High Energy Density Physics in matter generated by Heavy Ion Beam (HEDgeHOB) at FAIR

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ITEP, Moscow

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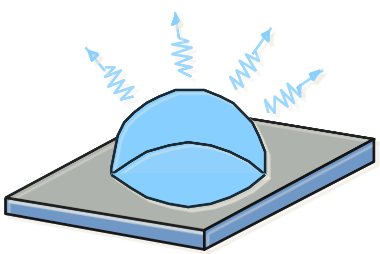
Worms, 13-17 October, 2014

High Energy Density in Matter

The collective interaction of the matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called High Energy Density Physics.

It is a field characterized by *extreme states* of matter previously unattainable in laboratory experiments (high concentration of energy: high temperatures and high pressures)



T ~ 2,000 – 500,000 K

ρ ~ 0.1 – 100 g/cm^3

P ~ kbar, Mbar, ...

Extreme states of matter: basic physics and applications

- **Plasma physics, atomic physics, thermophysics**
  fundamental properties of matter in unexplored regions of the phase diagram: equation-of-state, exotic phase transitions, transport and optical properties, effects of strong inter-particle interaction, ...

- **Astrophysics and planetary sciences**
  brown dwarfs, pulsars, supernova explosions, structure of the earth and sun interior, giant and extra-solar planets

- **Energy research and inertial confinement fusion**
  fusion energy, portable nuclear and MHD reactors, safety of power plants

- **Technologies**
  material research, pulsed and high-temperature technologies, dynamic synthesis of new materials, space technologies, defence applications

High Energy Density matter is interesting because it occurs frequently in Nature

Experimental methods in HED physics research

- **Static methods (diamond anvil cell)**
  isotherms $P(V, T=const \sim T_k)$, melting curve, volume and enthalpy changes at melting, binding energy, heat capacity, crystal structure;
  low temperatures, P < 6 Mbar

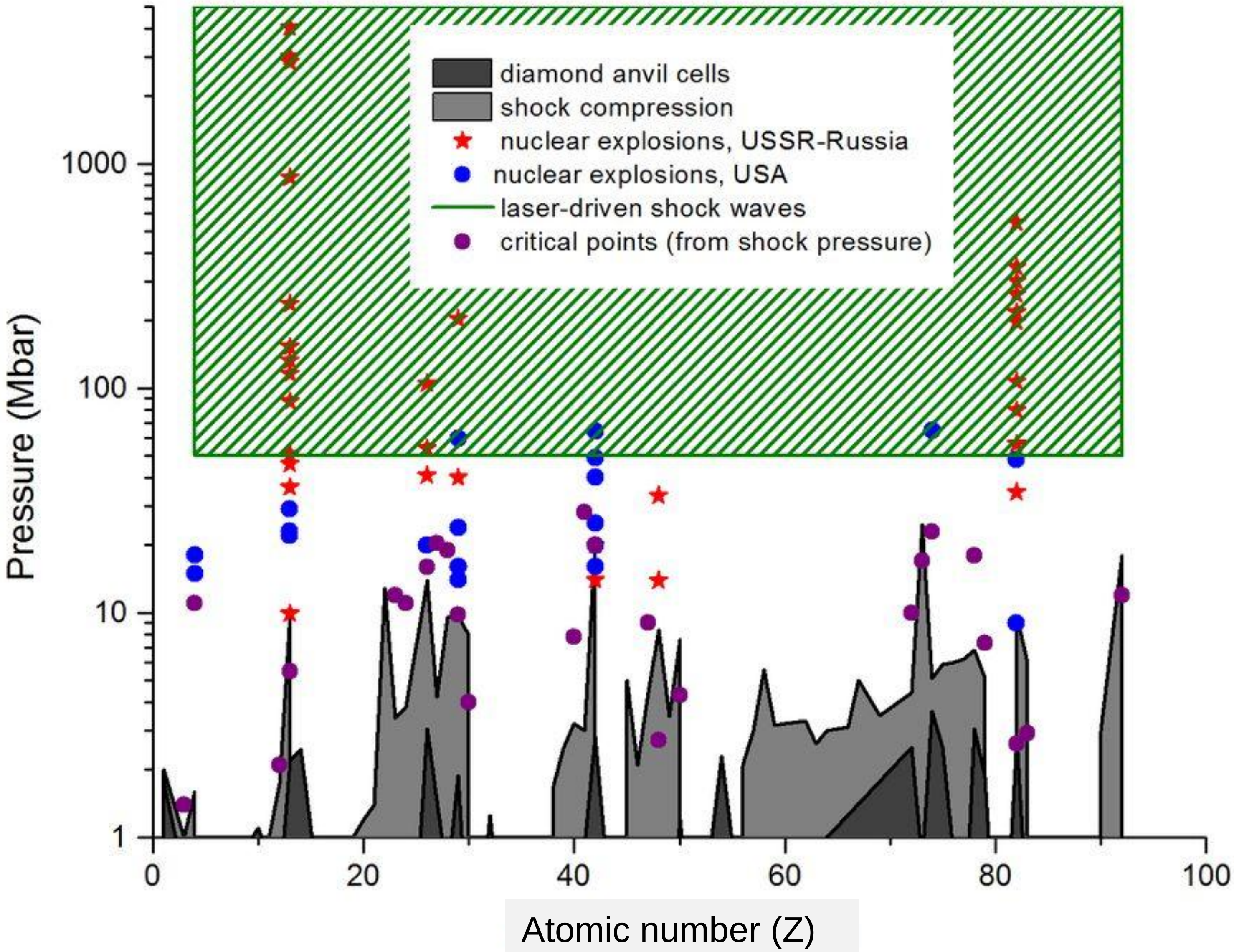
- **Shock wave compression**
  shock adiabats of solid and porous samples H_1, H_m, E(P,V), extremely high pressures; **max. temperature and density; data only along Hugoniots**

- **Isentropic release from shock-compressed state**
  isentropes near boiling curve and critical point, evaporation kinetics, P, U, (T), s=const; **complexity and accuracy of data**

- **Quasi-adiabatic compression**
  adiabatic compressibility at ultra-high densities, dynamic structural phase transitions, dielectric-metal transition, etc.

- **Fast electric heating ("wire explosion")**
  isobaric or isochoric heating, H, E, T, V, P, σ; **max, pressure, instabilities in two-phase region, radial uniformity**

Highest pressures achieved in shock wave experiments



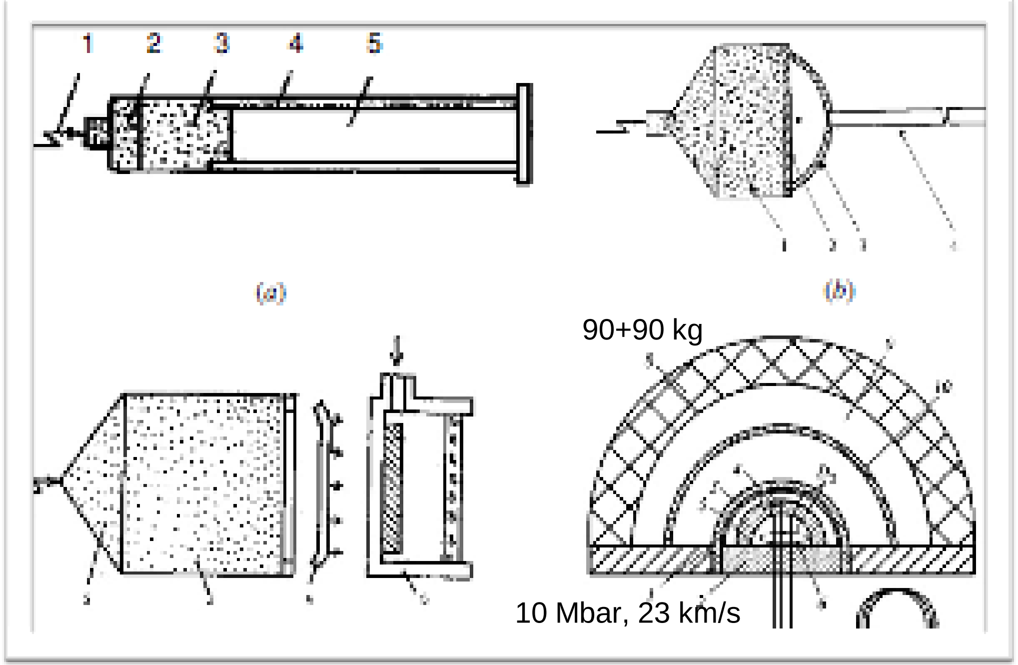
V.E. Fortov, I.V. Lomonosov. Ya B Zeldovich and equation of state problems for matter under extreme conditions. Physics-Uspekhi 57 (3) 219 - 233 (2014)

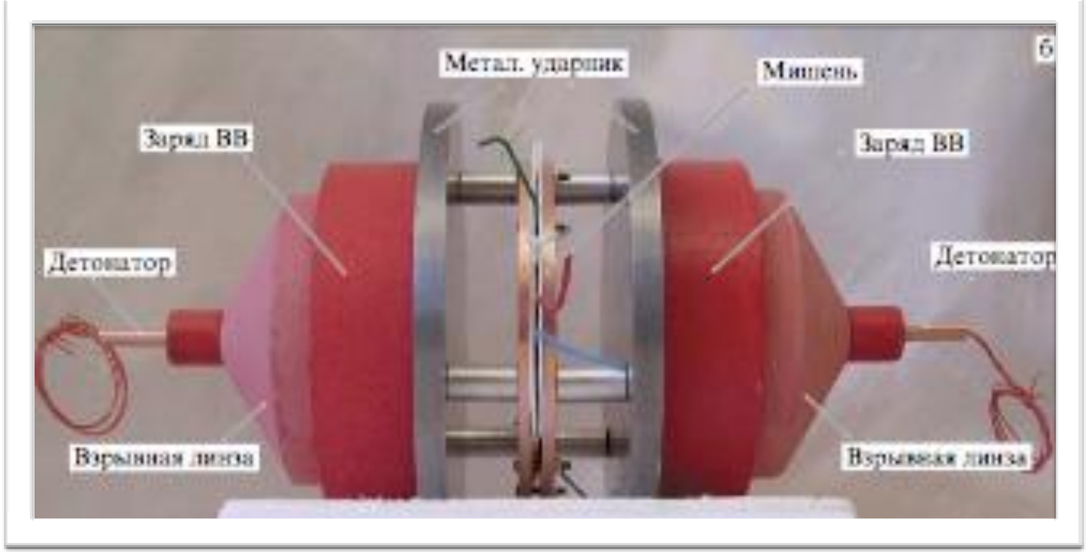
How much is one Gbar?

pressure on the tip of your thumb holding 10 fully loaded aircraft carriers

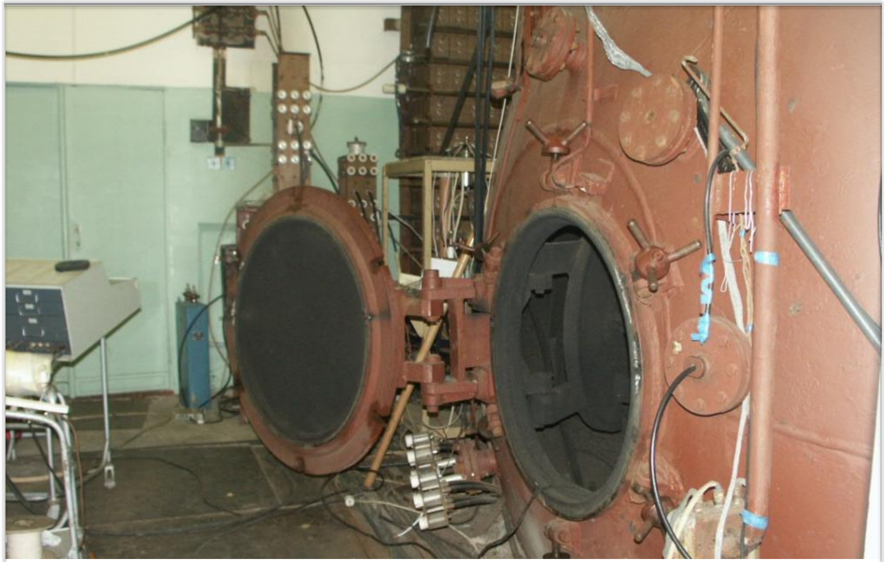
about energy density inside a bier bottle where ~1.3 ton of gasoline have burned

High explosive shock wave generators

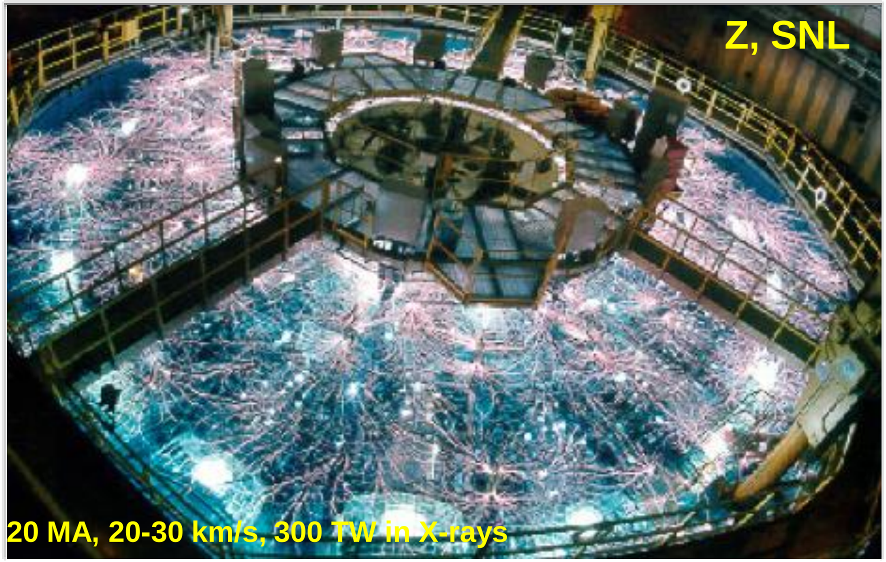


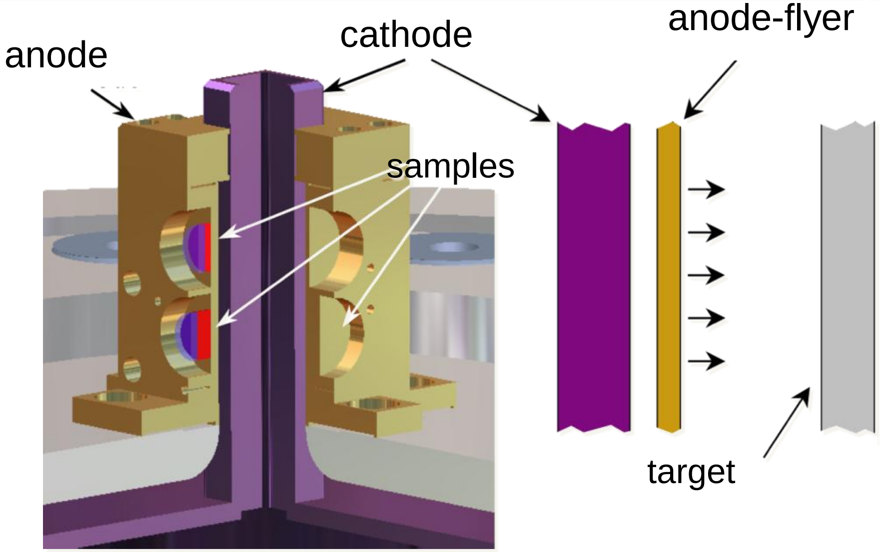


Experimental explosive areas at IPCP-Chernogolovka, Russia

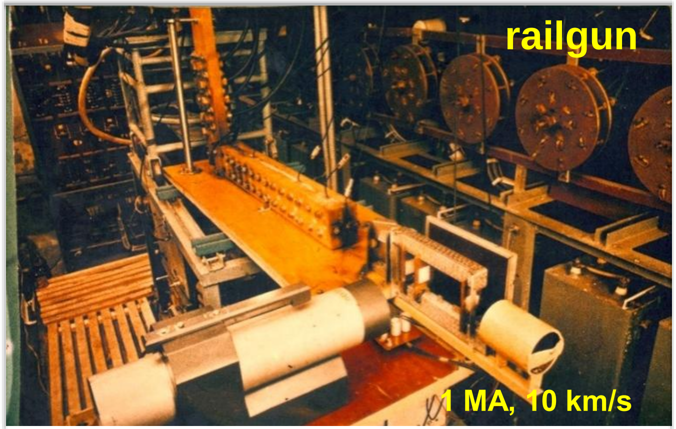


High current pulsed power generators

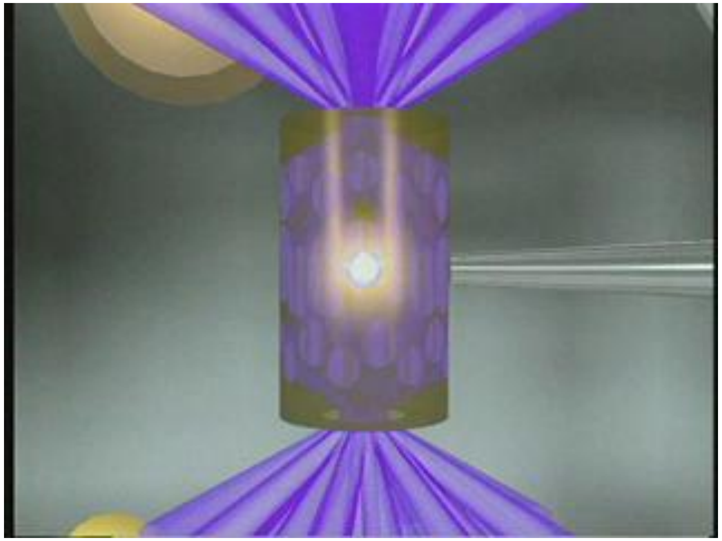




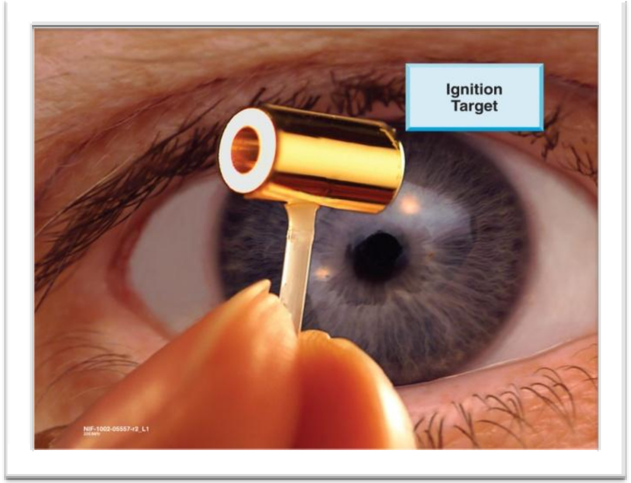
Magnetic acceleration of liner



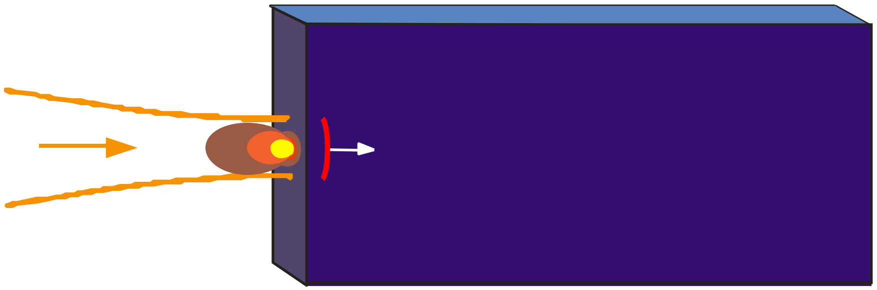
High power high energy lasers: NIF



- 192 lasers = 2 MJ, 500 TW
- > 3000 m^2 high-precision optics
- vacuum target chamber: 10 m, 500 t

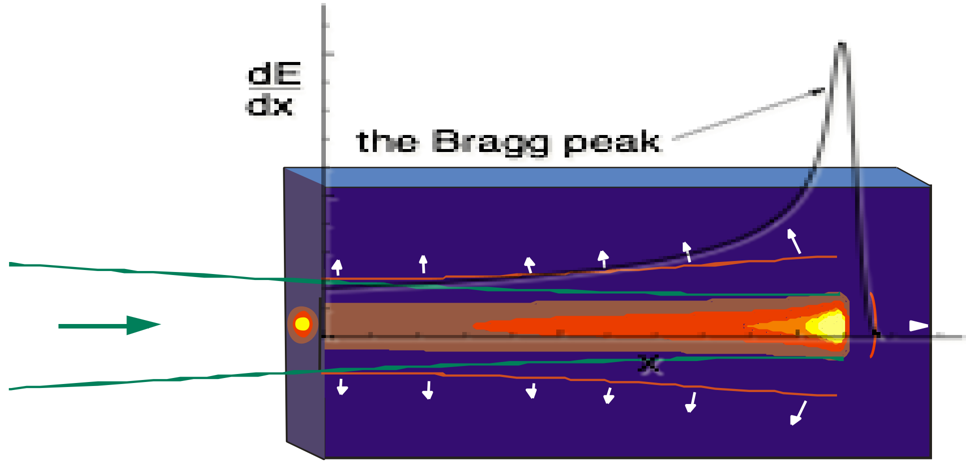


Energy deposition by a laser and by ions



Powerful lasers:

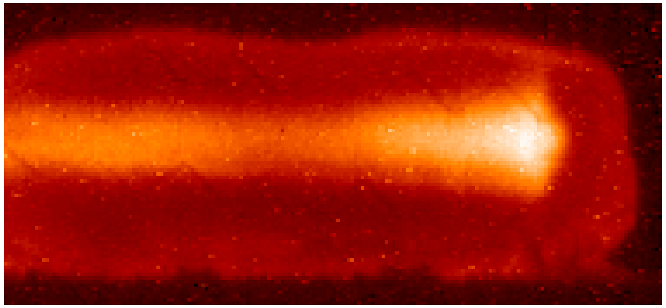
energy is absorbed on the target surface (critical density)
=> **shock wave, high gradients**



Intense ion beams:

energy is deposited in the bulk of the target
=> quasi-isochoric heating

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



Intense heavy ion beam is an excellent tool to generate large-volume homogeneous HED samples

Ion beam as a driver for HEDP experiments

$$E_s \propto \frac{1}{\rho} \cdot \frac{dE}{dx} \cdot \frac{N}{r_b^2}$$

- heavy ions (dE/dx ~ Z^2), Z_U = 92
- ion energy 200 – 1500 MeV/u (50 – 350 GeV for U)
- maximum beam intensity (number of ions per pulse) N ~ 10^9 – 10^{12}
- minimum pulse duration τ ~ 10 – 100 ns => bunch compression
- minimum focal spot size at the target r_b
  √ reducing transverse emittance – electron cooling
  √ special final focus system
- The important condition, which is not absolutely necessary but which would ensure much "cleaner" experiments, the pulse duration of the ion beam should be much smaller than the time of the hydrodynamic motion of the plasma This condition ensures that all the beam energy is deposited before the hydrodynamic expansion sets in.

Perspectives of HED-experiments at FAIR

Up to **200 times** the beam power and **100 times** higher energy density in the target will be available at FAIR

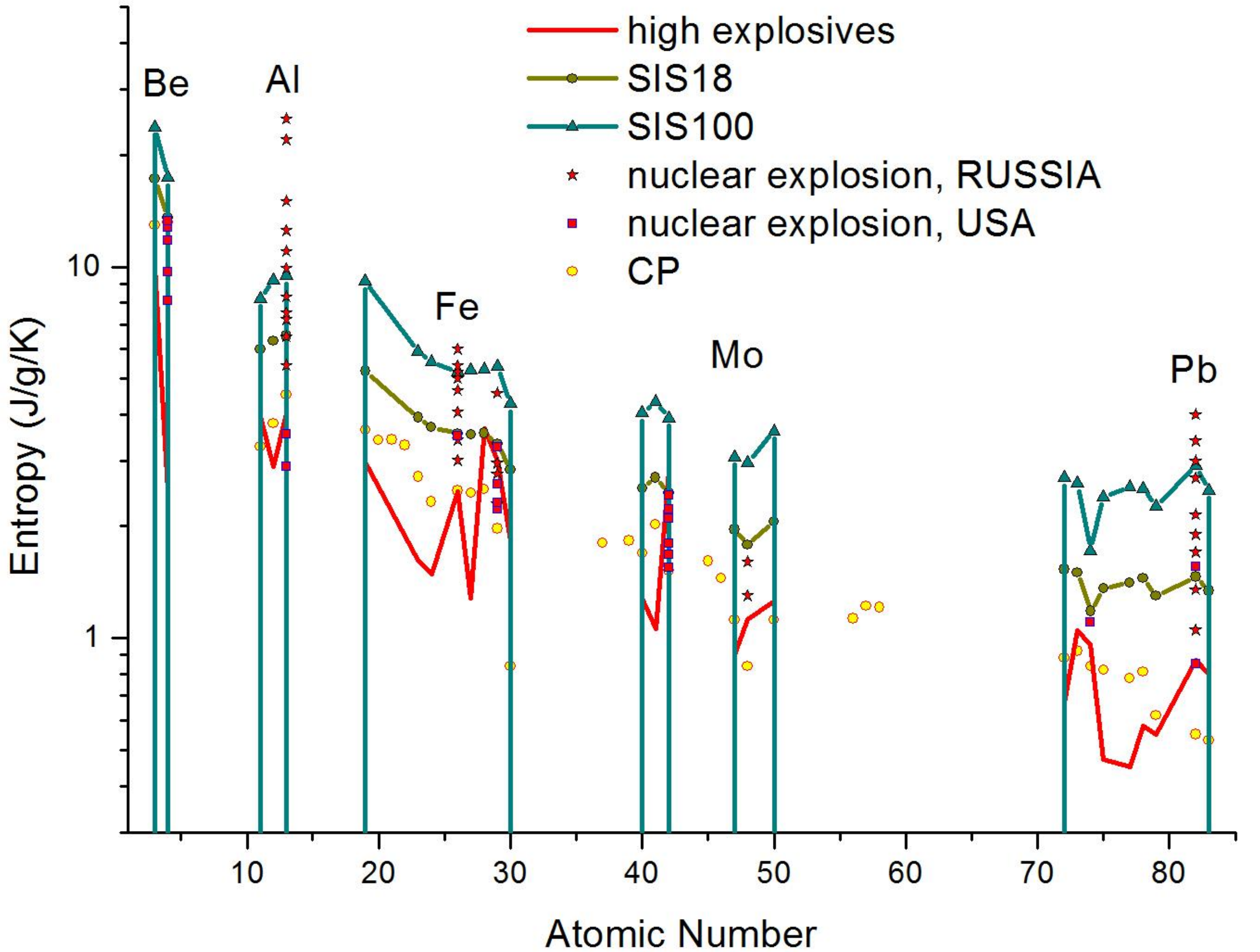
Ion beam U^{28+}	SIS-18	SIS-100	
Energy/ion	400MeV/u	0.4-27 GeV/u	
Number of ions	4.10^9 ions	5.10^{11} ions	X100
Full energy	0.06 kJ	6 kJ	
Beam duration	130 ns	50 ns	
Beam power	0.5 GW	0.1TW	X200

Lead Target

Specific energy	1 kJ/g	100 kJ/g	X100
Specific power	5 GW/g	1 TW/g	X200
WDM temperature	~ 1 eV	~10 eV	

only available at FAIR

High-entropy states of various metals: GSI & FAIR heavy ion beams in comparison with other drivers



Hoffmann D.H.H., Fortov V.E., Lomonosov I.V., Mintsev V, Tahir N.A., Varentsov D., Wieser J. Unique capabilities of an intense heavy ion beam as a tool for equation-of-state studies. Phys. Plasmas, 9, 3651-3655 (2002).

The **HEDgeHOB** collaboration:

Studies on high energy density matter with intense heavy ion and laser beams at FAIR

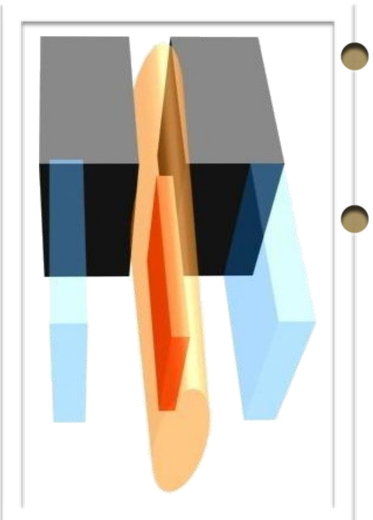
(officially inaugurated: June 2005)

- >170 scientists
- 46 institutes
- 14 countries

http://hedgehob.physik.tu-darmstadt.de

HEDgeHOB experiments: HIHEX and LAPLAS

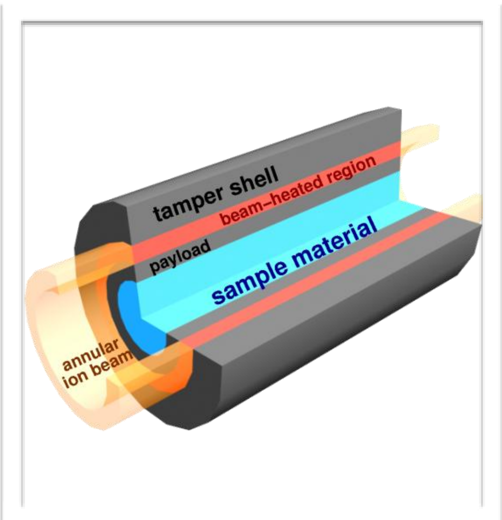
HIHEX
__H__eavy __I__on __H__eating and __Ex__pansion



- uniform quasi-isochoric heating of a large-volume dense target
- quasi-isentropic expansion in 1D (plane or cylindrical) geometry

- **Numerous high-entropy HED states:** EOS and transport properties of e.g., non-ideal plasmas, WDM and the critical point regions for various materials

LAPLAS
__La__boratory __Pla__netary __S__ciences



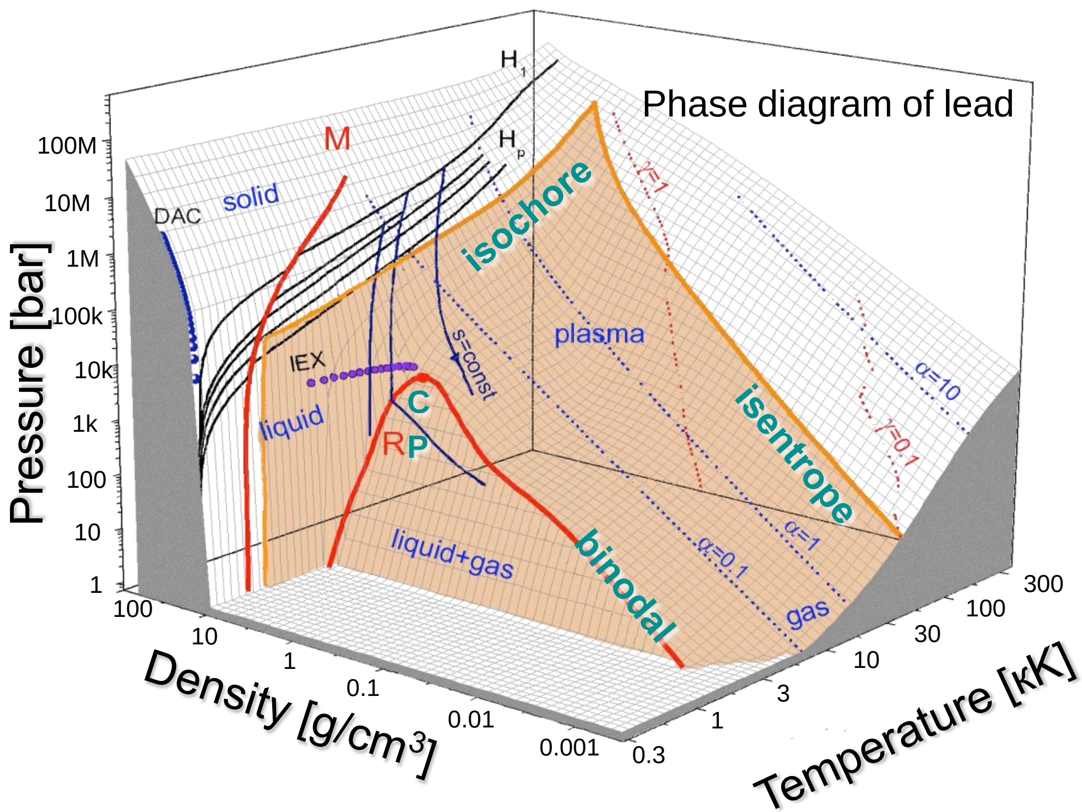
- hollow (ring-shaped) beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression

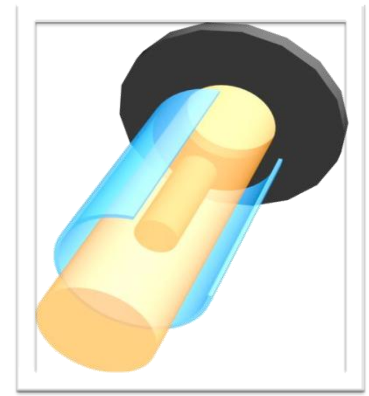
- **Mbar pressures @ moderate temperatures:** ultra-high density HED states, e.g. hydrogen metallization problem, interior of Jupiter, Saturn and Earth

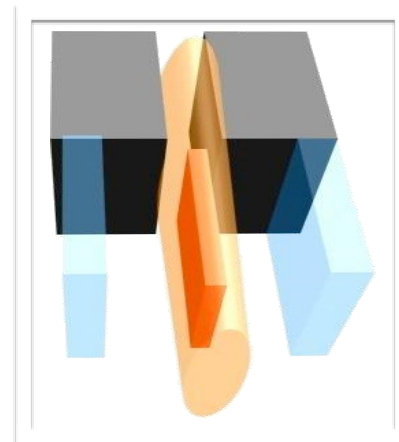
HIHEX: strongly coupled plasmas, HED phase transitions and critical points of various elements and materials

HIHEX

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

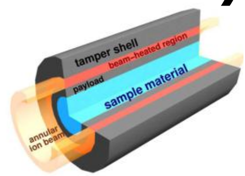






In a HIHEX experiment, a cylindrical or plane target is heated by an intense heavy ion beam fast compared to the hydrodynamic expansion time. By such quasi-isochoric heating, high entropy states as well as high energy density states are generated. After heating, the sample isentropically expands and passes through the regions of interest in the phase diagram. The variability of the beam focus at the target provided by a superconducting strong final focus system allows for cylindrical or plane geometries of the experiment.

LAPLAS (Laboratory Planetary Sciences) experiment

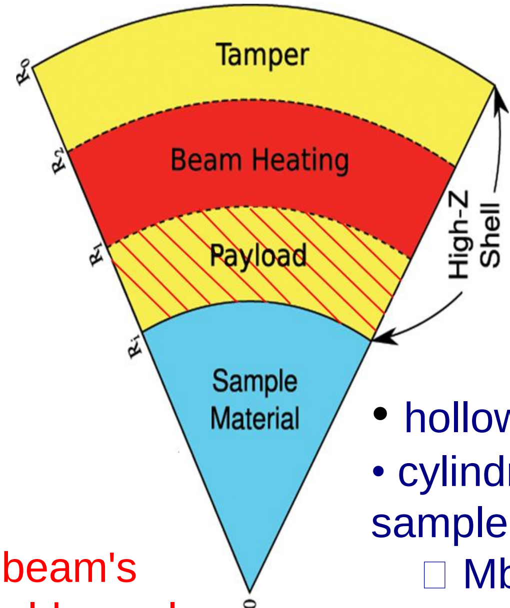


R_0 = 3.3 mm

R_2 = 2.1 mm

R_1 = 0.6 mm

R_i = 0.4 mm



Cylindrical implosion and low-entropy compression of the hydrogen sample will allow a very high density of Mbar order keeping the temperature relatively low

The size of beam's focal spot should equal to 1.5 mm

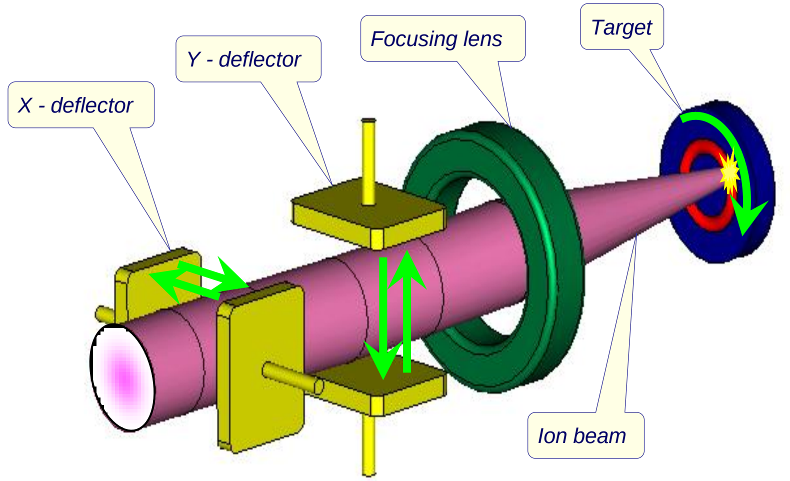
- hollow *(ring-shaped)* beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression of the sample
  - □ Mbar pressures @ moderate temperatures interior of Jupiter and Saturn, hydrogen metallization

The target consists of a cylinder of frozen hydrogen surrounded by a thick shell of a heavy material, typically gold or lead. One face of the target is irradiated with an intense heavy ion beam with annular (ring-shaped) focal spot. To ensure the required symmetry of beam irradiation, fast beam rotation around the cylindrical target axis is proposed.

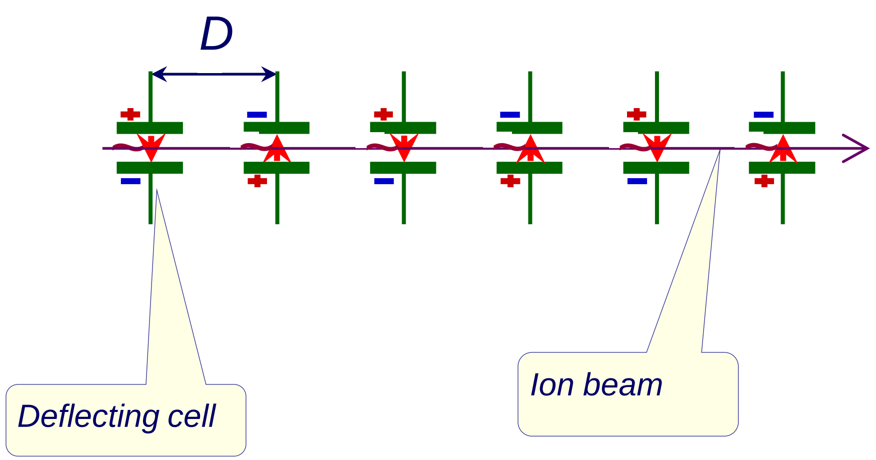
The principle of hollow beam formation

Cylindrical implosions with high radial convergence require high degree of azimuthal uniformity of the beam irradiation, especially when a cold pusher is used to compress the sample material in the central cavity. To ensure the required symmetry of beam irradiation, it was proposed to rotate the ion beam around the cylindrical target axis by means of a corresponding beam wobbler. An idea is to deflect the parallel beam by RF electric field in both transverse directions and then to focus it to the small rotating spot, illuminating the ring-shaped area on the target.

Mechanism of ring-shaped area illumination

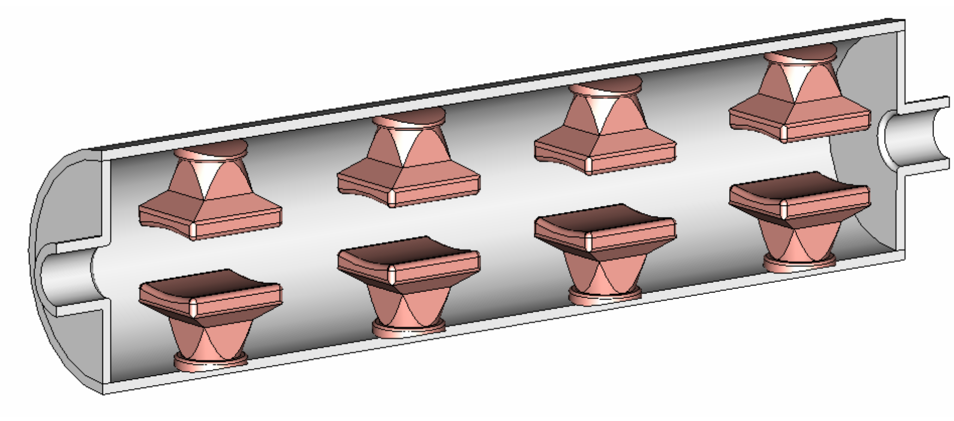


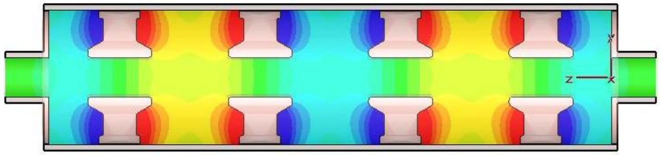
Principle of multi-cell RF deflector

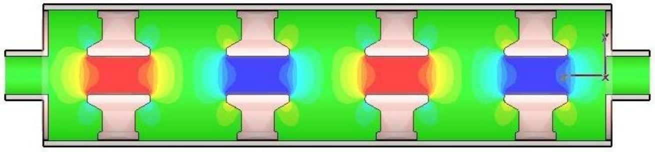


In order to keep the resonant interaction of the beam with the electric field, every cell must be as long as **D=** $\boldsymbol{\beta\lambda/2}$, where $\boldsymbol{\beta}$ is the normalized beam velocity and $\boldsymbol{\lambda}$ is the ***rf*** wavelength. When this condition is satisfied, particle crosses all the cell centers at the same phase, regularly increasing the transverse momentum dependently on the phase value.

Four-cell deflecting cavity based on H_{114} mode



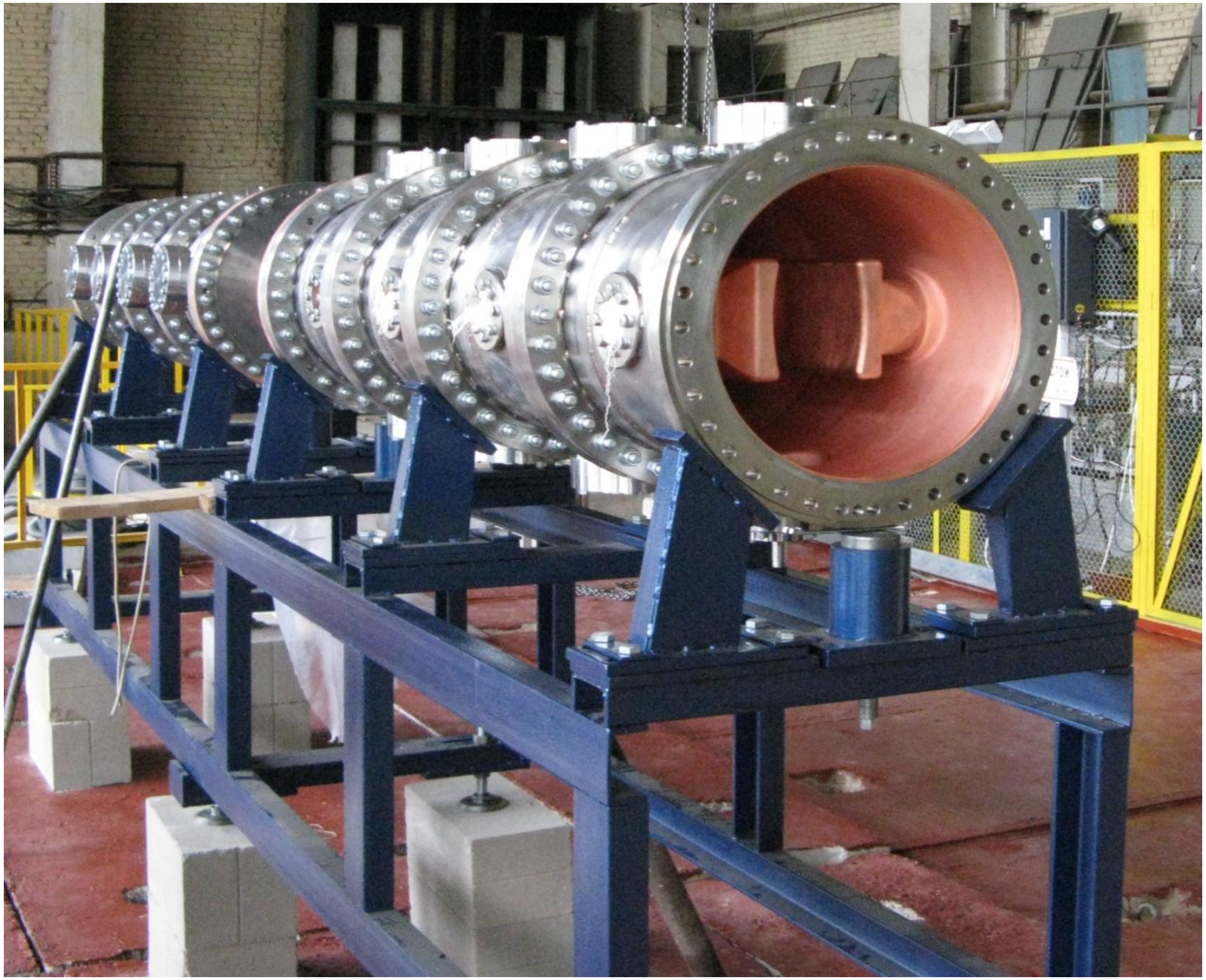


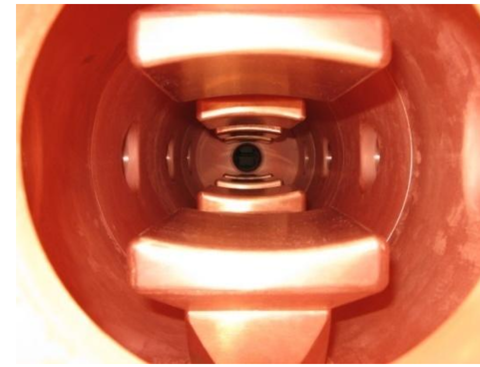


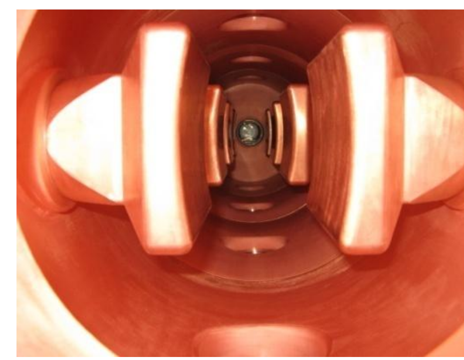
Deflecting angle: $$\Delta\alpha(rad) = \frac{eZ}{m_o c^2} \cdot \frac{\sqrt{1-\beta^2}}{\beta^2} \cdot E_{ef}(\phi_s) \cdot L$$

Parameter	*Unit*	*ITEP*	*FAIR*
Tank diameter	*mm*	*342*	*312*
Cell length	*mm*	*368*	*403*
Plate length	*mm*	*170*	*185*
Plate height	*mm*	*121*	*106*
RF field frequency	*MHz*	*298*	*325*

Assembled of the RF Wobbler cavities at ITEP
(the prototype for FAIR)







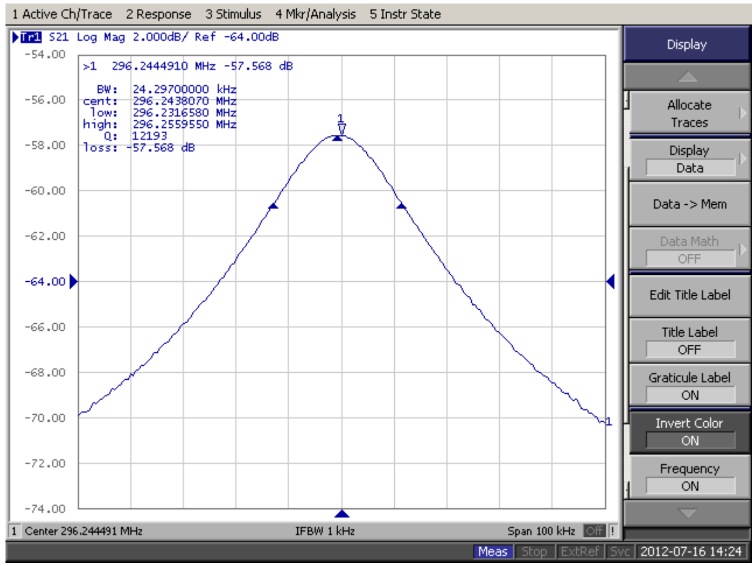
A.Sitnikov, T.Kulevoy, A.Kozodaev, D.Lyakin, V.Koshelev, V.Kuzmichev, Yu.Orlov, A.Kantsyrev, S.Vysotskyi, G.Smirnov …..

Measurement of the electrodynamics characteristics of the two cavities

Theoretical

$$f = 297\,\text{МГц}$$

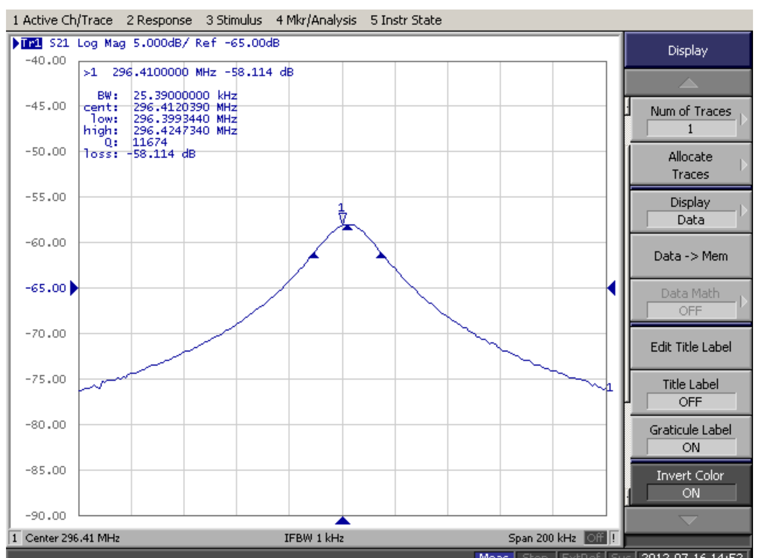
$$Q = 13000$$



Experimental

$$f = 296.244\,\text{МГц}$$

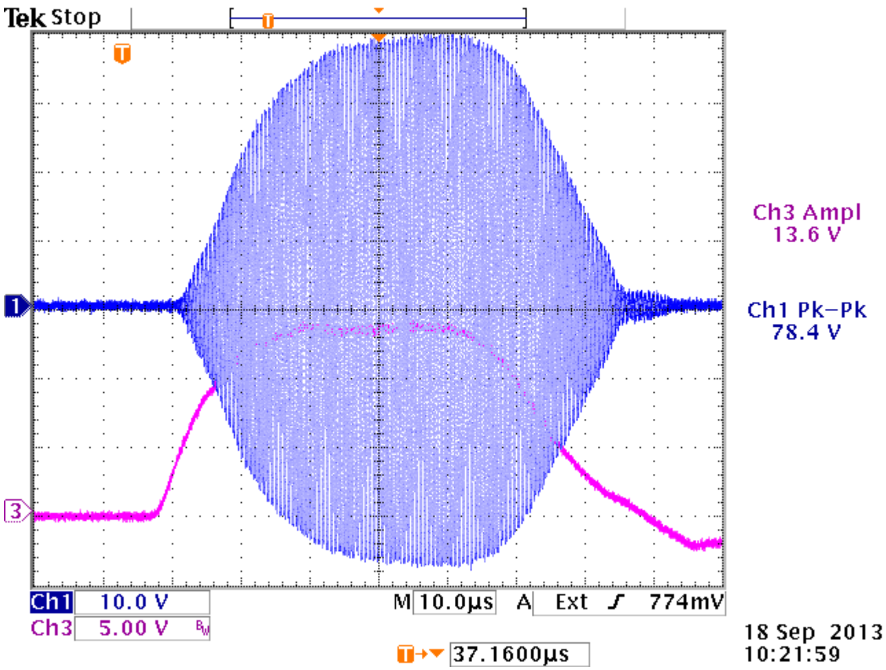
$$Q = 12200$$

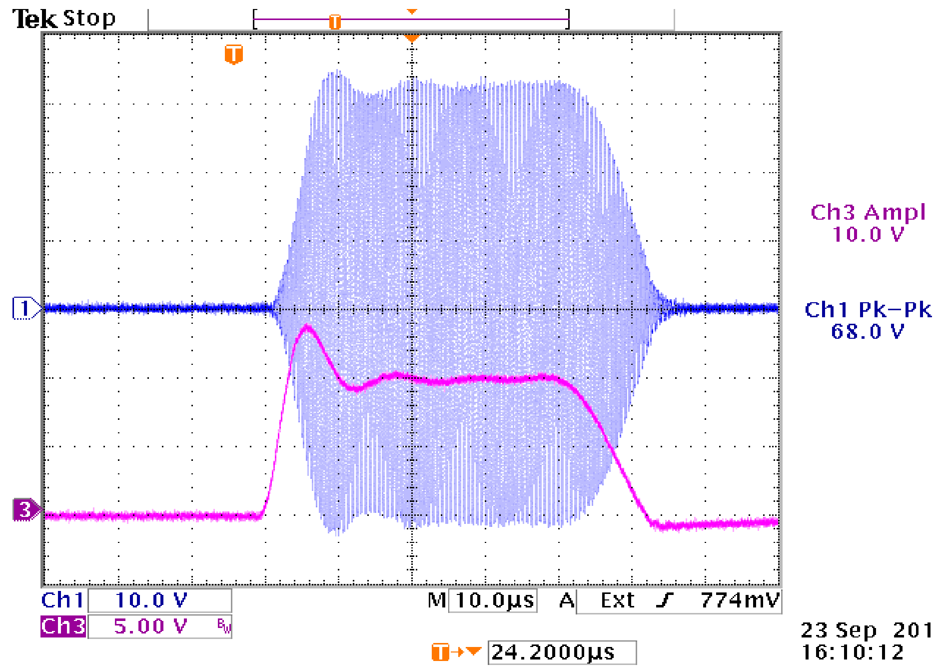


$$f = 296.412\,\text{МГц}$$

$$Q = 11700$$

RF power input





P_x = 150 kW

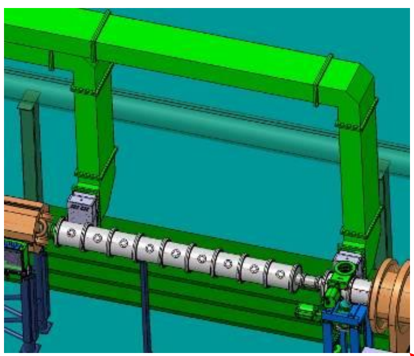
$P_{required}$ = 120 kW

P_y = 180 kW

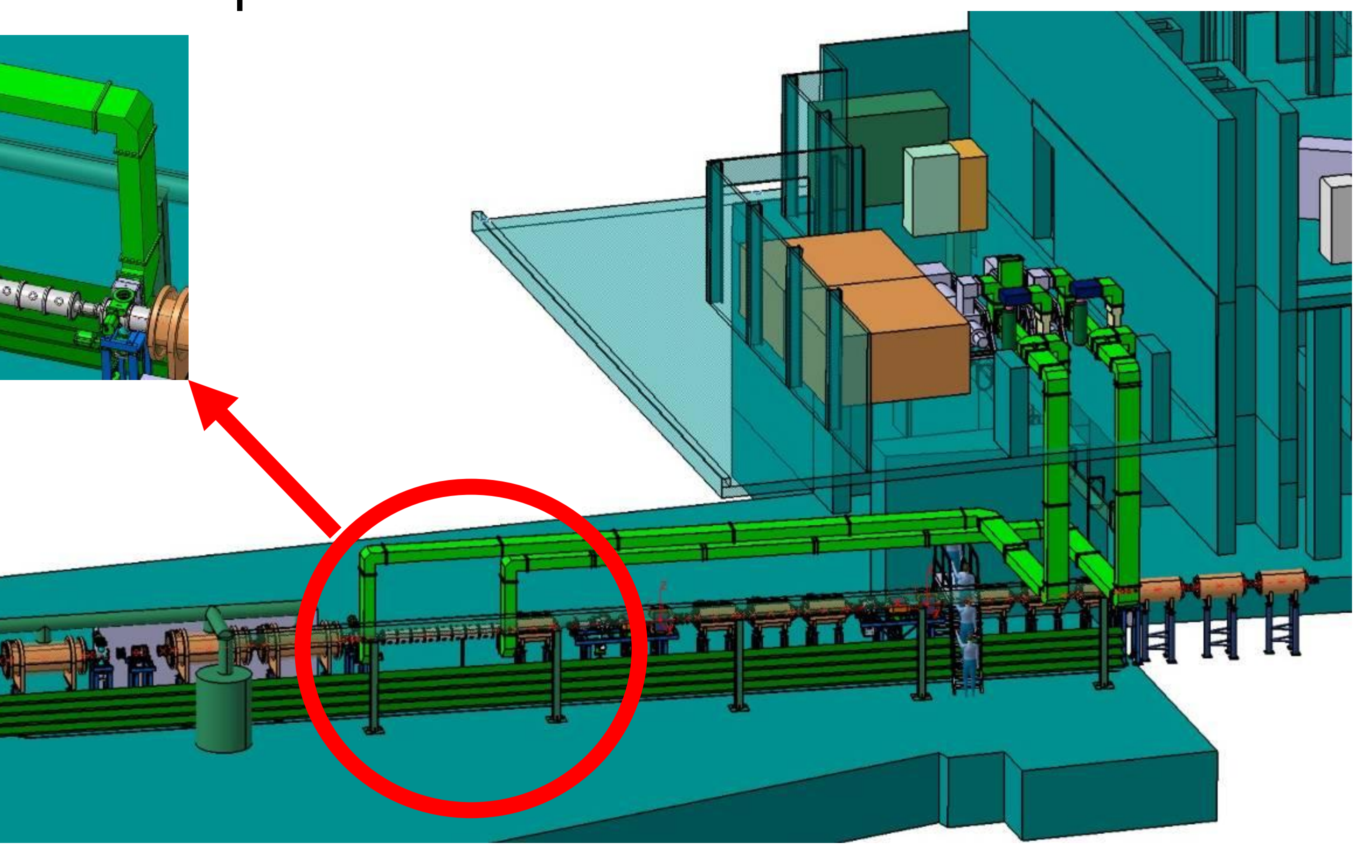
Technical Design Report for the RF multi-cell deflector (wobbler) for LAPLAS experiment

Technical Design Report for the RF multi-cell deflector (wobbler) for LAPLAS experiment.

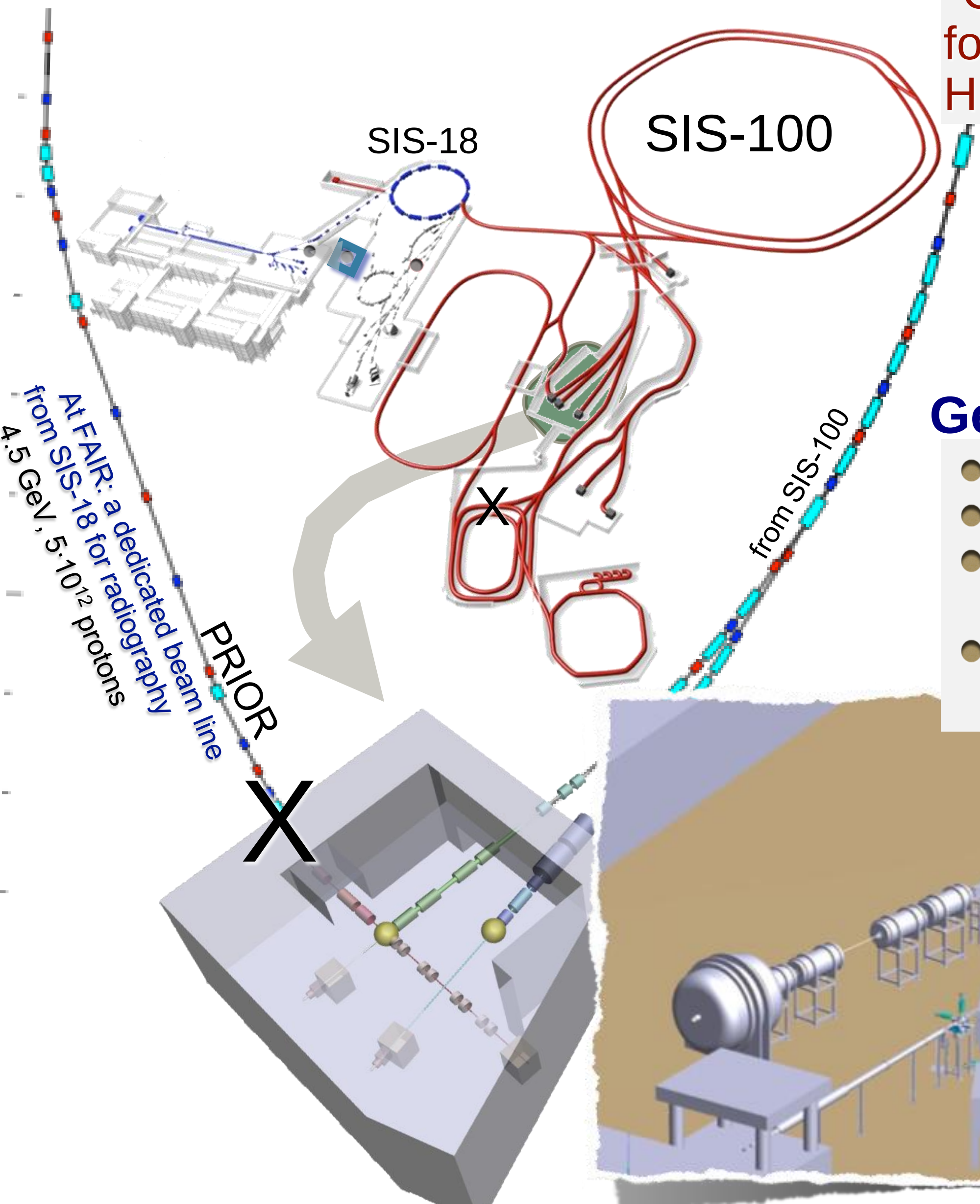
(The HEDgeHOB collaboration)



The Wobbler location on experimental beamline at FAIR



PRIOR at FAIR

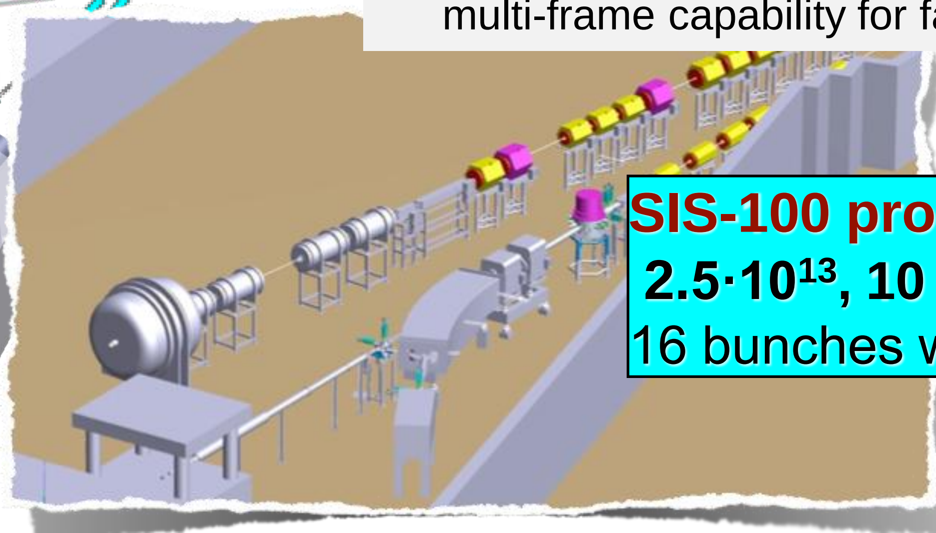


Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 µm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

GeV protons:

- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets high spatial resolution (microscopy)
- high density resolution and dynamic range multi-frame capability for fast dynamic events



SIS-100 protons:

2.5·10^{13}, 10 (29) **GeV, 50 ns**

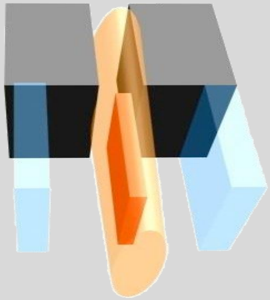
16 bunches within 3.4 µs

HEDgeHOB experiments

HIHEX

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

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

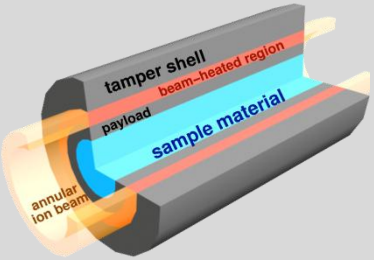


- uniform quasi-isochoric heating of a large-volume dense target and isentropic expansion
- numerous high-entropy HED states: EOS and transport properties of non-ideal plasmas / WDM for various materials

LAPLAS

***La**boratory **Pla**netary **S**ciences*

U^{28+}, 1 GeV/u, $5 \cdot 10^{11}$, Wobbler

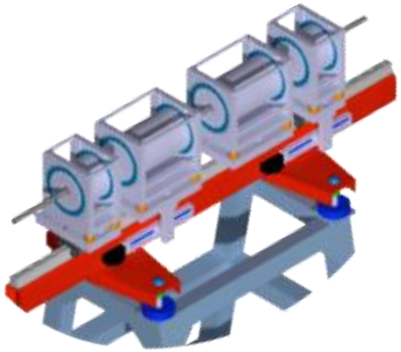


- ring-shaped beam implodes a heavy tamper shell, low-entropy compression of hydrogen
- Mbar pressures @ moderate temperatures: hydrogen metallization, interior of Jupiter, Saturn or Earth

PRIOR

Pr**oton M**i**crosc**o**pe for FAI**R

p, 5 – 10 GeV, $2.5 \cdot 10^{13}$, PRIOR



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

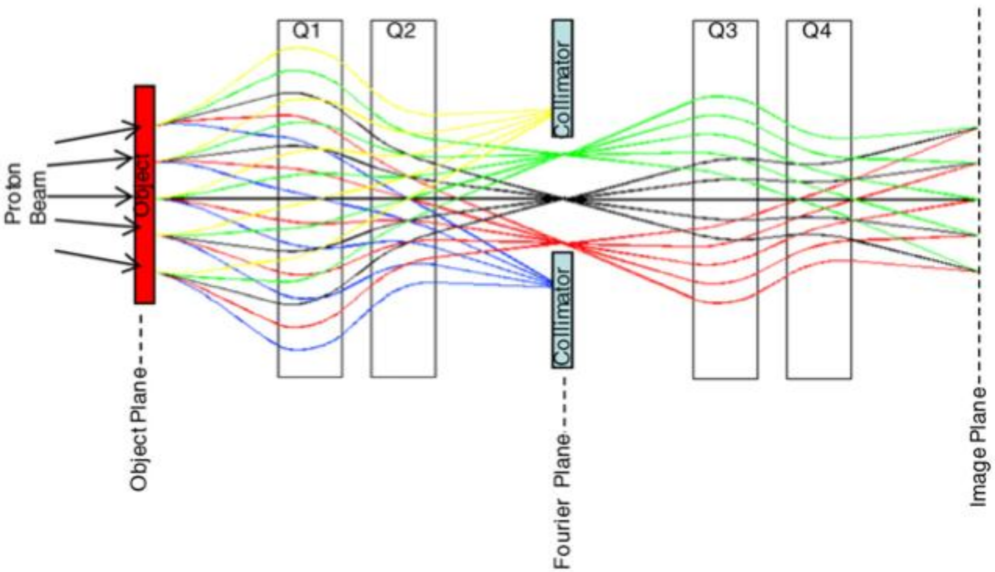
Proton microscopy will offer unique diagnostic capabilities for dense samples

Method has been developed at the pRAD facility at Los Alamos using 800 MeV protons

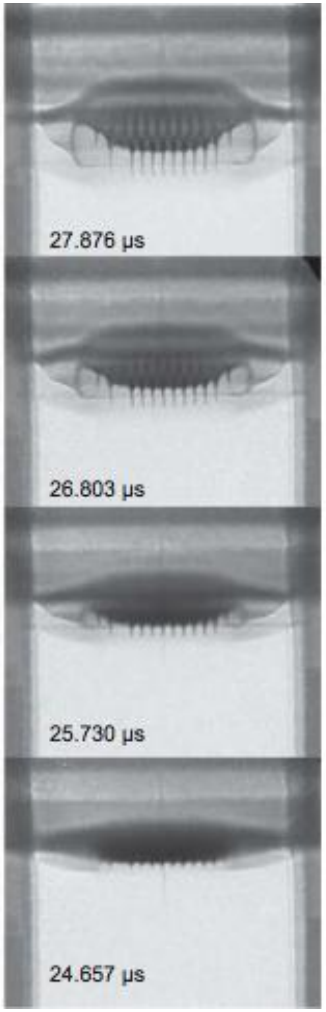
Setup using 5-10 GeV protons is planned for FAIR

Better than 10 μm spatial resolution, ns temporal resolution

In later stages of FAIR, a dedicated proton beamline will be available



Morris et. al., Rep. Prog. Phys. 76 (2013) 046401



Morris et. al., Los Alamos Science no. 30 p. 32

A prototype using permanent magnets is currently being tested at GSI

Setup for proton microscopy is developed at GSI in collaboration with LANL and ITEP

Construction and commissioning of a prototype at HHT (SIS-18)

First beamtime in April 2014 using 4.5 GeV protons

Successfully tested static targets, achieving a lateral resolution of 30 μm

Tests with dynamic targets have been carried out in July/August 2014
  ➞ data analysis is ongoing

PRIOR setup at GSI

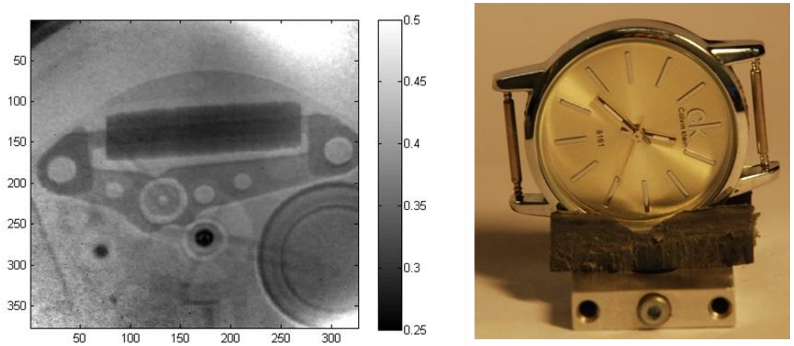
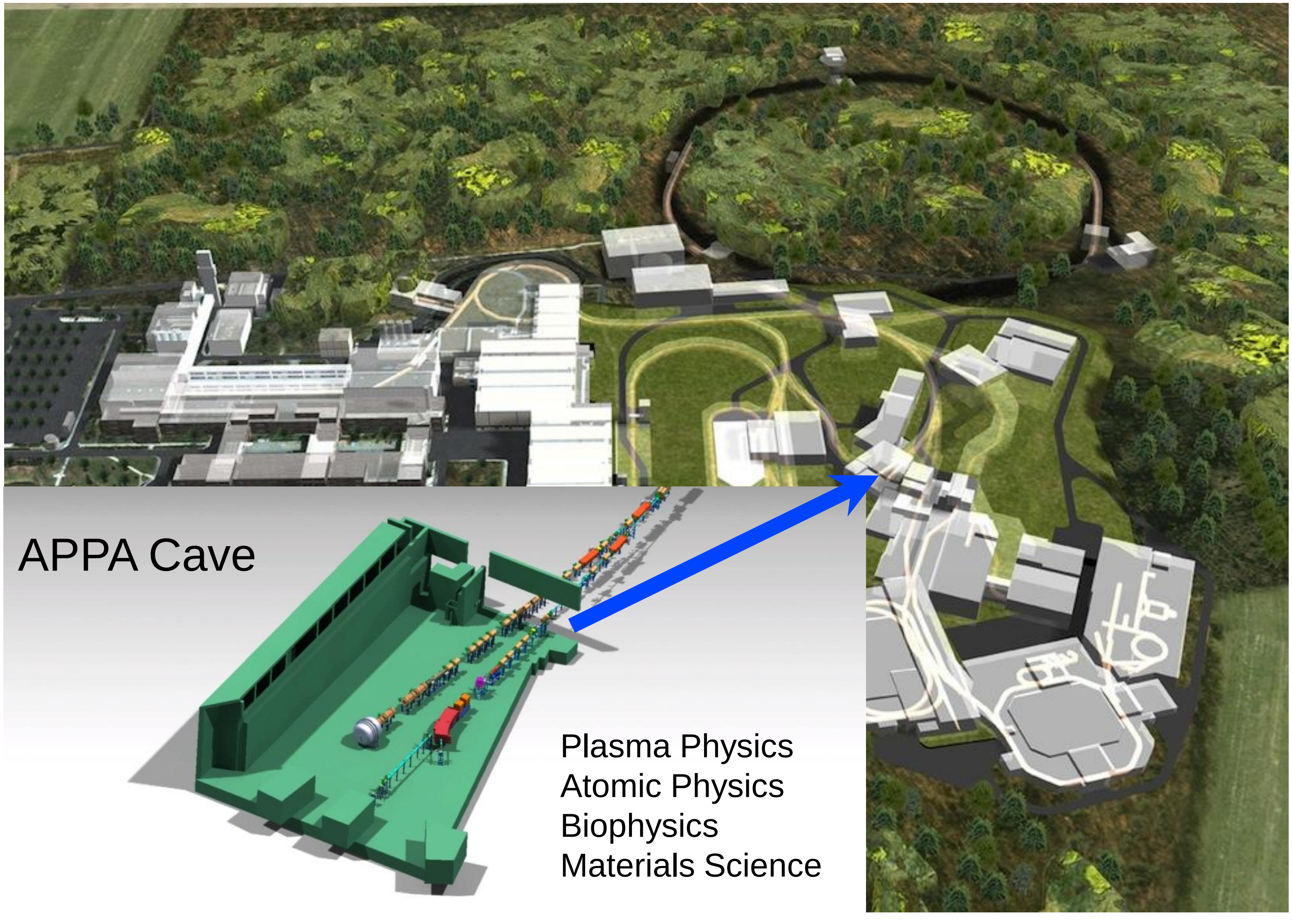
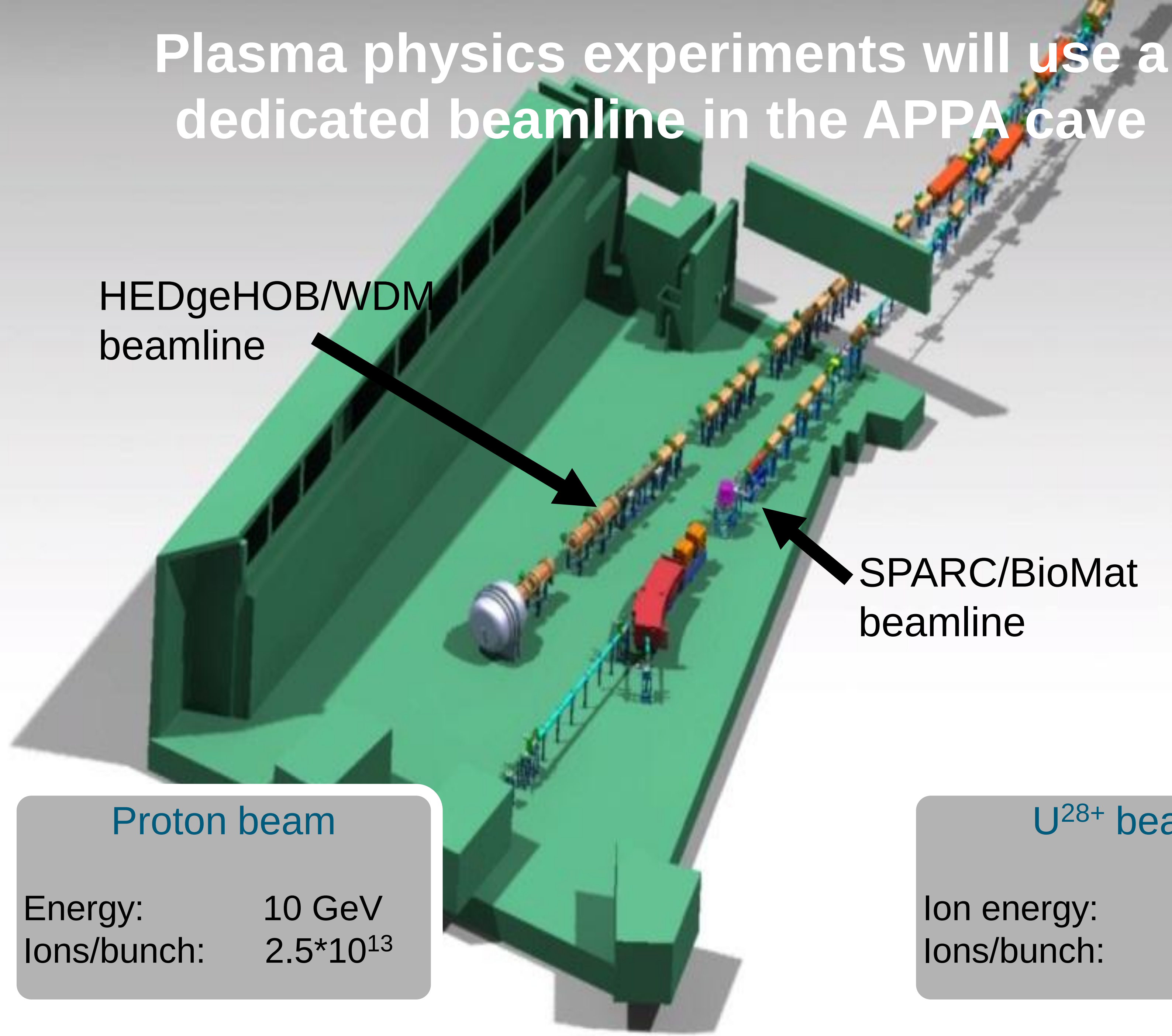


Image taken with PRIOR at GSI

Plasma physics experiments will take place in the APPA cave



Plasma physics experiments will use a dedicated beamline in the APPA cave



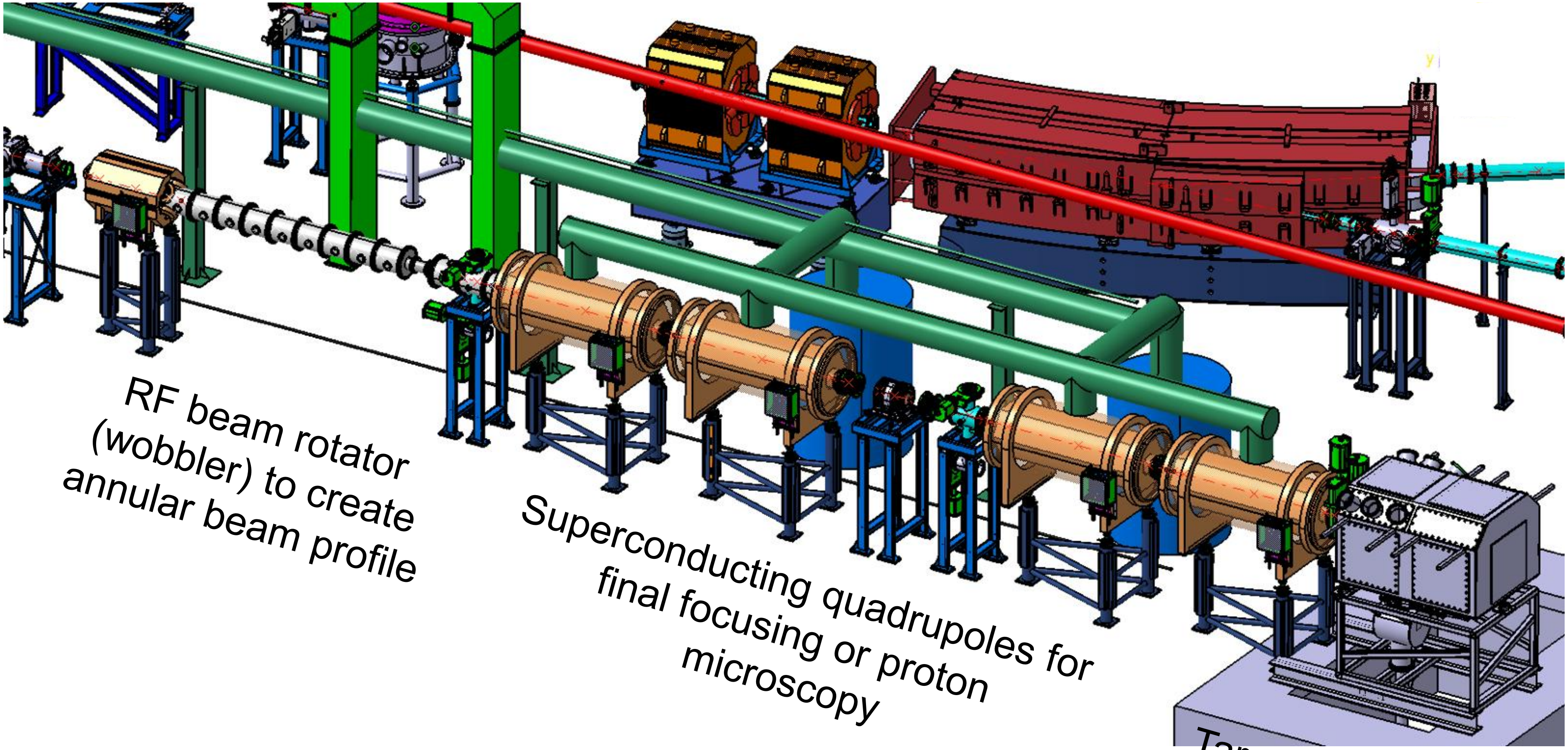
Proton beam

Energy: 10 GeV
Ions/bunch: $2.5*10^{13}$

U^{28+} beam

Ion energy: 2 GeV/u
Ions/bunch: $5*10^{11}$

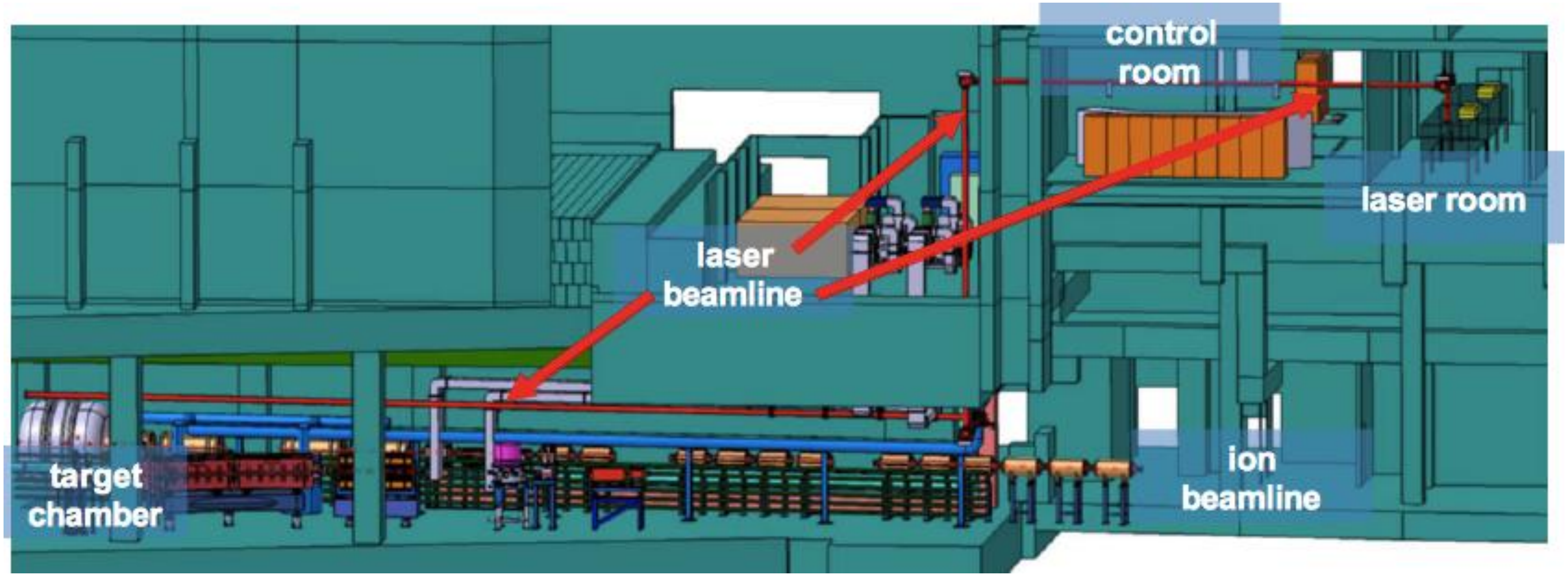
Versatile beamline design will make a wide range of experiments possible



Beamline can handle a 2 GeV/u uranium beam as well as a 10 GeV proton beam

Beamline can be coupled to a short-pulse laser system

A laser will provide essential diagnostics



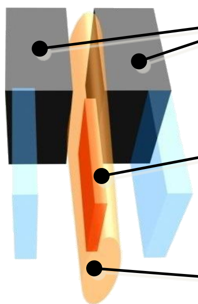
Energy	Repetition rate	Pulse length	Pulse shaping	Wavelength
100 J	up to 1 shot/minute	0.1 - 20 ns	Yes	532 nm

Will be used

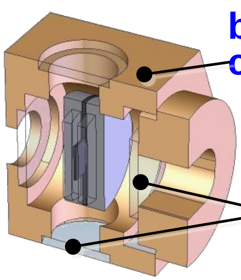
- For x-ray backlighting
- To drive shock waves
- For laser-driven particle acceleration
- To test and commission detectors

Diagnostics: experimental setup at HHT

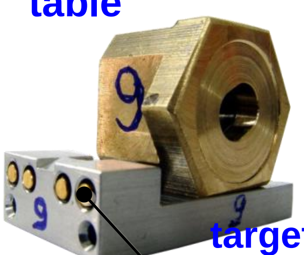
Physics package



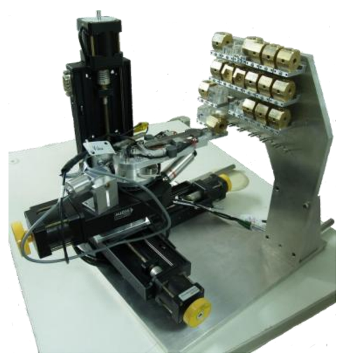
Package in container

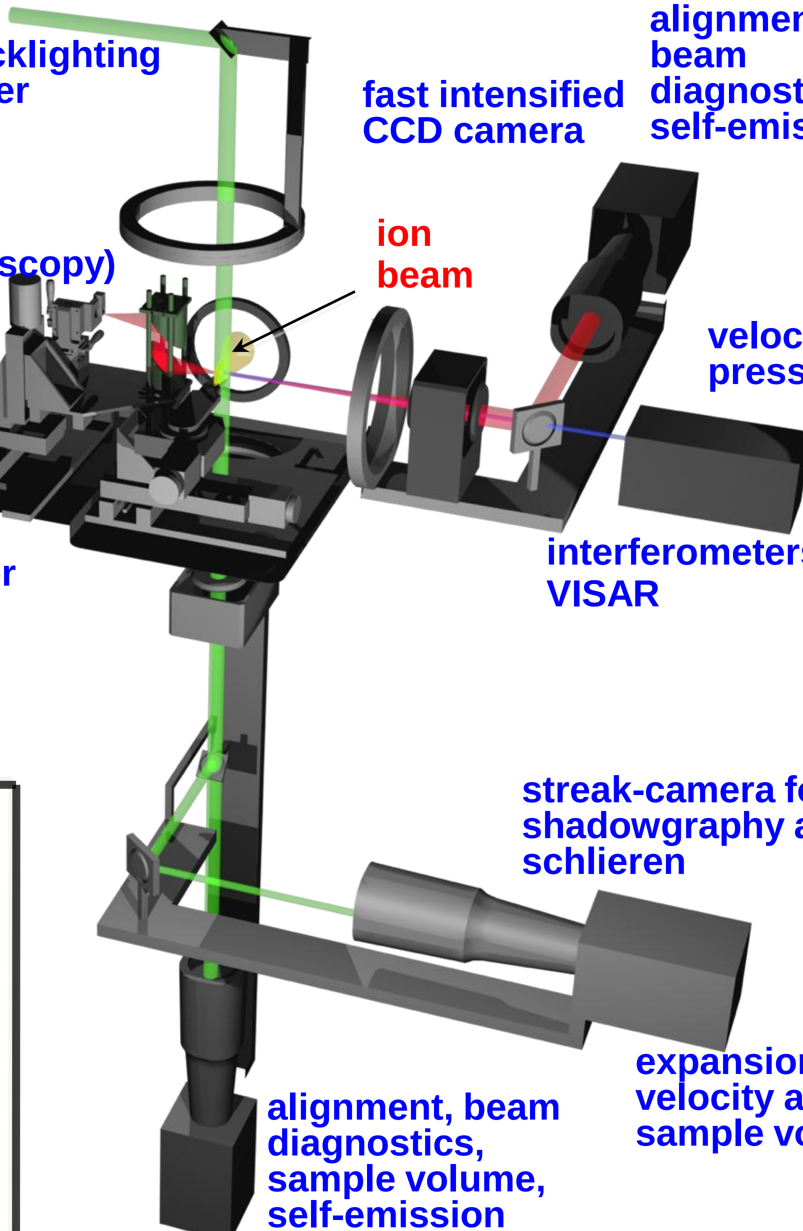


Container no the target table

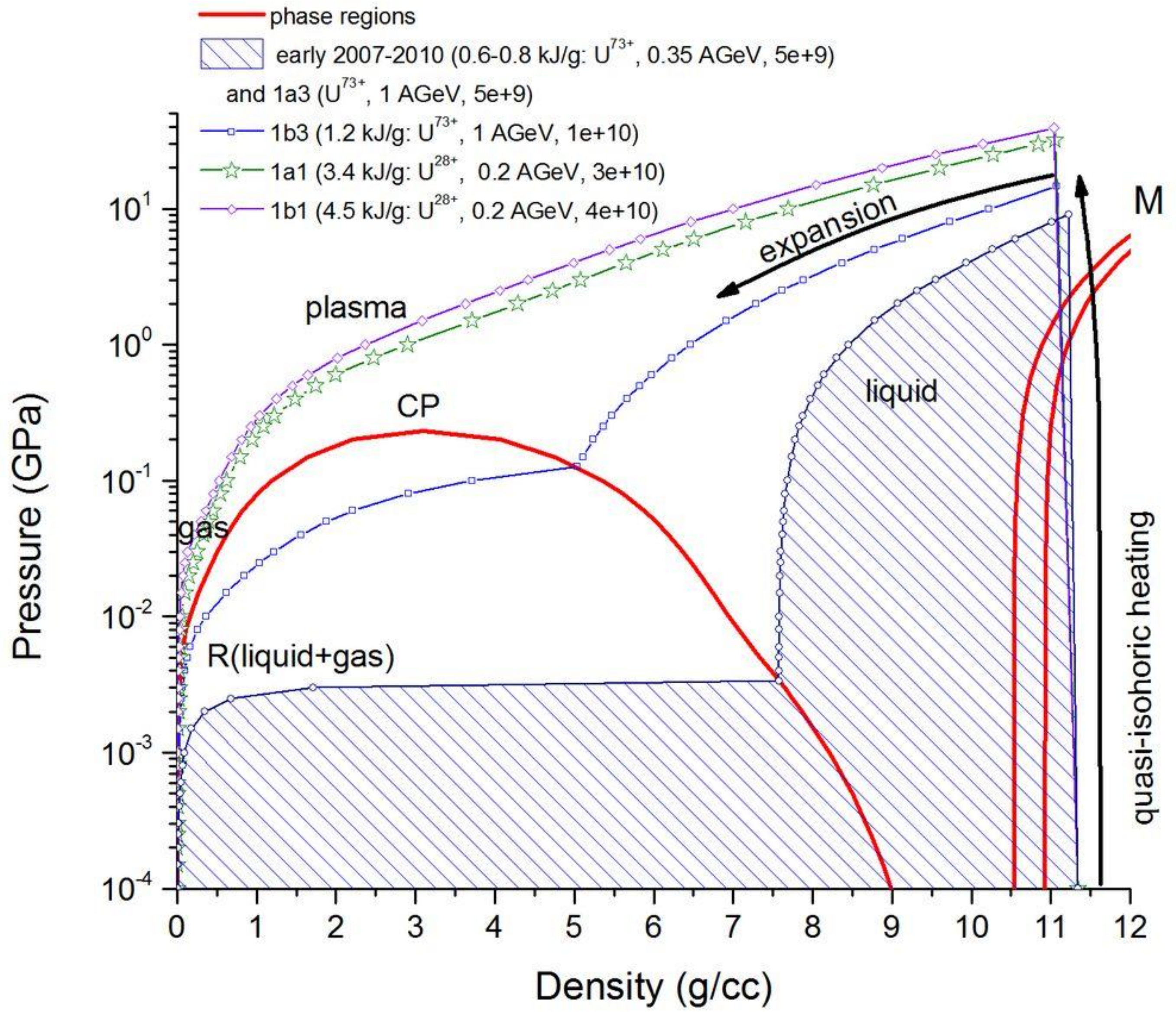


6-axis target manipulator and target shelves





Highest pressures achieved Pb target in the first experiments



3D numerical simulation by V.Kim & I.Lomonosov IPCP Chernogolovka , unpublished

Code: V. E. Fortov, V. V. Kim, I. V. Lomonosov, et el , Intern J Impact Engineering, 33, 244-253 (2006).

EOS:I.V. Lomonosov, Multi-phase equation of state for aluminum. Laser and Particle Beams, 25, 567-584 (2007)

Conclusions

Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of matter <u>in reproducible experimental conditions.</u>

The FAIR facility will offer unique possibilities for such research

- Homogeneous samples
- Millimeter sized targets
- Electronvolt temperatures

Proton microscopy will provide precision density diagnostics

- Provides diagnostics for dense materials
- Spatial resolution better than 10 μm
- Nanosecond time resolution

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