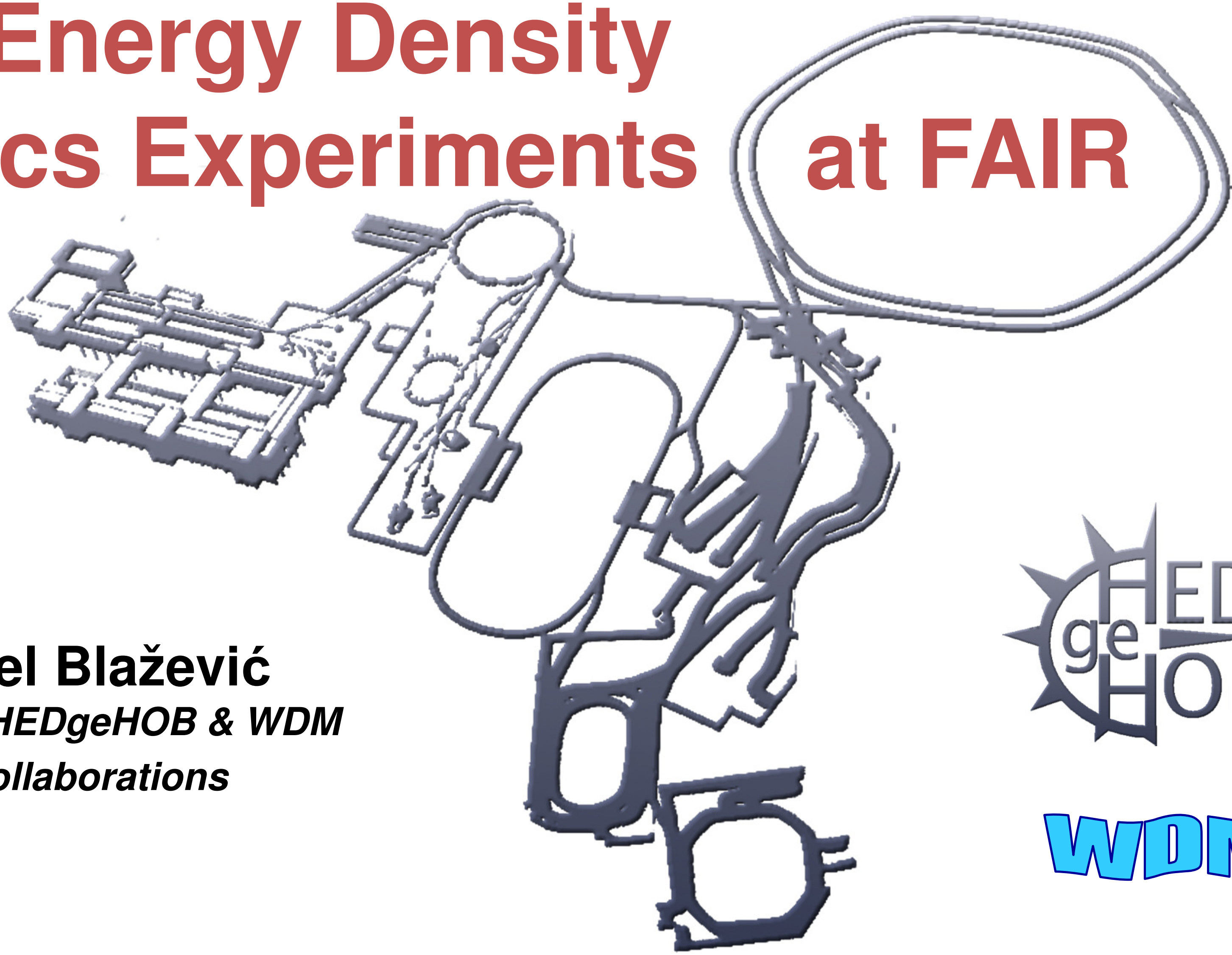
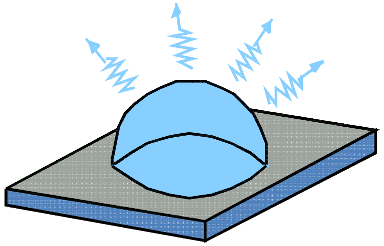
High Energy Density Physics Experiments at FAIR



Abel Blažević

for the HEDgeHOB & WDM collaborations

High Energy Density Matter (Warm Dense Matter)



T ~ **2,000 – 200,000 K**

ρ ~ **solid density**

P ~ **kbar, Mbar**

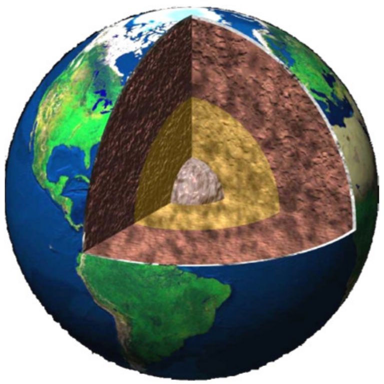
→ EOS

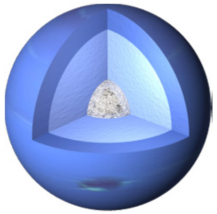
→ thermodynamical properties

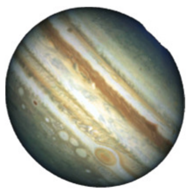
- phase transitions
- critical points

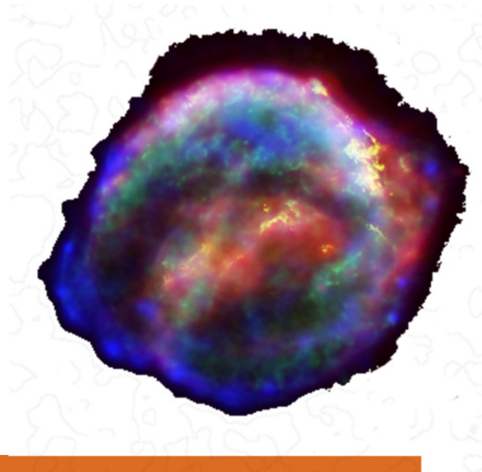
→ radiative properties

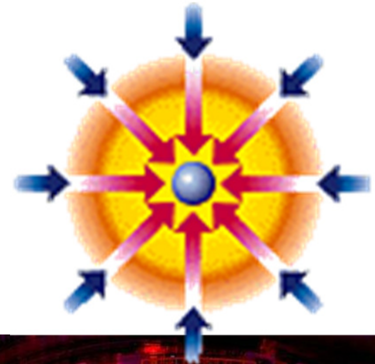
→ conductivity

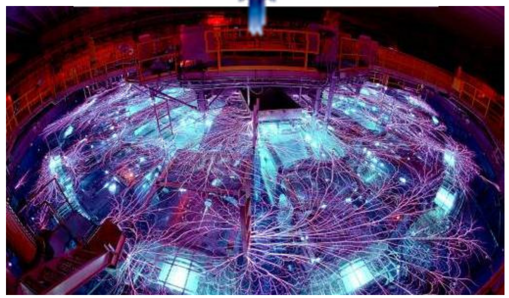






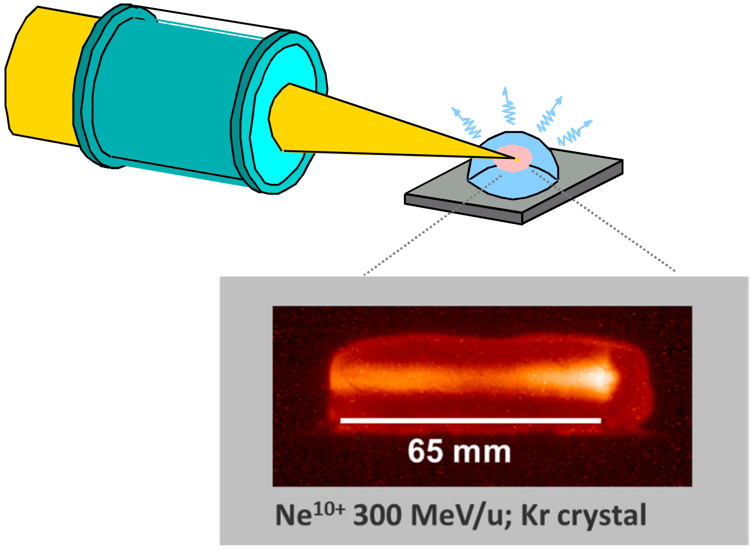






Ion beam as a driver for HED physics experiments

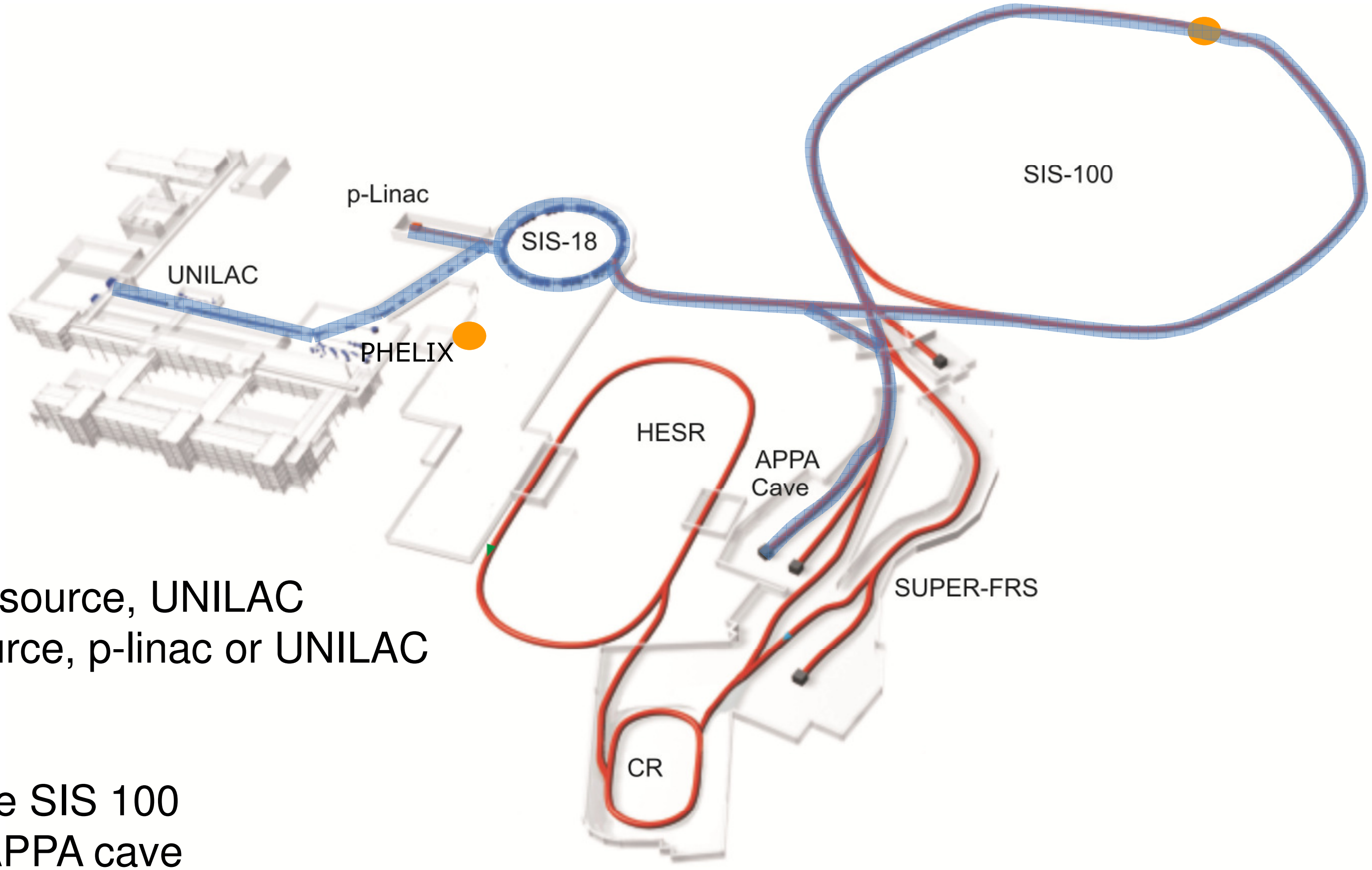
- large volume of sample (mm^3)
- highly uniform, well defined conditions
- high entropy @ high densities
- high rep. rate and reproducibility
- any target material



$$P_s = E_s/t\ ,\ E_s \propto \frac{1}{\rho} \cdot \frac{dE}{dx} \cdot \frac{N}{r_b^2}$$

- heavy ions ($dE/dx \sim Z^2$), $Z_U = 92$
- maximum beam intensity (number of ions per pulse) $N \sim 10^9 - 5 \cdot 10^{11}$
- minimum focal spot size at the target $r_b < 0.5$ mm
  - √ reducing transverse emittance – electron cooling
  - √ special final focus system
- minimum pulse duration $t \sim 50 - 100$ ns => bunch compression

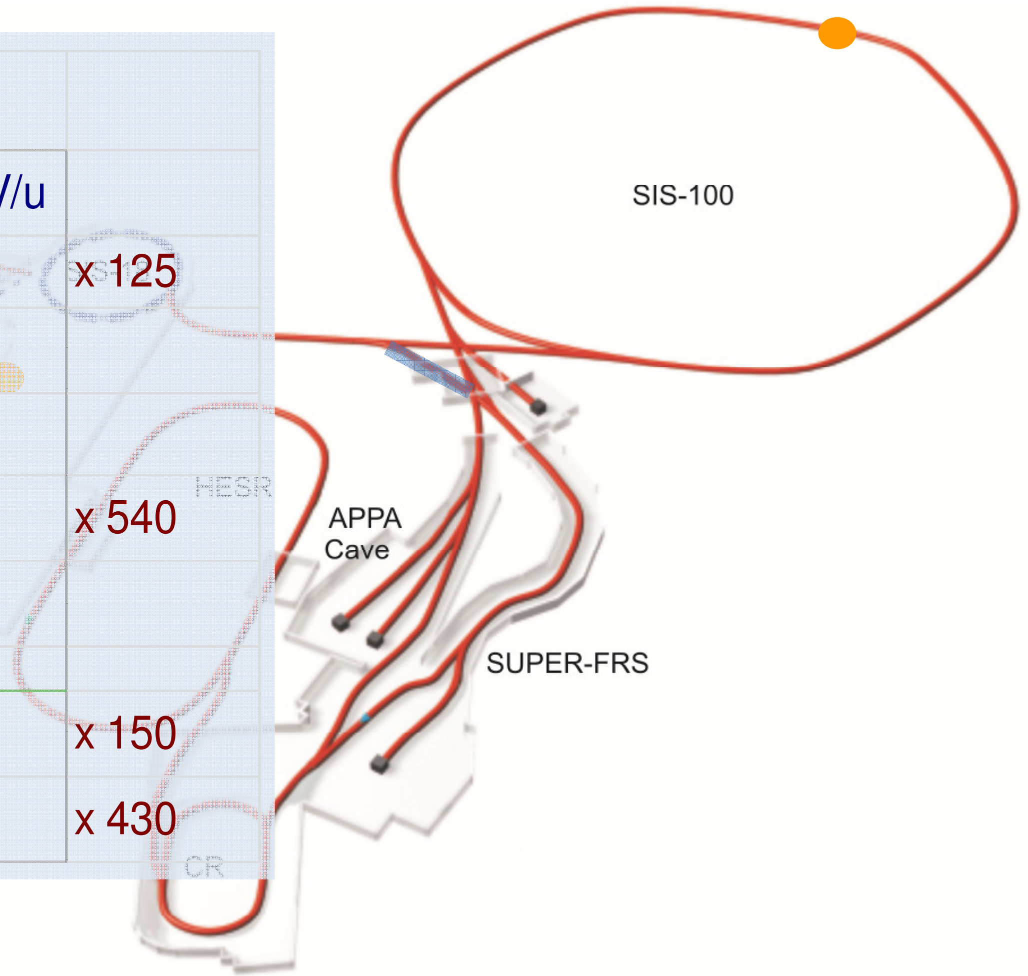
Accelerator components needed for HEDgeHOB/WDM



- heavy ion source, UNILAC
- proton source, p-linac or UNILAC
- SIS 18
- SIS 100
- bypass line SIS 100
- HEBT to APPA cave
- APPA cave

Comparison GSI - FAIR

Uranium beam	GSI	FAIR	
E_o	400 MeV/u	0.4 – 2.7 GeV/u	
N	$4{\cdot}10^9$	$5{\cdot}10^{11}$	x 125
E_{beam}	0.06 kJ	19 kJ	
τ	130 ns	70 ns	
P_{beam}	0.5 GW	270 GW	x 540
S_f	~1 mm	~1 mm	
	Lead target		
E_s	1 kJ/g	150 kJ/g	x 150
P_s	5 GW/g	2 TW/g	x 430



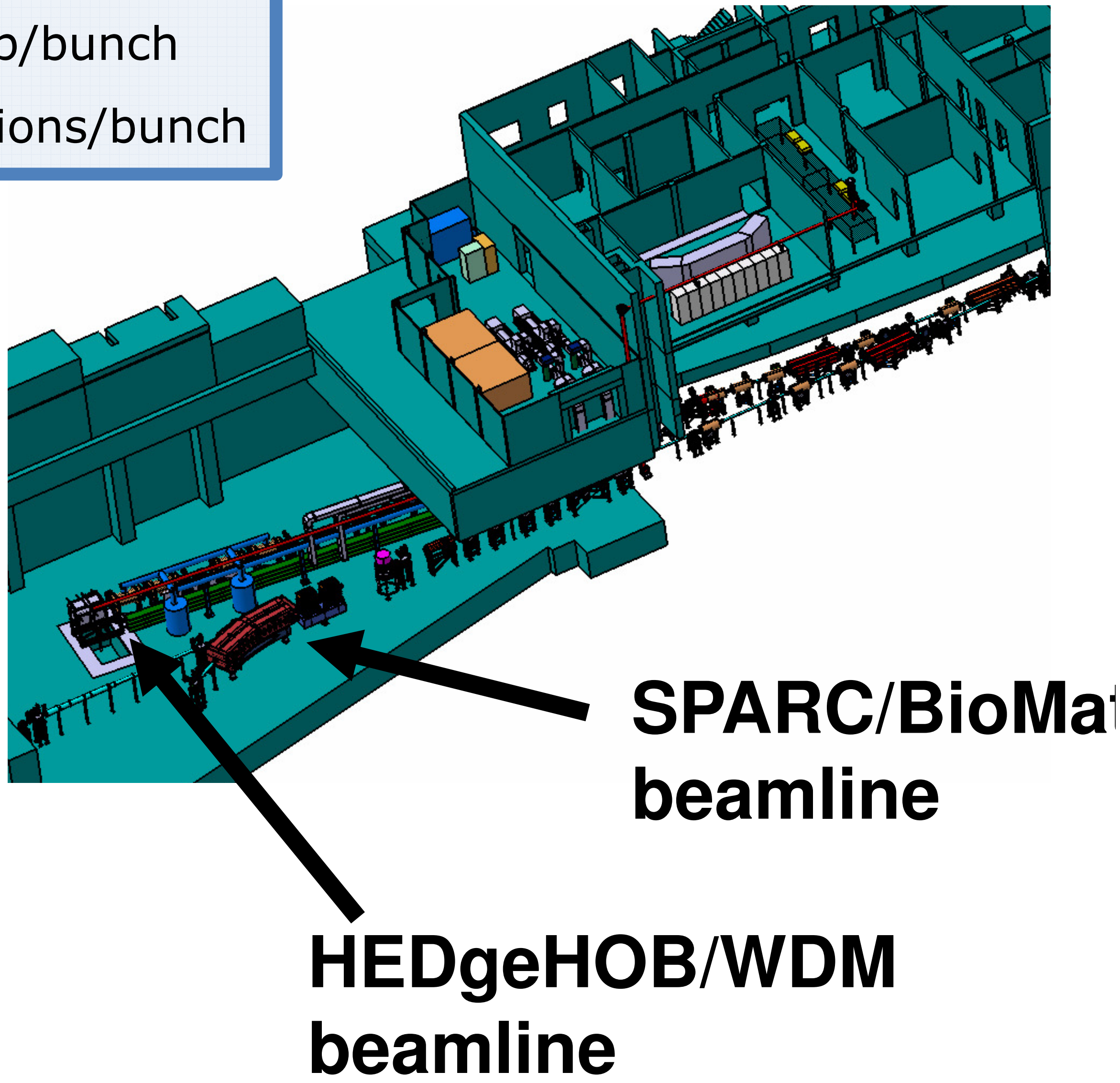
Interesting experiments are foreseen even with beam intensities much lower (10^{10}-10^{11}) than the FAIR design value

FAIR-MSV: APPA Cave

protons (10 GeV): 2 x 10^{13} p/bunch

U^{28+} (2 GeV/u): 5 × 10^{11} ions/bunch

1. Matching section: preforming the ion beam for the different experimental demands
2. Wobbler: creating a ring shaped focus for LAPLAS
3. PRIOR: proton radiography
4. Final focusing system: 4 sc quadrupoles for final focusing and PRIOR imaging
5. Target chamber: target positioning, exchange, diagnostics
6. Laser: plasma diagnostics, plasma driver



HEDgeHOB experimental frameworks

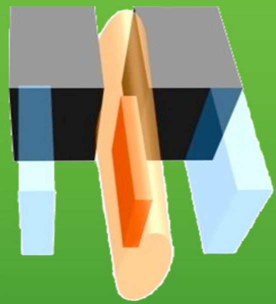
Possible with early SIS-100 or SIS-18 beams!

HIHEX

Heavy Ion Heating and Expansion

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

heavy ions



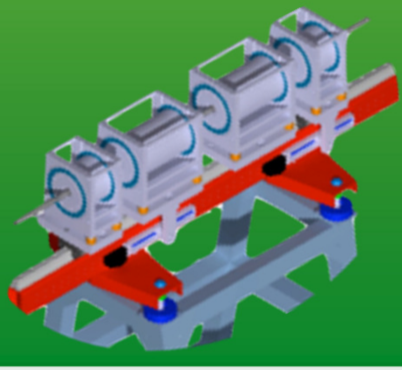
- uniform quasi-isochoric heating of a large-volume dense target and isentropic expansion
- numerous high-entropy HED states:
  EOS and transport properties of non-ideal plasmas / WDM for various materials

PRIOR

Proton Microscope for FAIR

p, 5–10 GeV, $2{\cdot}10^{13}$, PRIOR

protons

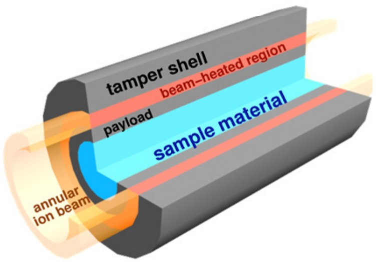


- worldwide unique high-energy proton microscopy setup with SIS-100 proton beam
- dynamic HEDP experiments and PaNTERA:
  unparalleled dynamic density distribution measurements and Proton Therapy and Radiography project (with BIOMAT)

LAPLAS

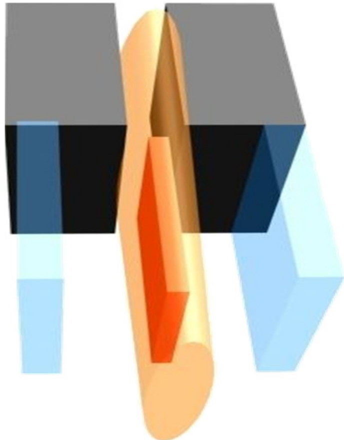
Laboratory Planetary Sciences

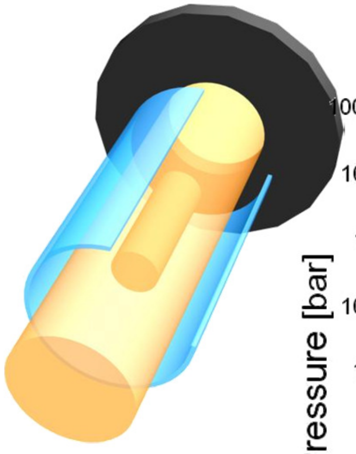
U^{28+}, 1 AGeV, $5{\cdot}10^{11}$, Wobbler

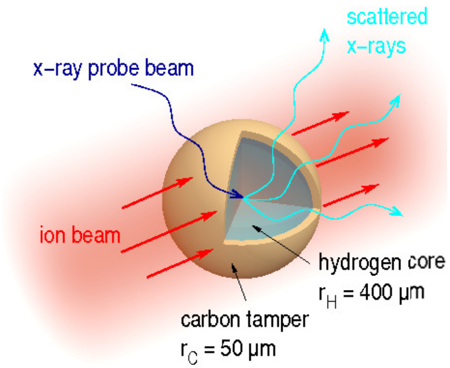


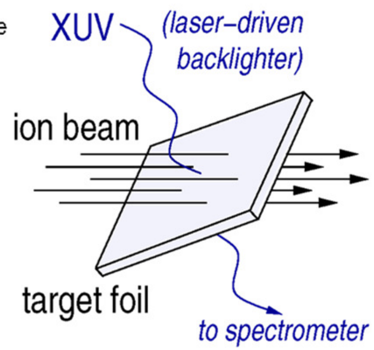
- ring-shaped beam implodes a heavy tamper shell, low-entropy compression of hydrogen
- Mbar pressures @ moderate temperatures:
  hydrogen metallization, interior of Jupiter, Saturn or Earth

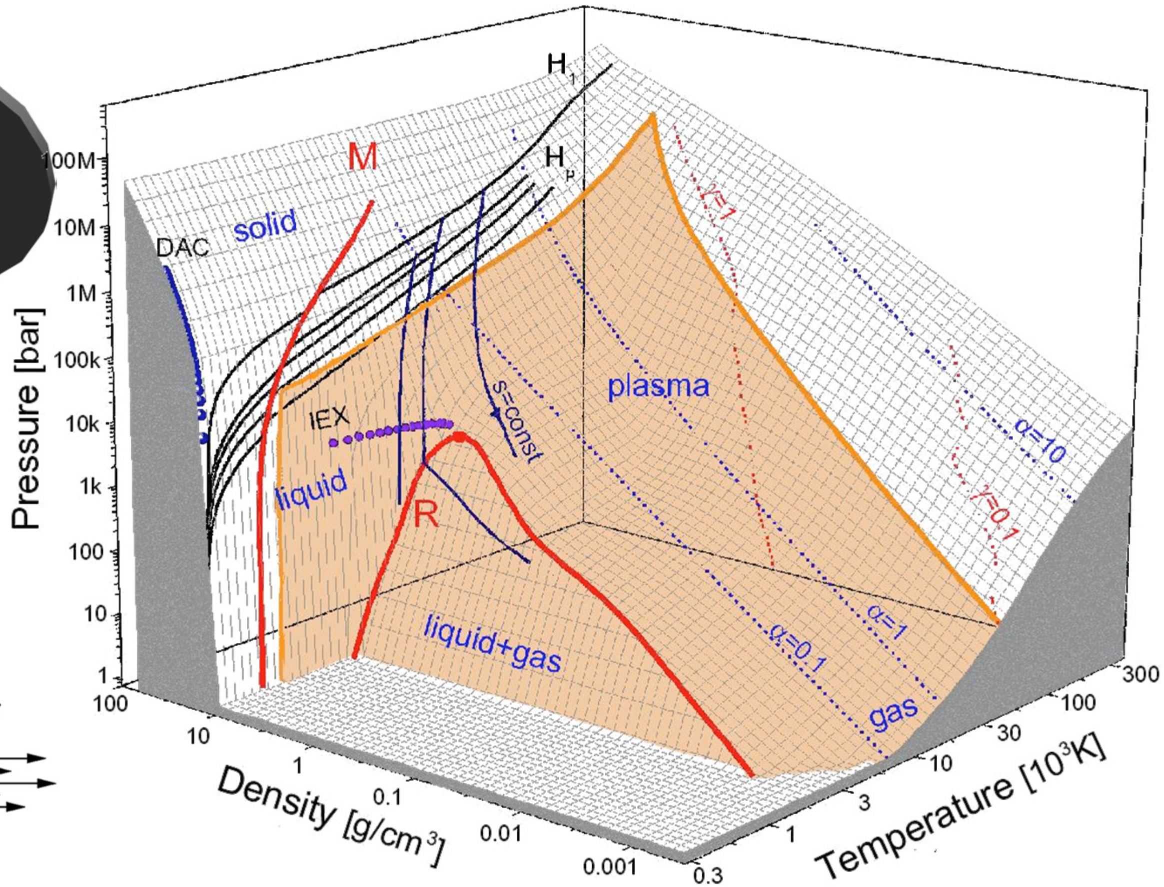
HIHEX/WDM - Heavy Ion Heating and Expansion





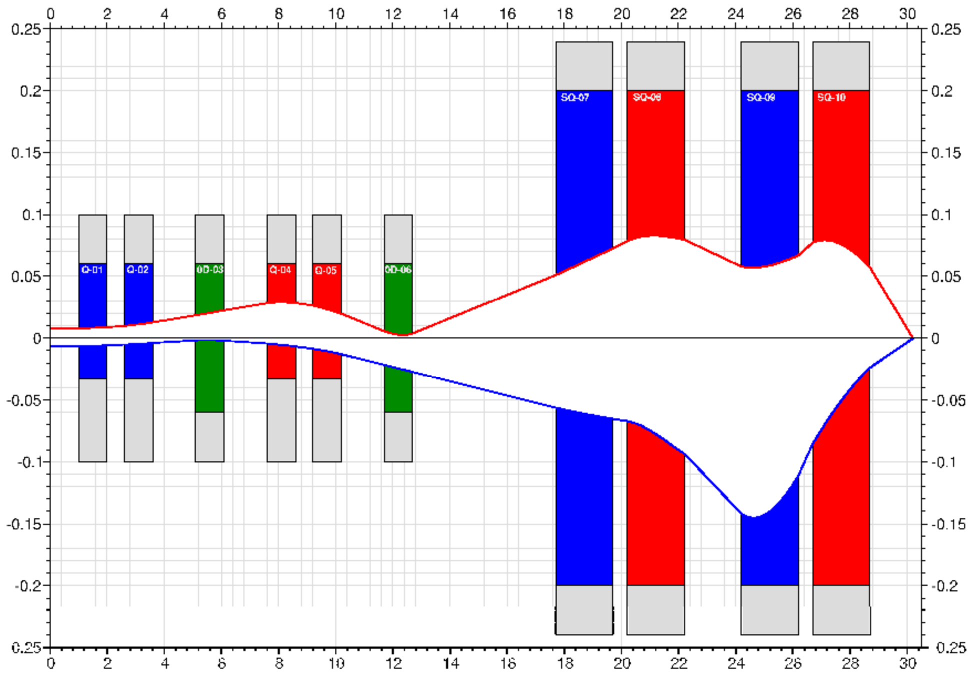




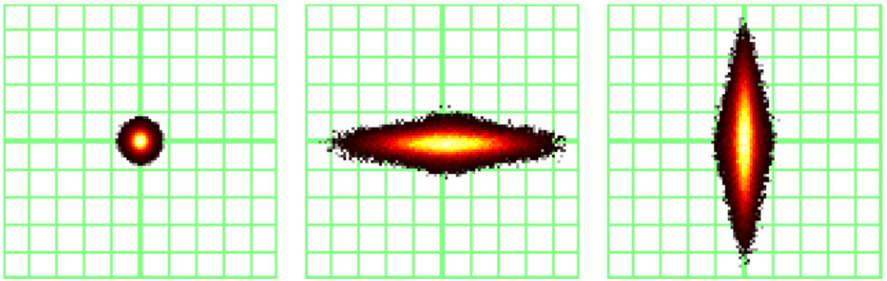


Ion optical design of the HIHEX beam line

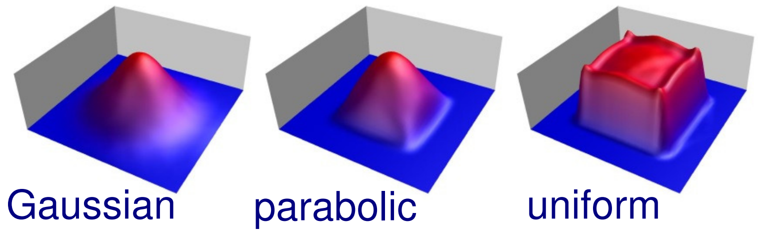
Layout of the **HIHEX** beam line

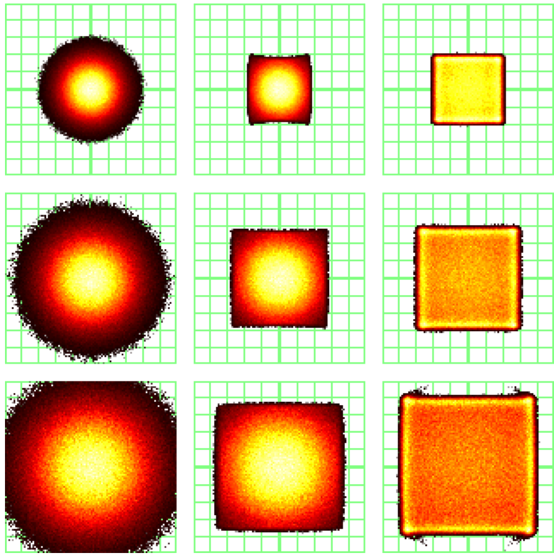


Focusing capabilities: 0.85mm focal spot



Beam shaping/correction system using non-linear ion optical elements



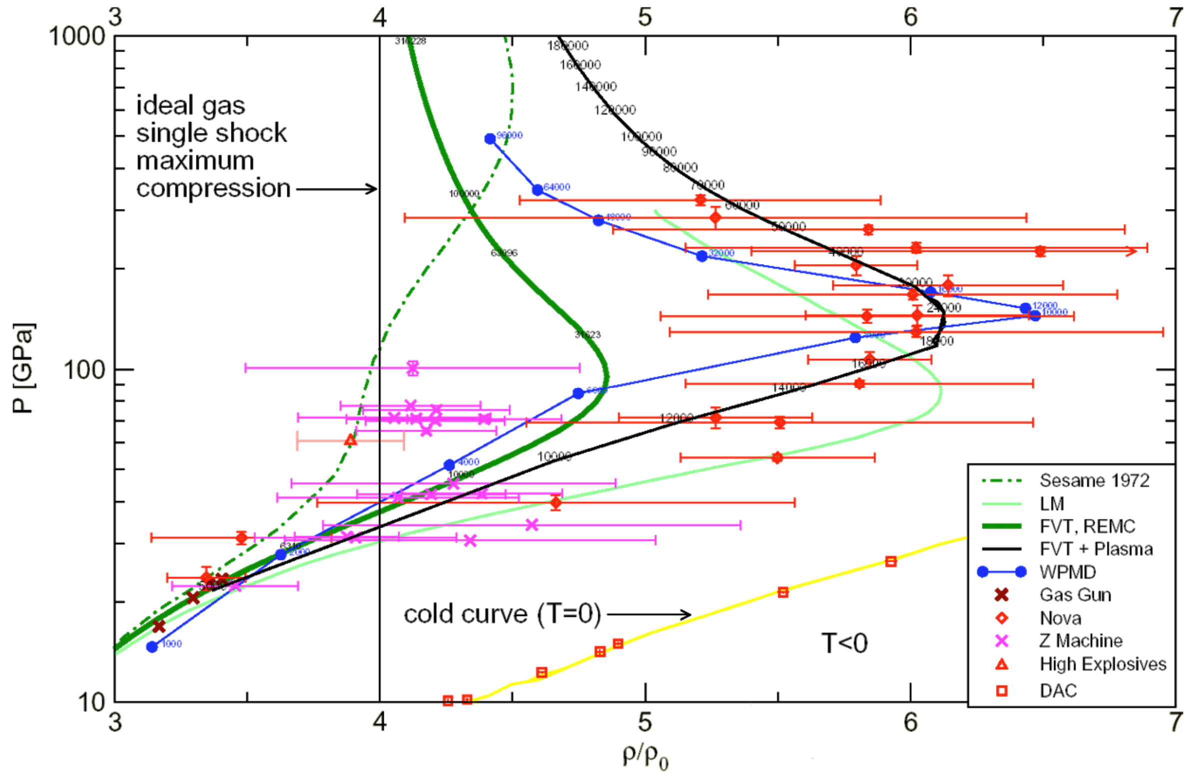


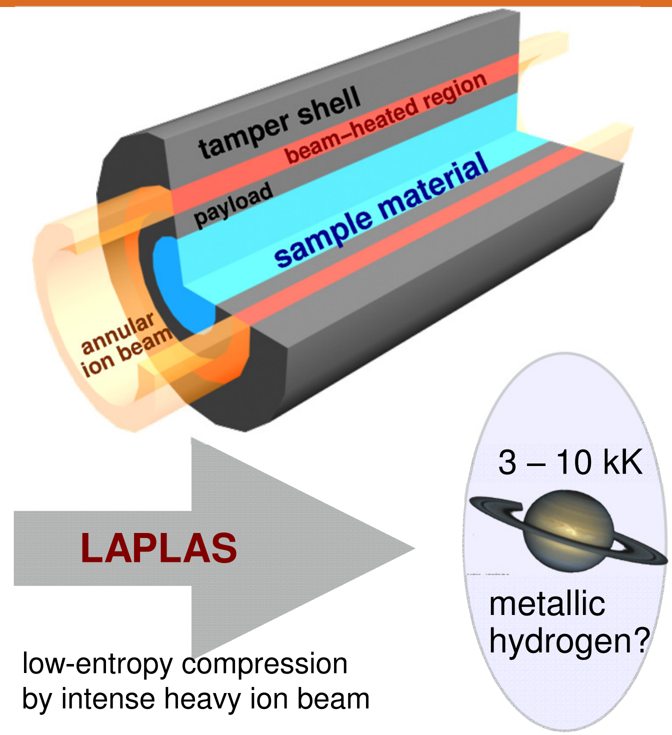
Ion beam parameters - HIHEX/WDM

- Heavy ions, Xe to U
- high intensities: 10^{10} – 5×10^{11}
- E = 0,4 – 2 GeV
- $\Delta E/E > 5 \times 10^{-4}$
- smallest transversal emittance, preferably cooled
- bunch compression, pulse length: τ = 50 ns
- steep rising edge of pulse

Five proposals for early HIHEX/WDM experiments @FAIR were submitted

LAPLAS and hydrogen EOS problem





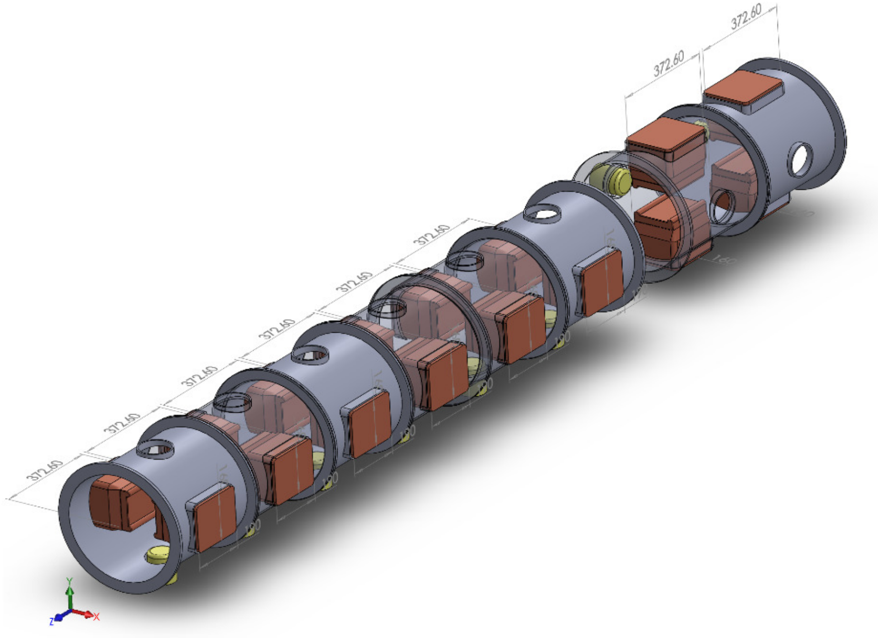
Hydrogen is the simplest and the most abundant element in the universe

and yet very little is known about its properties in HED states:

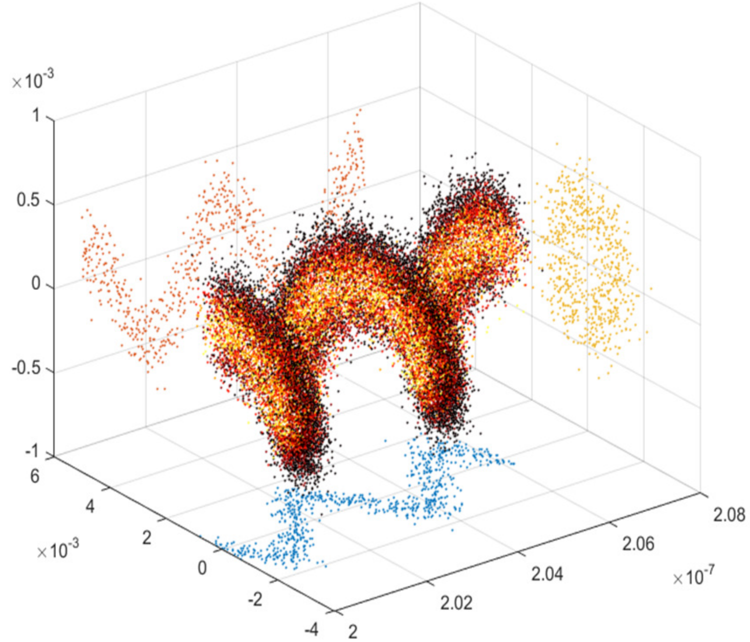
metallization?, metastable state?, superconductor?, structure of Jupiter and Saturn?

LAPLAS – Laboratory Planetary Science

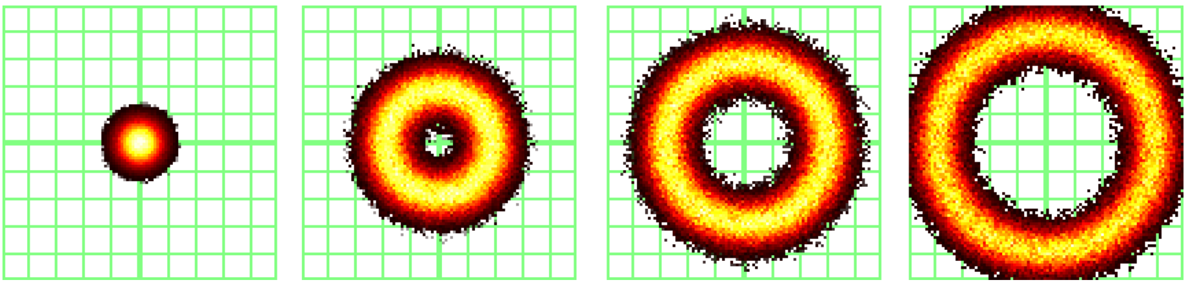
Design of rf beam deflector (wobbler)



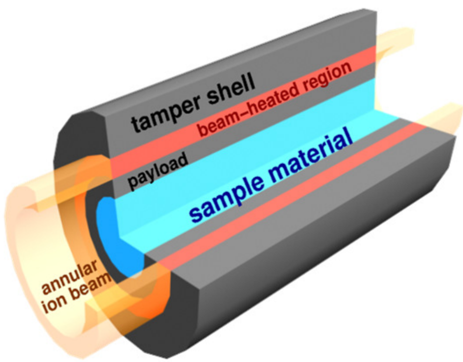
3D simulation of deflected ion beam



Transverse beam intensity distribution in the focal spot



LAPLAS target for compression



Ion beam parameters - LAPLAS

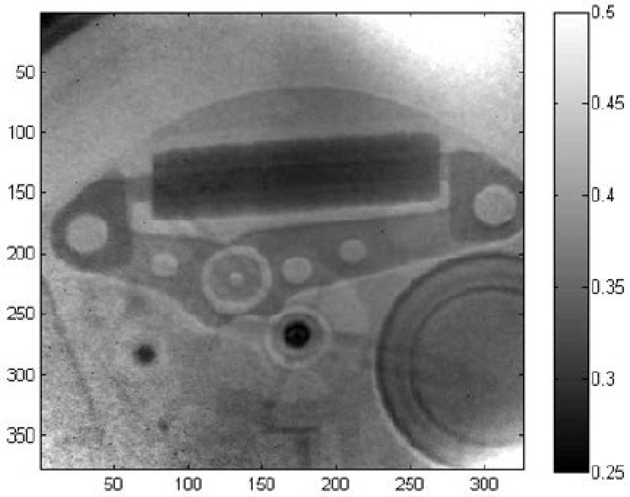
- Heavy ions, preferably U
- highest intensities: 5×10^{11}
- E = 0,4 – 2 GeV
- $\Delta E/E > 5 \times 10^{-4}$
- smallest transversal emittance, preferably cooled
- bunch compression, pulse length: $\tau = 50$ ns
- steep rising edge of pulse
- homogeneous intensity distribution over time

Commissioning of PRIOR

PRIOR: high-energy proton microscopy facility

measures density distribution (µm and ns scale)

- Construction of prototype at HHT (SIS18)
- Commissioned in 2014 with 4.5 GeV protons:
  - successful static test → lateral resolution 30 µm
  - successful dynamic test → temporal resolution ~ 10 ns



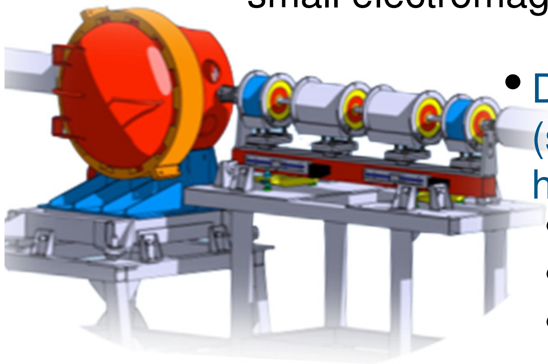
Radiograph of quartz watch
(density distribution)

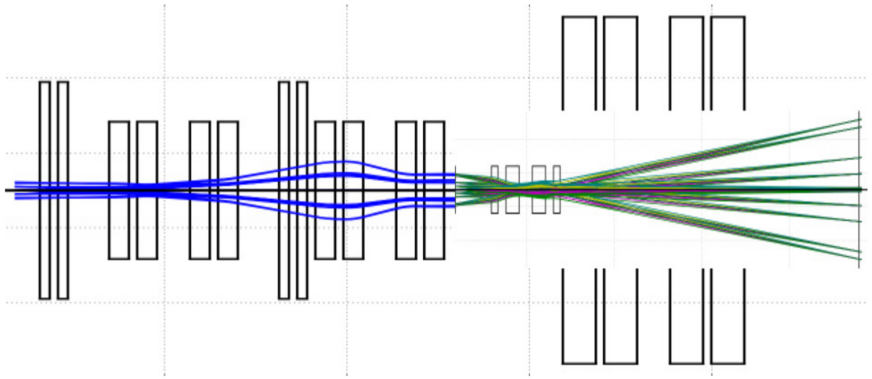
high-gradient PRIOR magnets

PRIOR at FAIR

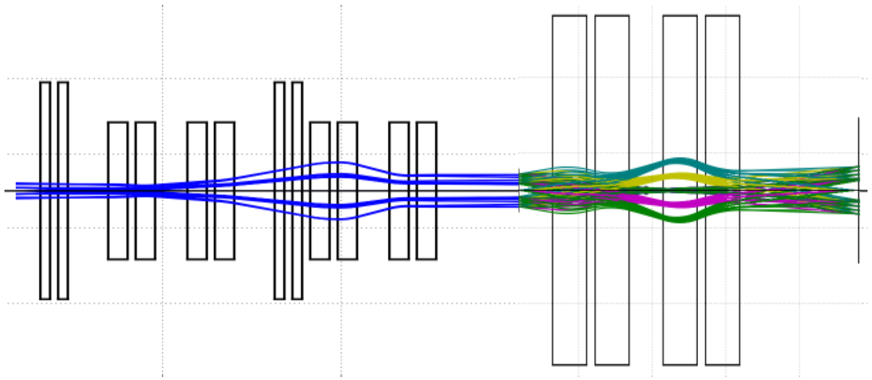
- Built in SIS-100 HEDgeHOB beam line
- SIS-18 (1 - 4 bunches within 0.6 µs) or SIS-100 (1 - 16 bunches within 3.4 µs) proton beams:
  3 – 10 GeV proton energy, moderate (10^{11}) to high ($2 \cdot 10^{13}$) intensity

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

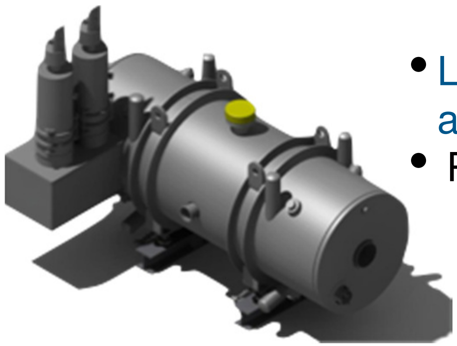




- Dynamic compression (shocks, ramp) or fast heating by external drivers:
  - pulsed power generator
  - high energy laser
  - light gas gun
  - HE generators



Superconducting imager with high-gradient quadrupoles



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

Proton beam parameters - PRIOR

- high spatial resolution (~10 um)
- high temporal resolution (~5 ns)
- good density reconstruction (~ 1%)

$\Big\}$ at the same time

- for ~3 cm FOV @10 um: 10 Mpix detector
- 1% density reconstruction accuracy (Poisson: ~$1/\sqrt{N}$): N/pixel = 5×10^4
- System efficiency (transmission, detector): 25%
- $\rightarrow$ N = 2×10^{12} protons/image

- time resolution of 5 ns: N/t = 4×10^{11} / ns = 2×10^{13} / 50 ns

- SIS-18 (1 - 4 bunches within 0.6 µs) or
  SIS-100 (1 - 16 bunches within 3.4 µs)
- E = 3 – 10 GeV
- $\Delta E/E > 5 \times 10^{-4}$
- smallest transversal emittance, preferably cooled
- pulse length: t = 50 ns – 3.4 µs

Five proposals for early PRIOR experiments @FAIR were submitted

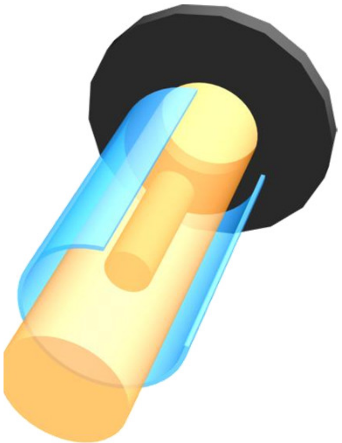
Summary: Ion beam parameters for HEDgeHOB/WDM

	HIHEX/WDM	LAPLAS	PRIOR
Ion	heavy, Xe - U	U	p
Intensity	$10^{10} - 5 \times 10^{11}$	5×10^{11}	$10^{12} - 5 \times 10^{13}$
Energy	0.4 - 2 GeV/u	0.4 - 2 GeV/u	3 - 10 GeV
$\Delta E/E$	5×10^{-4}	5×10^{-4}	5×10^{-4}
Puls length	50 - 100 ns	50 ns	50 ns - 3.4 µs
Extraction	fast, 1 bunch	fast, 1 bunch	fast, 1-16 bunches
Rep. rate	2 - 20 shots/h	2 - 20 shots/h	2 - 20 shots/h
Synch. with diagnostics/laser	1 ns	1 ns	1 ns

Questions to the accelerator team:

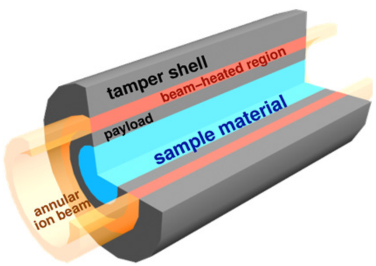
- pointing stability
- pulse form, 50 ns FWHM?, foot
- Does the focus vary with intensity?
- transversal homogeneity
- parallel operation, especially p?

Target: lead cylinder, l = 2 mm, r = 300 µm



Intensity U^{28+}, τ = 50 ns	Focus (FWHM, mm)	E (kJ/g)	P (kbar)	T(K)
10^{10}	1	1.4	180	9450
10^{11}	1	14	830	56000
10^{11}	4	0.9	103	6250

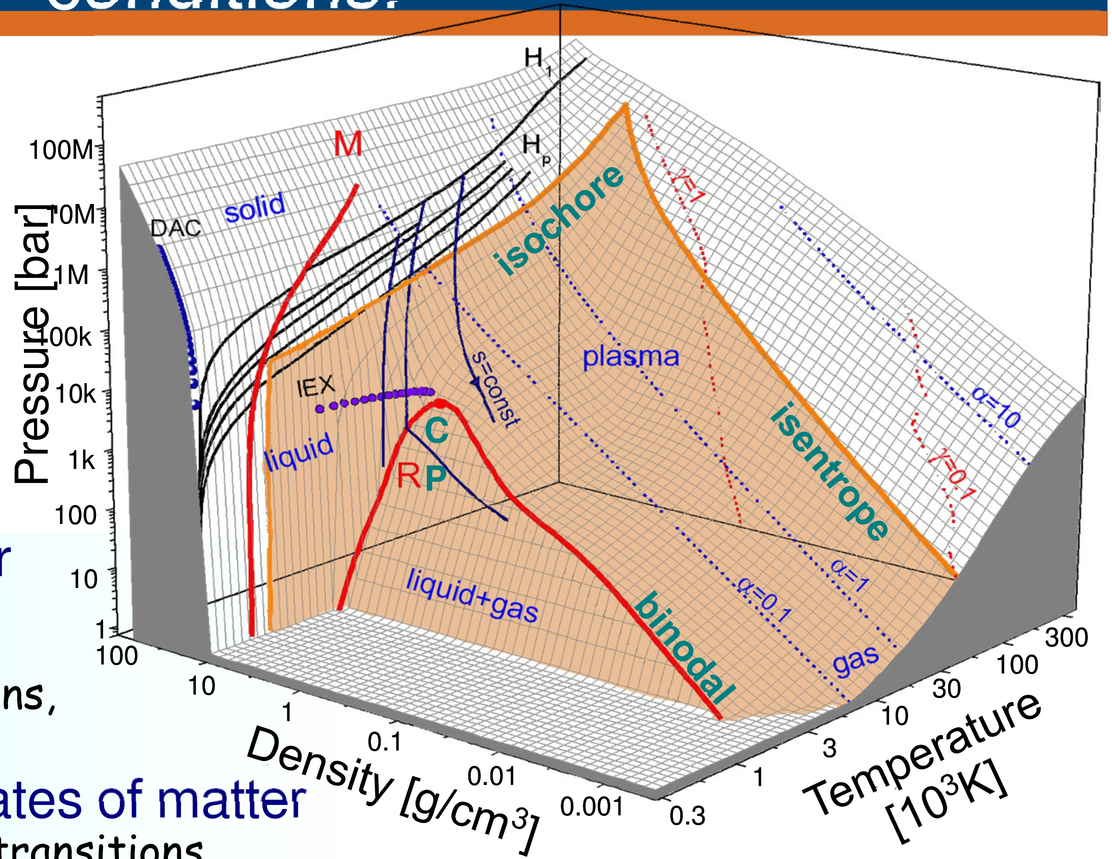
Target: frozen Hydrogen, l = 5 mm, r = 400 µm



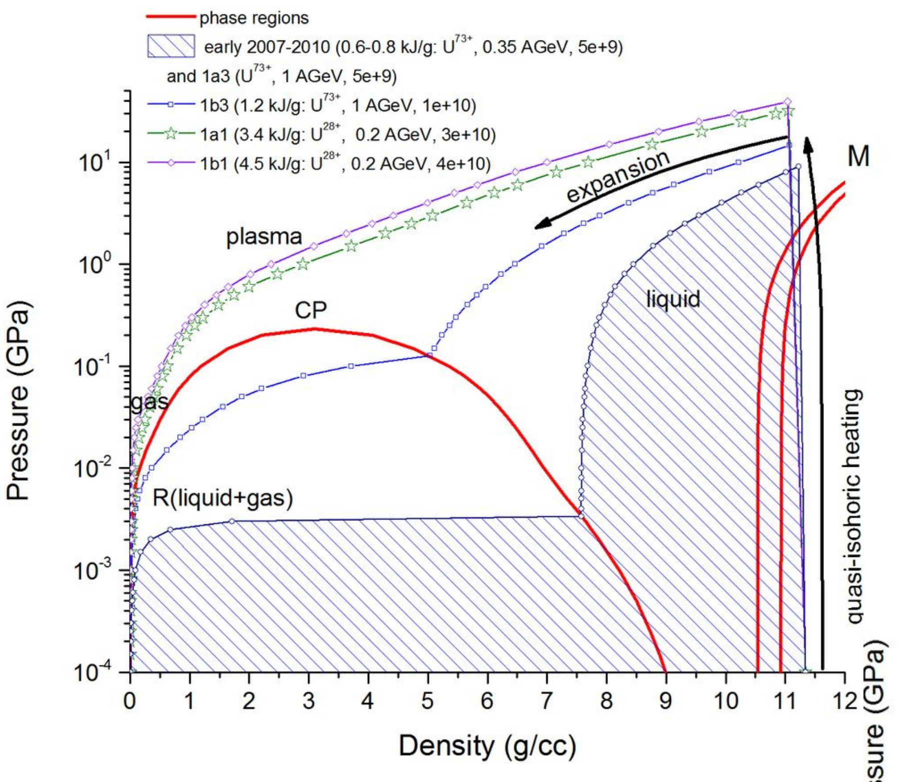
5 x 10^{11}	1	19	3000	3000

Physics program - fundamental properties of matter under extreme conditions:

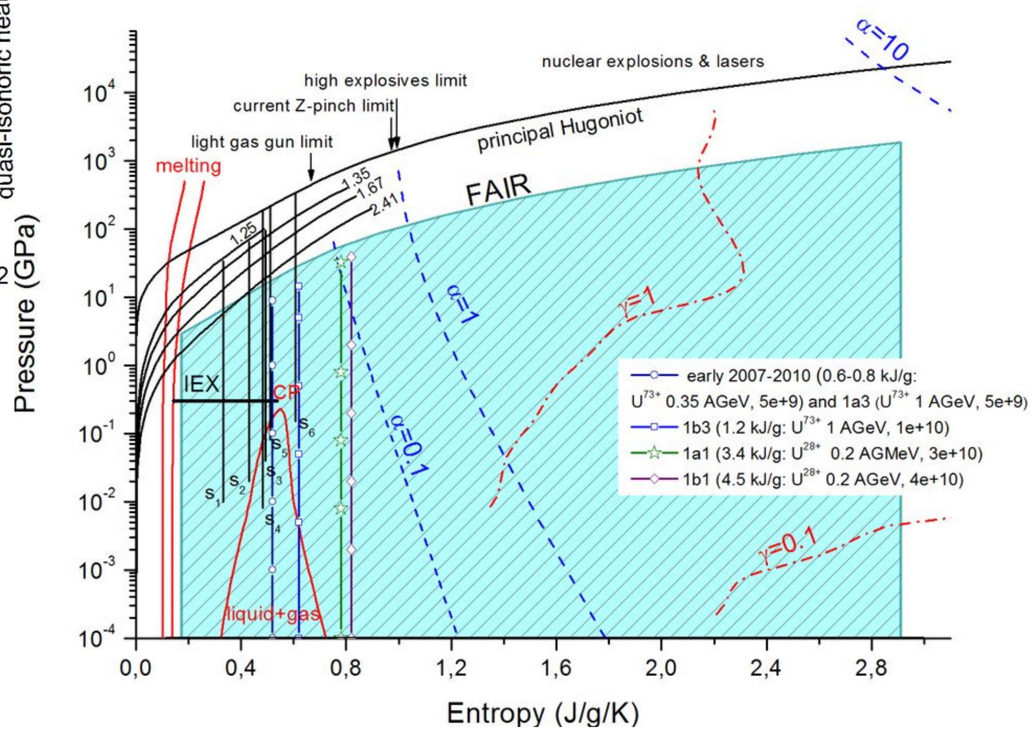
HED regions of Pb EOS accessible at FAIR



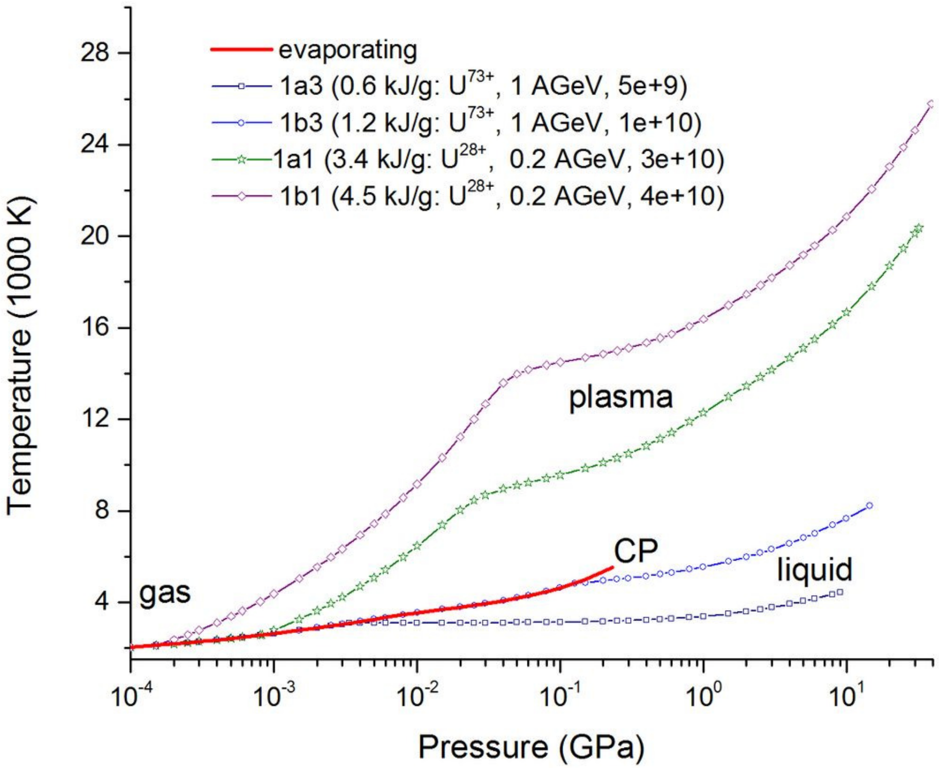
- **Equation-of-state of HED matter**
  basic thermodynamic properties of matter in unexplored regions of the phase diagram (two-phase regions, critical points, non-ideal plasmas)
- **Phase transitions and exotic states of matter**
  metal-to-insulator or plasma phase transitions, hydrogen metallization problem, etc.
- **Transport and radiation properties of HED matter**
  electrical and thermal conductivity, opacity, etc.
- **Stopping properties of non-ideal plasma**
  anomalous temperature and density dependence of the heavy ion stopping and charge-exchange cross sections



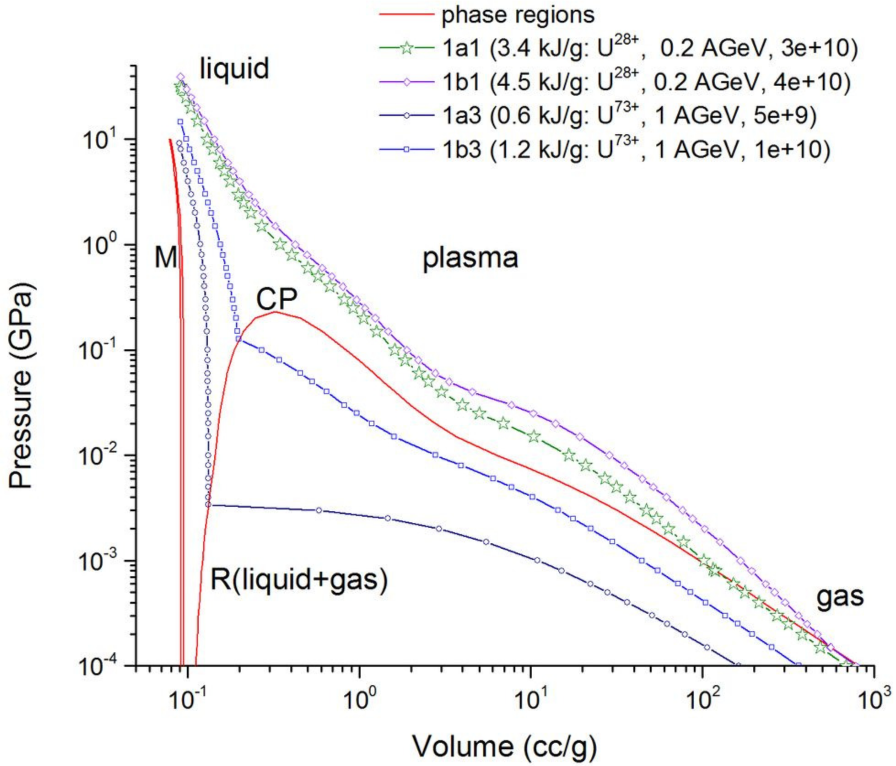
phase regions
early 2007-2010 (0.6-0.8 kJ/g: U73+, 0.35 AGeV, 5e+9)
and 1a3 (U73+, 1 AGeV, 5e+9)
1b3 (1.2 kJ/g: U73+, 1 AGeV, 1e+10)
1a1 (3.4 kJ/g: U28+, 0.2 AGeV, 3e+10)
1b1 (4.5 kJ/g: U28+, 0.2 AGeV, 4e+10)
plasma
expansion
M
CP
liquid
gas
R(liquid+gas)
quasi-isohoric heating
Pressure (GPa)
Density (g/cc)



α=10
nuclear explosions & lasers
high explosives limit
current Z-pinch limit
principal Hugoniot
light gas gun limit
melting
FAIR
1.35
1.67
2.41
1.25
α=1
γ=1
IEX
CP
α=0.1
early 2007-2010 (0.6-0.8 kJ/g: U73+ 0.35 AGeV, 5e+9) and 1a3 (U73+ 1 AGeV, 5e+9)
1b3 (1.2 kJ/g: U73+ 1 AGeV, 1e+10)
1a1 (3.4 kJ/g: U28+ 0.2 AGMeV, 3e+10)
1b1 (4.5 kJ/g: U28+ 0.2 AGeV, 4e+10)
γ=0.1
liquid+gas
Pressure (GPa)
Entropy (J/g/K)

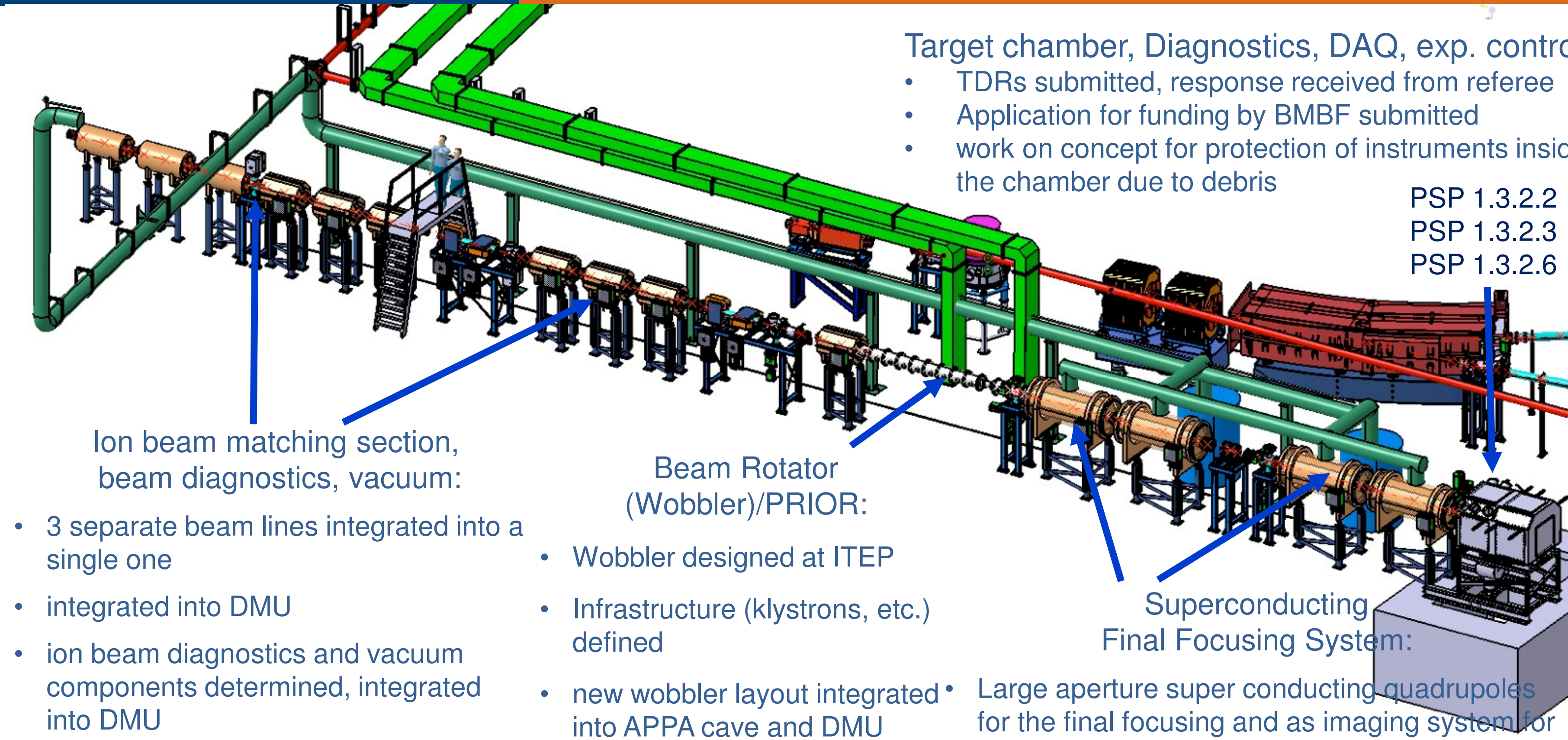


evaporating
1a3 (0.6 kJ/g: U73+, 1 AGeV, 5e+9)
1b3 (1.2 kJ/g: U73+, 1 AGeV, 1e+10)
1a1 (3.4 kJ/g: U28+, 0.2 AGeV, 3e+10)
1b1 (4.5 kJ/g: U28+, 0.2 AGeV, 4e+10)
plasma
CP
liquid
gas
Temperature (1000 K)
Pressure (GPa)



phase regions
1a1 (3.4 kJ/g: U28+, 0.2 AGeV, 3e+10)
1b1 (4.5 kJ/g: U28+, 0.2 AGeV, 4e+10)
1a3 (0.6 kJ/g: U73+, 1 AGeV, 5e+9)
1b3 (1.2 kJ/g: U73+, 1 AGeV, 1e+10)
liquid
M
plasma
CP
R(liquid+gas)
gas
Pressure (GPa)
Volume (cc/g)

Plasma Physics beam line



Target chamber, Diagnostics, DAQ, exp. controls:
- TDRs submitted, response received from referee
- Application for funding by BMBF submitted
- work on concept for protection of instruments inside the chamber due to debris

PSP 1.3.2.2
PSP 1.3.2.3
PSP 1.3.2.6

Ion beam matching section, beam diagnostics, vacuum:
- 3 separate beam lines integrated into a single one
- integrated into DMU
- ion beam diagnostics and vacuum components determined, integrated into DMU
- optical layout in progress
- TDR in progress

PSP 1.3.2.1.1

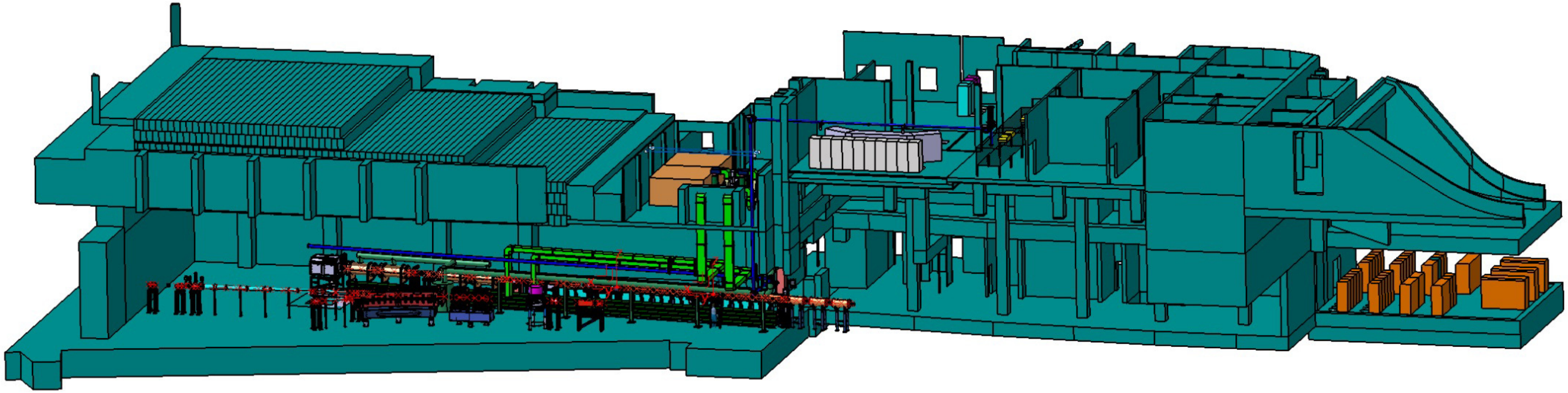
Beam Rotator (Wobbler)/PRIOR:
- Wobbler designed at ITEP
- Infrastructure (klystrons, etc.) defined
- new wobbler layout integrated into APPA cave and DMU
- TDR submitted

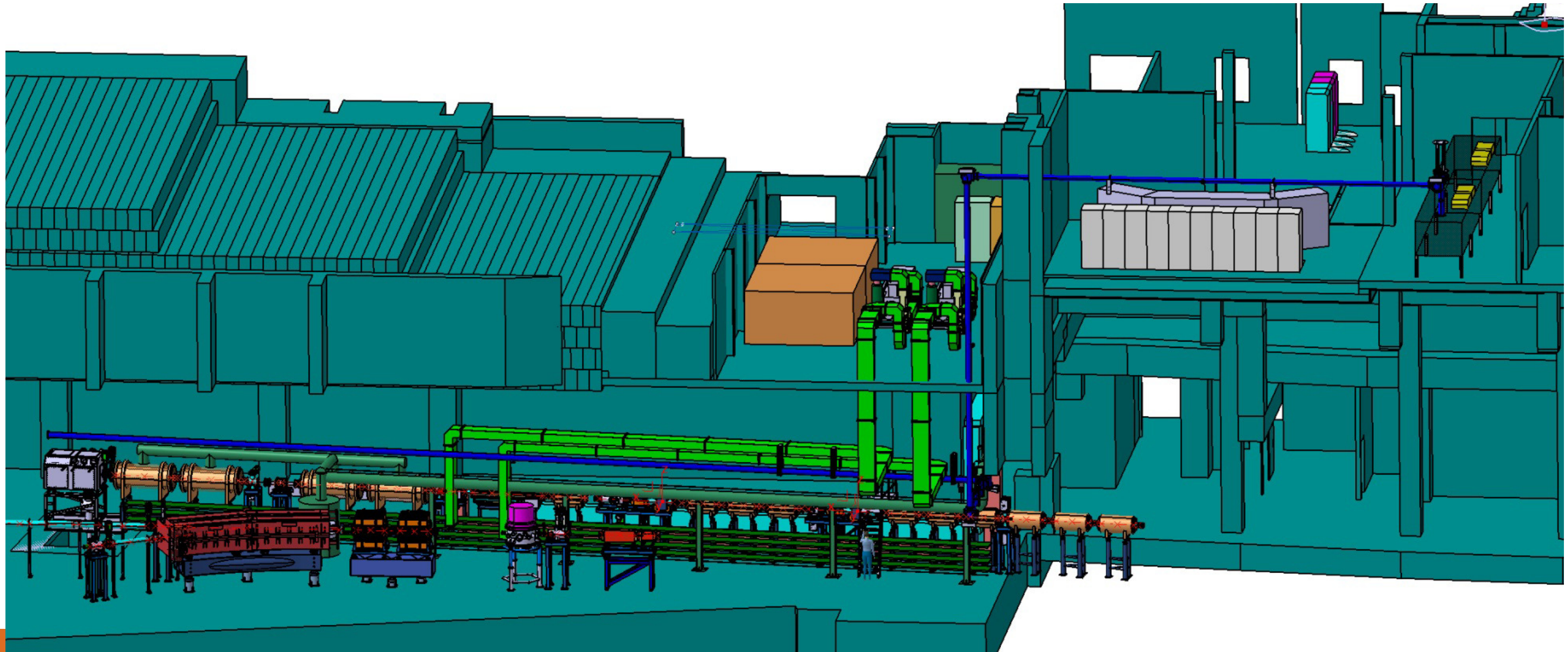
PSP 1.3.2.1.4

Superconducting Final Focusing System:
- Large aperture super conducting quadrupoles for the final focusing and as imaging system for PRIOR
- designed and to be built by IHEP
- TDR submitted and approved
- specification for SC current leads in EDMS
- First draft of specifications for Quads
- contract in preparation

PSP 1.3.2.1.2

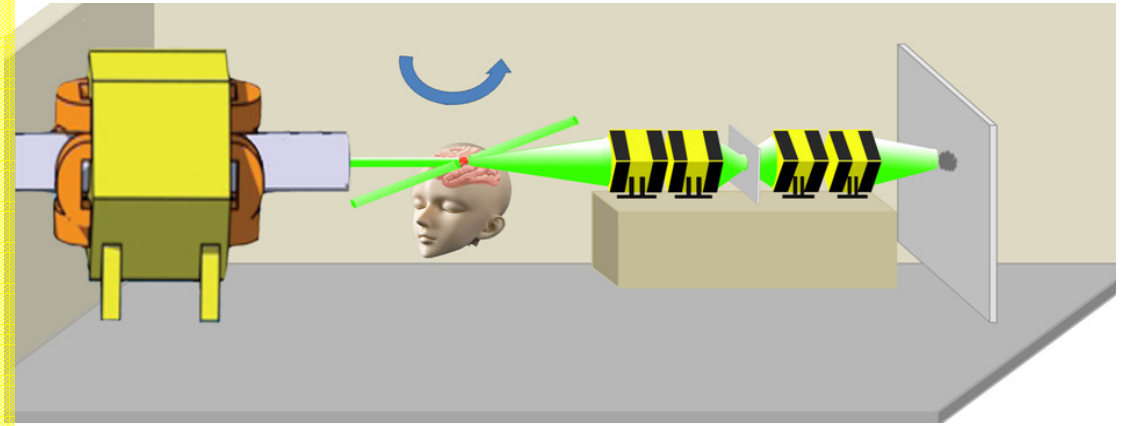
APPA cave

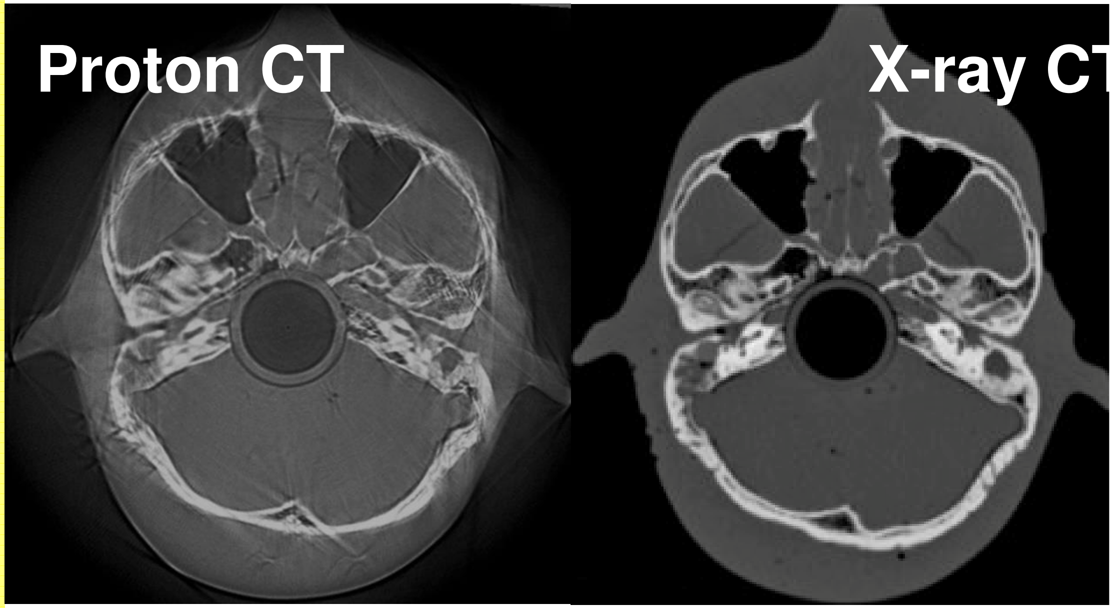




Particle Therapy at FAIR

- **New project (PaNTERA)** within APPA to exploit the PRIOR setup for therapy
- **Relativistic protons** (4.5 GeV) for image-guided, high-resolution, realtime, stereotactic radiosurgery (proton theranostics), (PRIOR setup)
- **CT of phantoms and animals** at LANL (800 MeV protons)
- **Further plans for tests of ^{11}C** and antiprotons in therapy



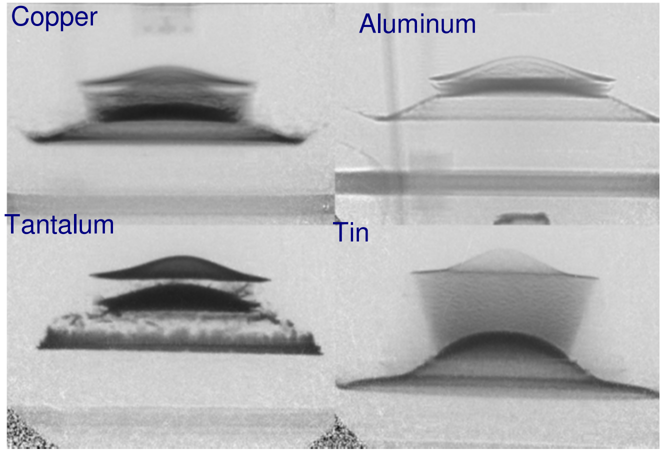


PRIOR – Proton Microscope for FAIR

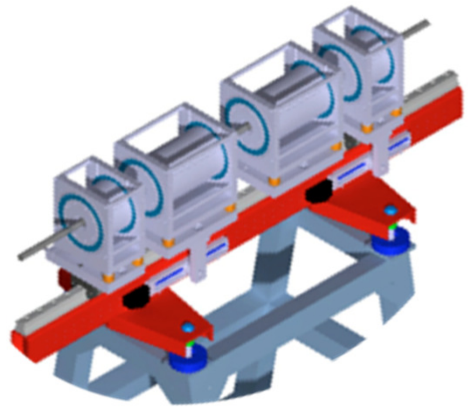
Pump-Probe: Ion and Proton beams

- the worldwide unique high energy proton microscopy facility PRIOR (10 µm / 10 ns resolution, sub-percent density reconstruction) will be integrated into the HEDgeHOB beam line
- using high-energy (5 – 10 GeV), high intensity ($5\cdot10^{12}$) SIS-100 proton beams

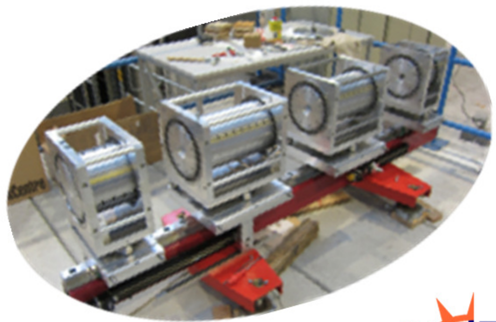
Material spall and fragmentation at micrometer level



courtesy of LANL



- joint multidisciplinary research of HEDgeHOB and BIOMAT during FAIR MSV:
  - materials at extreme dynamic environments generated by external drivers (plasma physics and materials research)
  - PaNTERA (Proton therapy and radiography) project (biophysics)

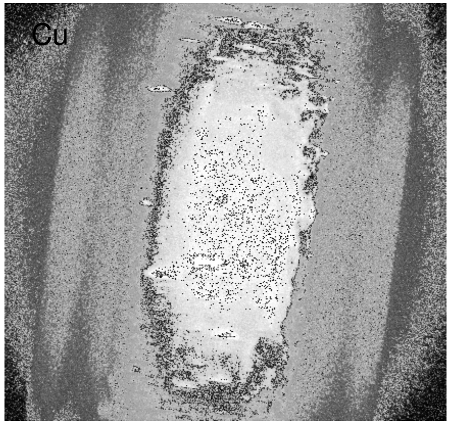


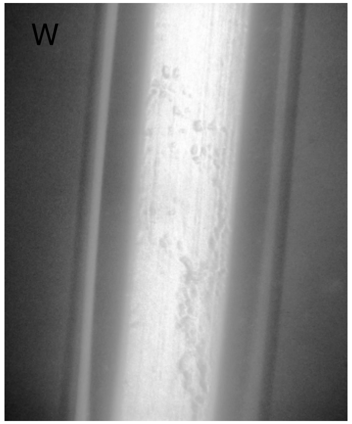
- PRIOR setup beam time commissioning at GSI: 2013/2014

HEDgeHOB

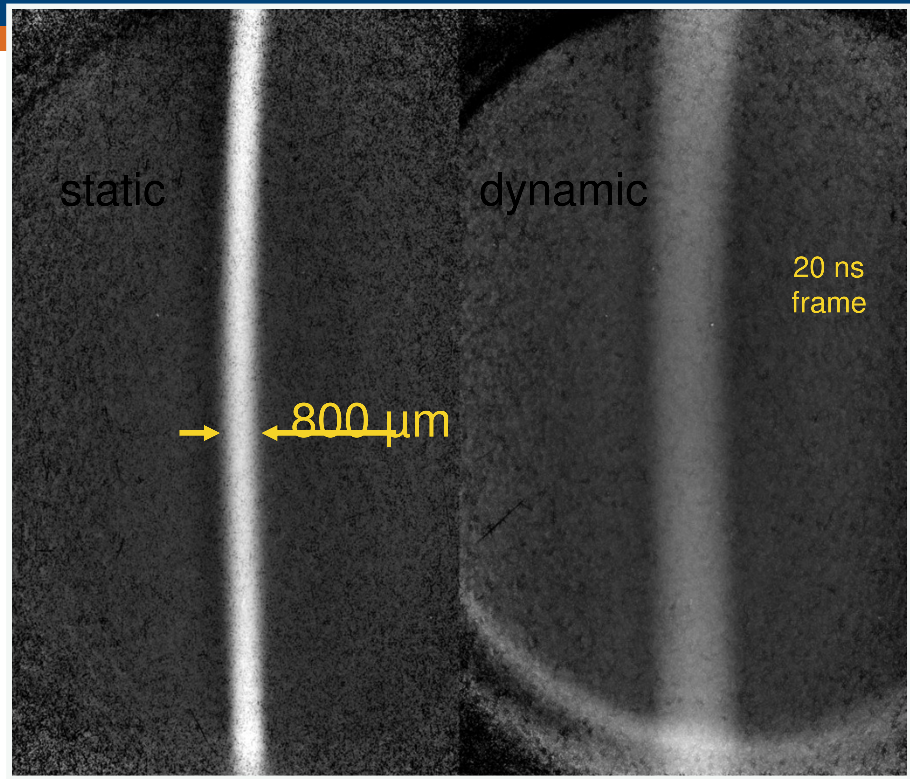
PRIOR prototype: dynamic experiments, July 2014

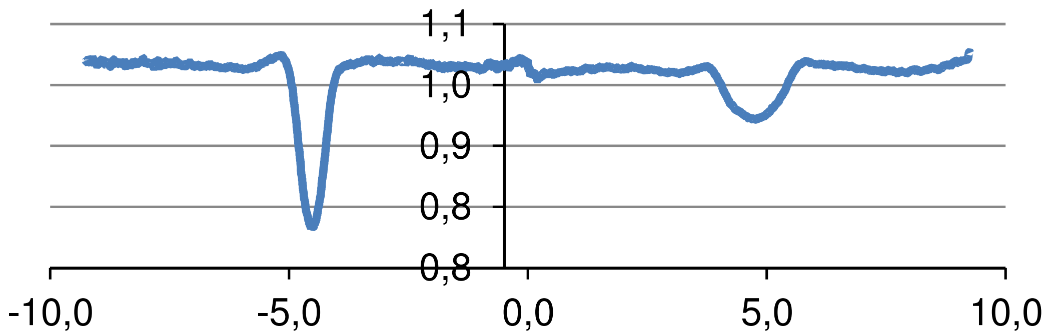
- Underwater electrical wire explosions (0.8 mm Ta wire in 2 cm of water).
- 35 kV, 40 MA/cm^2, 5 GW deposited
- WDM states in Ta: 10 kJ/g specific energy, ~2 eV temperature, ~km/s expansion velocity.
- Several dynamic experiments were performed to build a time history of the wire expansion.
- Main goal: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



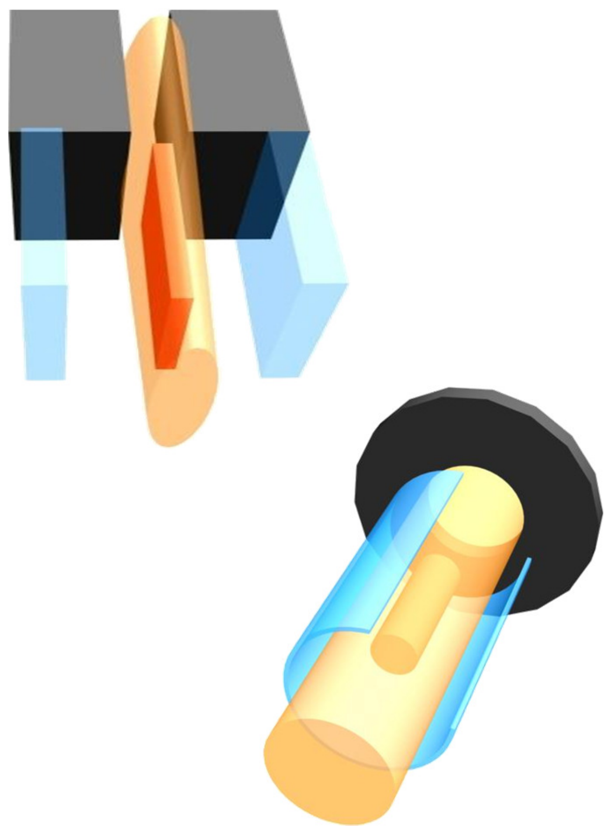


Self-emission images

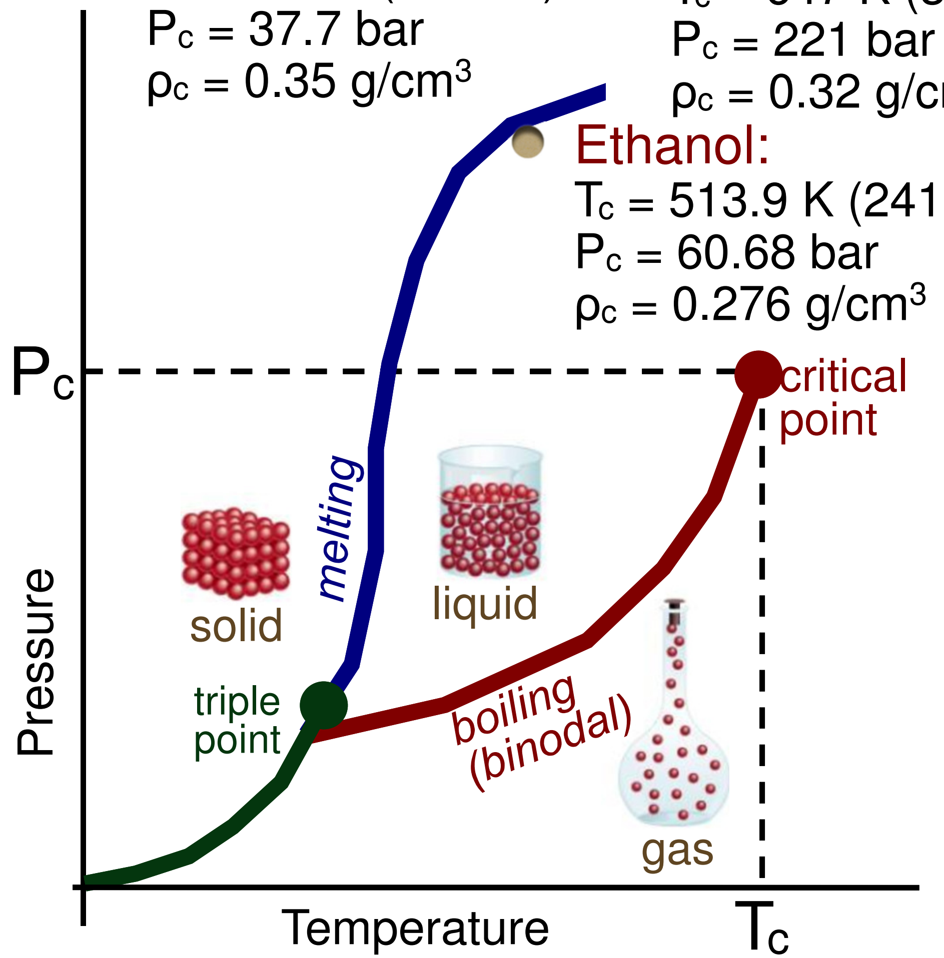




Proton radiographs

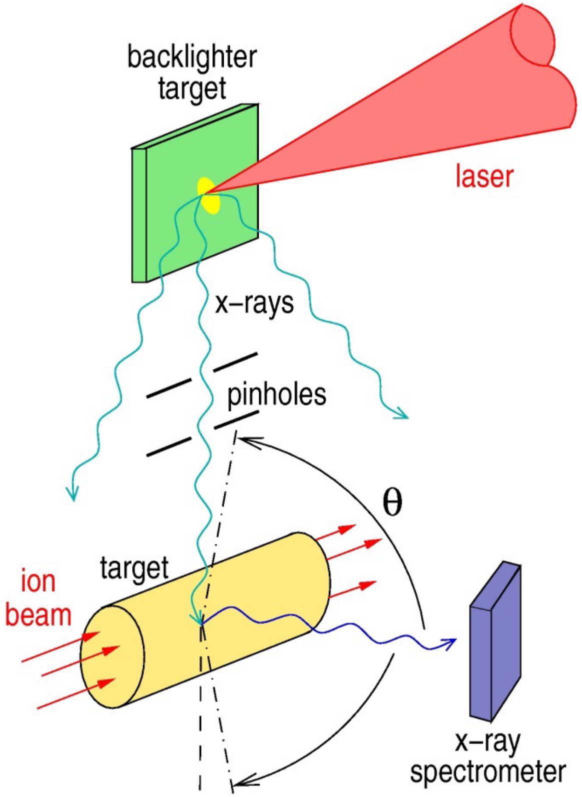


- **Air:**
  T_c = 414 K (141 °C)
  P_c = 37.7 bar
  ρ_c = 0.35 g/cm³
- **Water:**
  T_c = 647 K (374 °C)
  P_c = 221 bar
  ρ_c = 0.32 g/cm³
- **Ethanol:**
  T_c = 513.9 K (241 °C)
  P_c = 60.68 bar
  ρ_c = 0.276 g/cm³

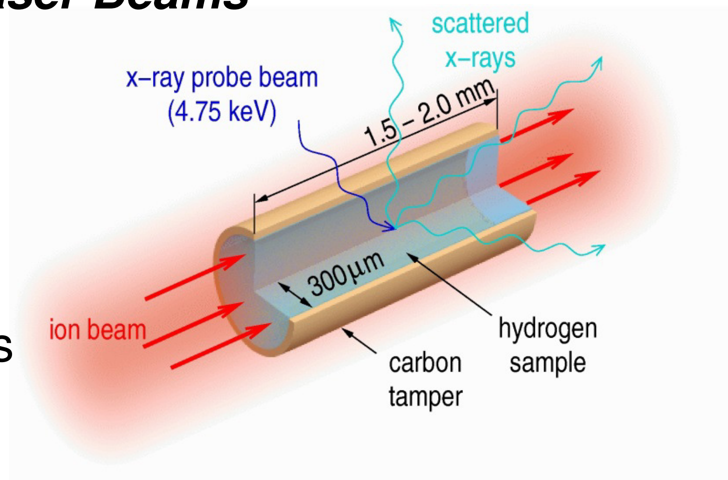


Radiative Properties of Warm Dense Matter*

Produced by Intense Heavy Ion Beams
and Diagnosed by Intense Laser Beams



Unique combination
of intense heavy ion
beam driven experiments
+
PHELIX driven diagnostics
at FAIR



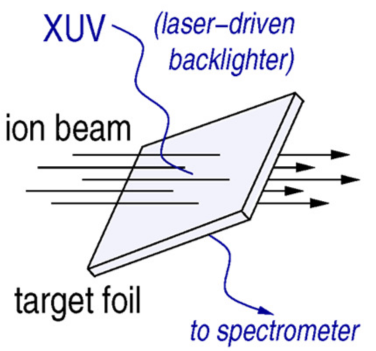
Atomic physics in dense environments

- temperature
- electron density
- average charge
- particle correlations
- spectral opacity

WDM: Investigation of Atomic and Thermophysical Properties in Dense Plasma Environments

Opacity measurements at constant temperature

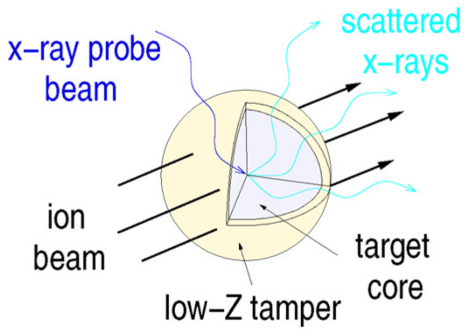
Isothermal expansion of thin foil targets



- **Opacities are very sensitive to electronic levels and population** (test of atomic physics in dense environments)
- **Benchmark for theoretical approaches** (existing models strongly diverging)

Optical diagnostics at constant volume

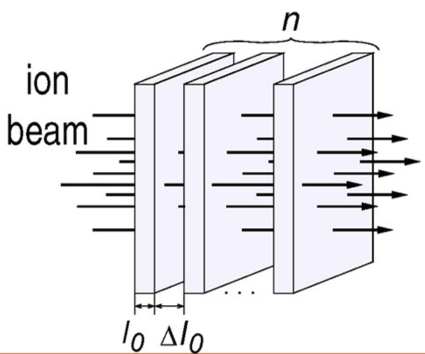
Dynamic confinement of low-Z targets



- **Investigation of WDM with emphasis on Optical properties** (atomic physics in dense environments)
- **Laser as key diagnostics tool** (XANES, X-ray scattering)

EOS measurements at constant pressure

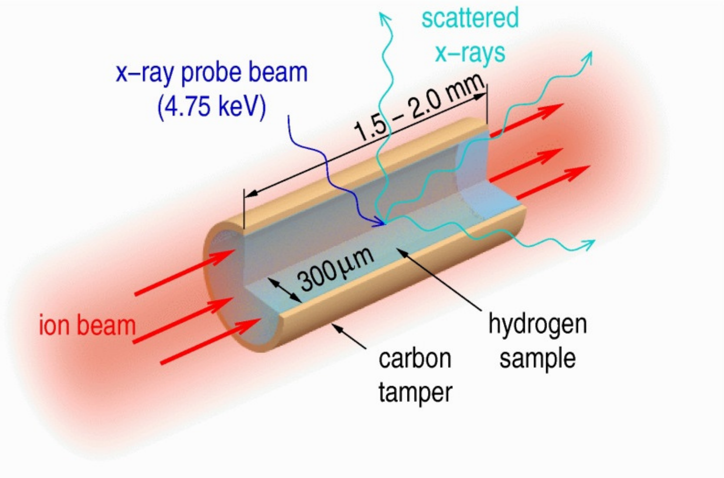
Quasi-static heating of stacked foil targets



- **Thermophysical properties along the two-phase boundary**
- **Quasistatic heating ensures homogeneous pressure, density and temperature**

Target design: extension to new geometries and materials

Dynamic Confinement*

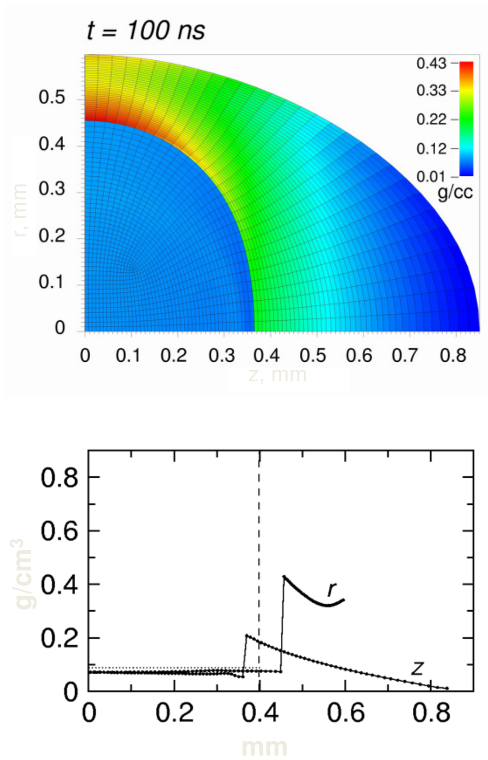


Investigation of WDM with emphasis on:

- **Optical properties**
  (atomic physics in dense environments)
- **Laser as key diagnostics tool**
  (X-ray scattering)
- **Limitation to low to mid-Z targets**

*A. Kozyreva (Tauschwitz) et al., PRE **68**, 056406 (2003)

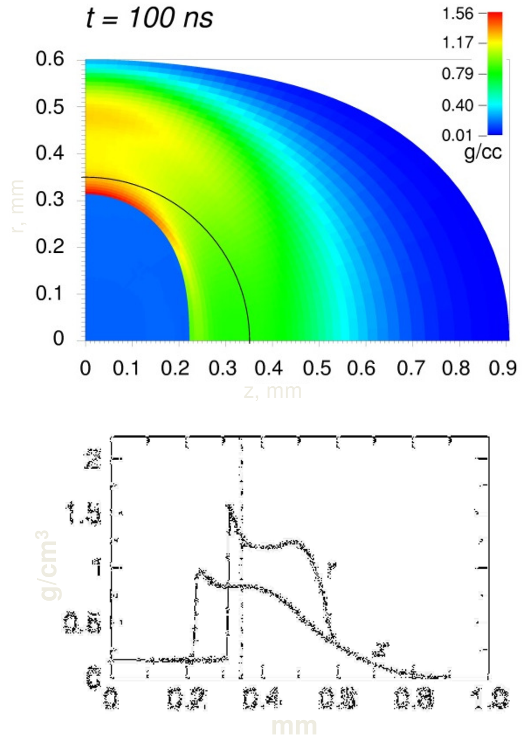
Dynamic Confinement (spherical geometry)



- improved homogeneity
- lower tamper line density
- wide range of ion energy
- large volume of confined material

An. Tauschwitz et al., HEDP **3,** 371 (2007)

Compression with low-Z tamper



- no special beam shaping required
- compression by factor 2
- compatible with scattering diagnostics

An. Tauschwitz et al., Proc. IFSA 2007, in print