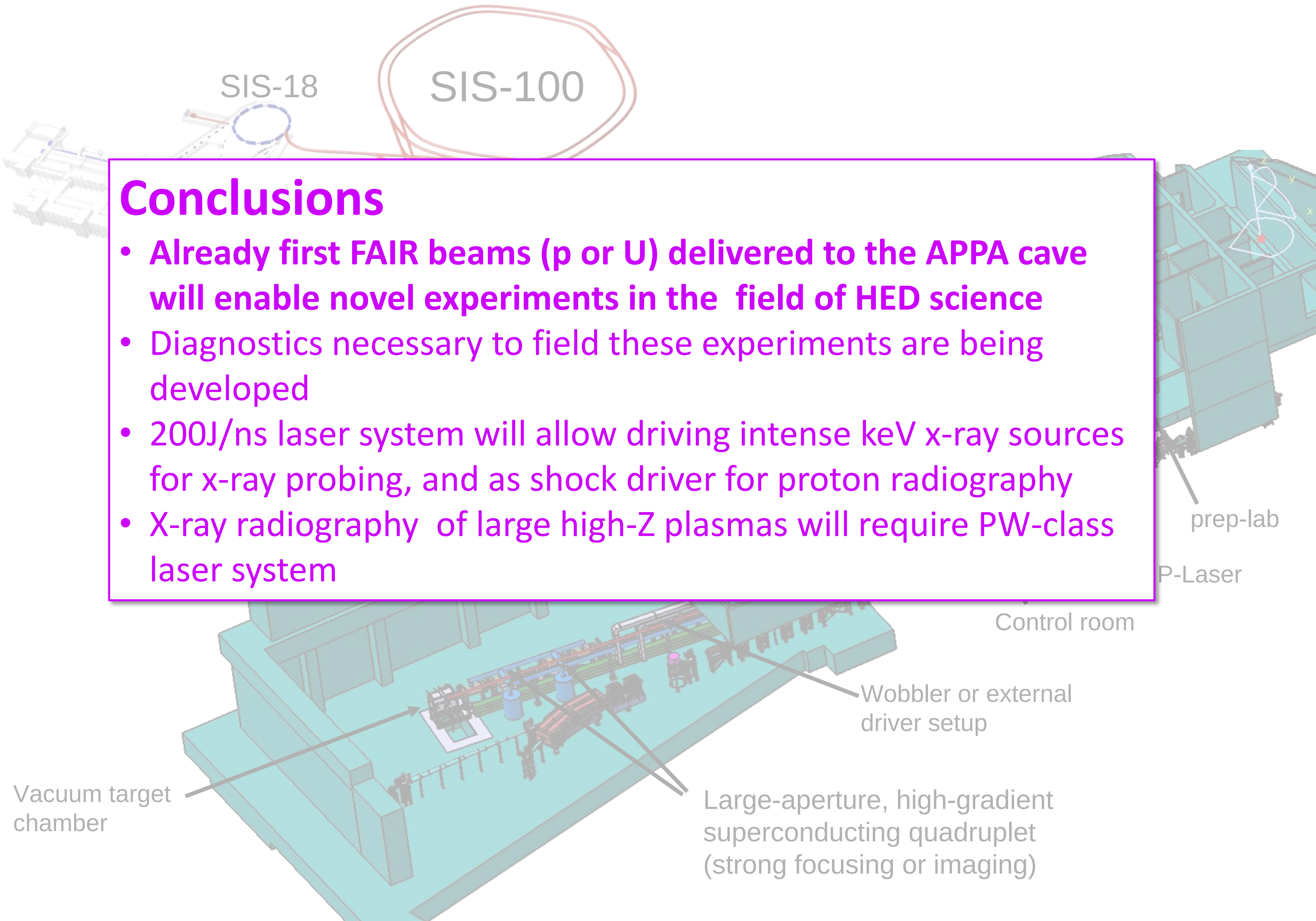
Target: 1-dimensional isothermal expansion of ion beam heated foil provides a sample with constant temperature



Homogeneous temperature distribution
→ simple pyrometric temperature measurement sufficient

- Sufficient sensitivity to discriminate between opacity models demonstrated
- Program can be extended to higher target density and low-Z targets with increased beam power

Experimental area at FAIR: APPA hall



Conclusions

- **Already first FAIR beams (p or U) delivered to the APPA cave will enable novel experiments in the field of HED science**
- Diagnostics necessary to field these experiments are being developed
- 200J/ns laser system will allow driving intense keV x-ray sources for x-ray probing, and as shock driver for proton radiography
- X-ray radiography of large high-Z plasmas will require PW-class laser system