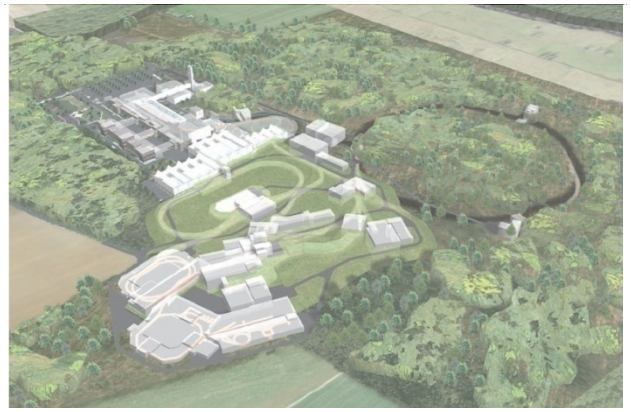
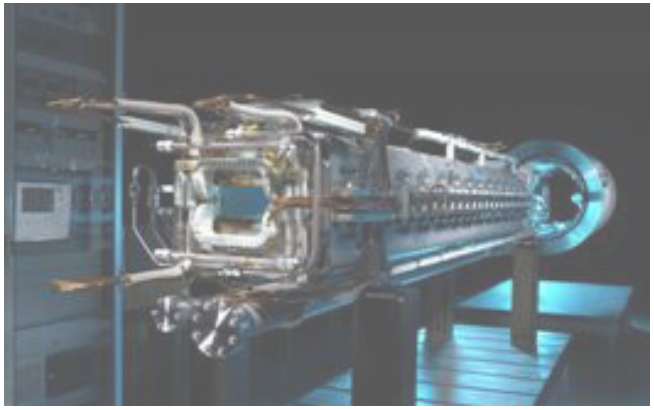



Experiments towards HIF at FAIR

Boris Sharkov

FAIR Scientific Director,
Chairman of the management board

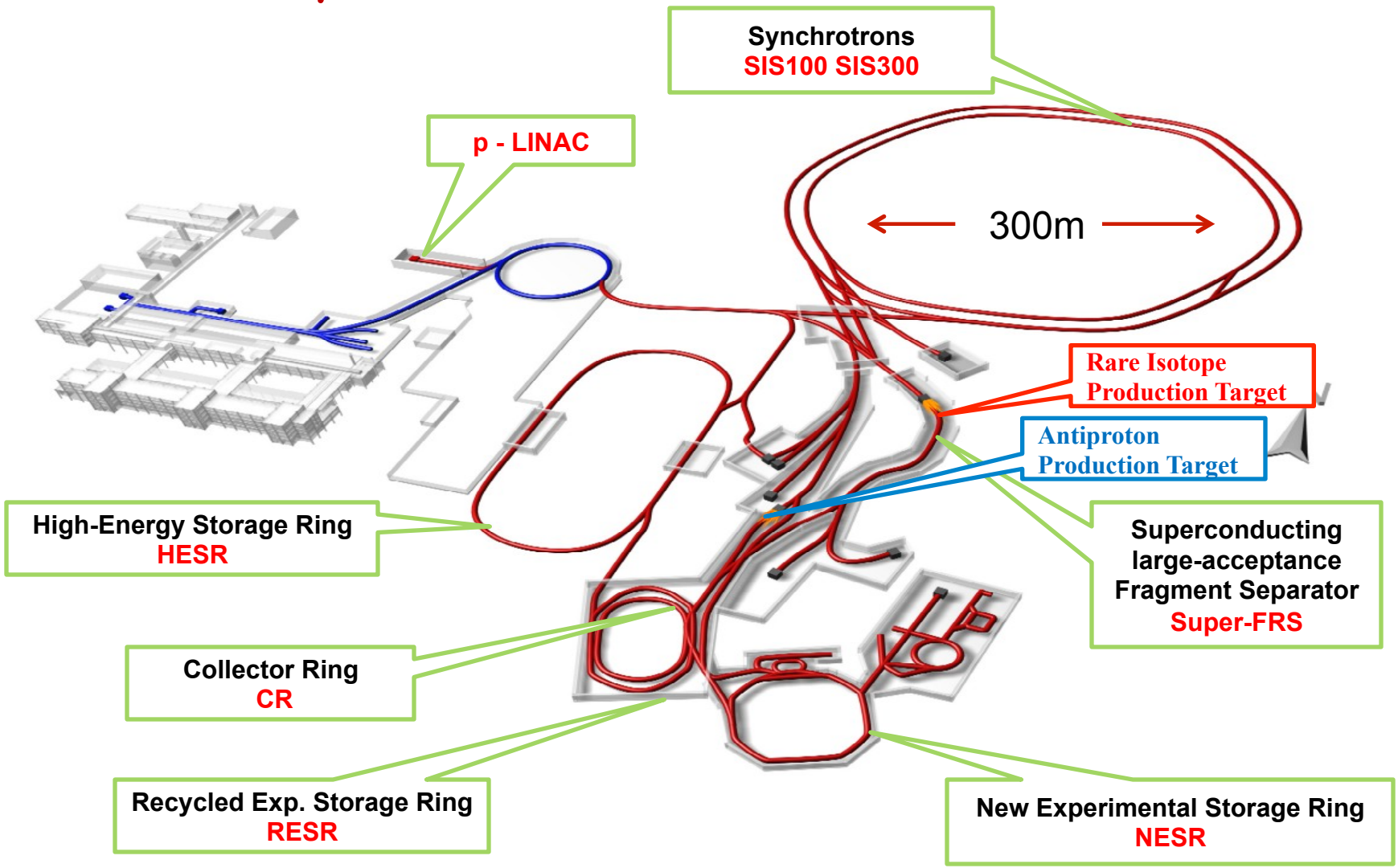
@ HIF 2012 Berkeley

Outline

1. HI IFE (introduction)
2. RU IFE concept and respective activities
3. International FAIR
4. HED Physics with Intense HIB at FAIR
   - basic experiments
   - results of numerical simulations
   - relevance to HI IFE
   - requirements for performance of experimental campaign
   - specific diagnostic methods
   - current experimental activities towards FAIR
5. Outlook

Facility for Antiproton and Ions Research -

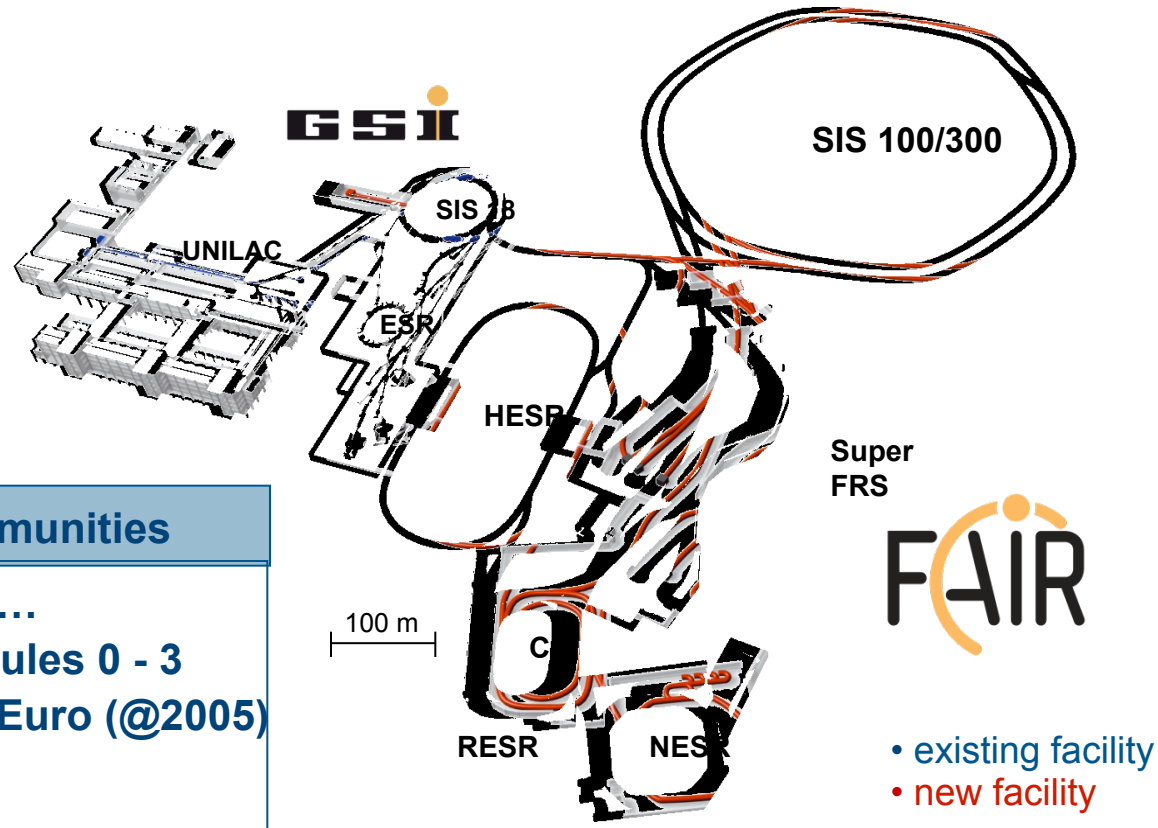
New accelerator systems to be constructed



The present Main Project: FAIR – the intensity frontier

Added value

§ Beam intensity by a factor of 100 - 10000
§ Beam energy by a factor of 20
§ Anti-matter beams
§ Unique beam quality
§ Parallel operation



Construction, cost, scientific communities

§ **Construction in modules 0 – 6, …**
§ **Modularized Start Version: Modules 0 - 3**
Construction cost: 1.027 Billion Euro (@2005)
§ **Scientific Pillars:**
- **CBM:** Compresed Baryonic Matter
- **NuSTAR:** Nucl Structure & Astrophysics
- **PANDA:** Hadron Structure & Dynamics
- **APPA:** Atomic Physics, **Plasma Physics**, Applic

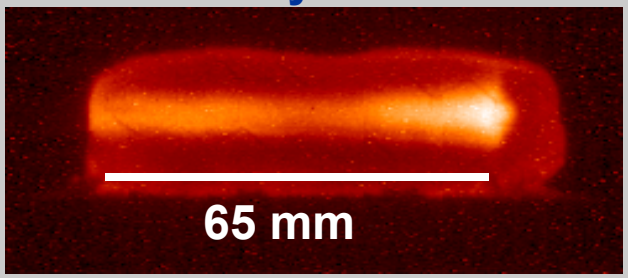
In total: 2500 – 3000 Users

Funding (Construction)

§ 65 % Federal Republic
§ 10 % State of Hessen
§ 25 % International Partners

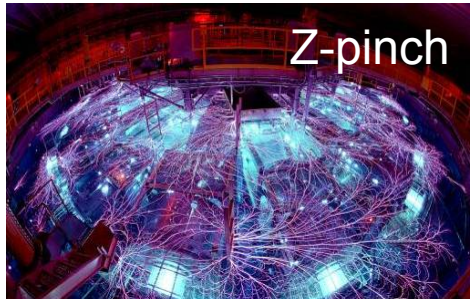
The uniqueness of heavy ion beams compared to other techniques (Laser, Z-pinch)

intense, energetic beams of heavy ions



Ne^{10+} 300 MeV/u; Kr crystal

- large volume of sample (mm^3)
- fairly uniform physical conditions
- thermodynamic equilibrium
- any material



Already within module 1: Compared to GSI, FAIR will provide an ***intensity and energy density increase by a factor of 100.***

WDM-parameters: **T:** up to 10 eV **ρ:** ~ solid **P:** up **to 1** Mbar

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

Atomic, Plasma Physics and Applied Physics (APPA)

Plasma-physics

- 246 scientists
- 55 institutions
- 16 countries

BIOMAT

- 110 scientists
- 28 institutions
- 12 countries

SPARC

- 284 scientists
- 83 institutions
- 26 countries

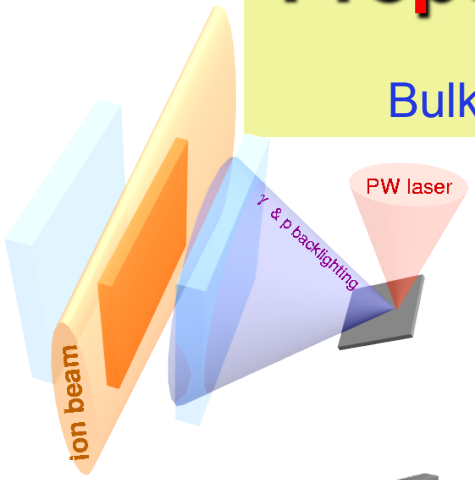
FLAIR

- 144 scientists
- 49 institutions
- 15 countries

Proposed experiments on Plasma Physics

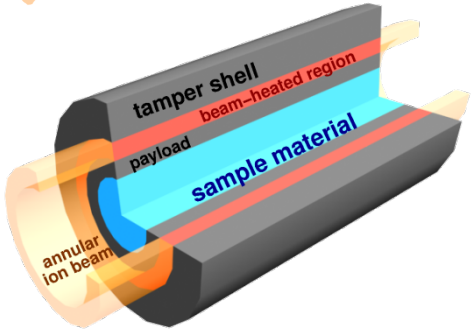
with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures



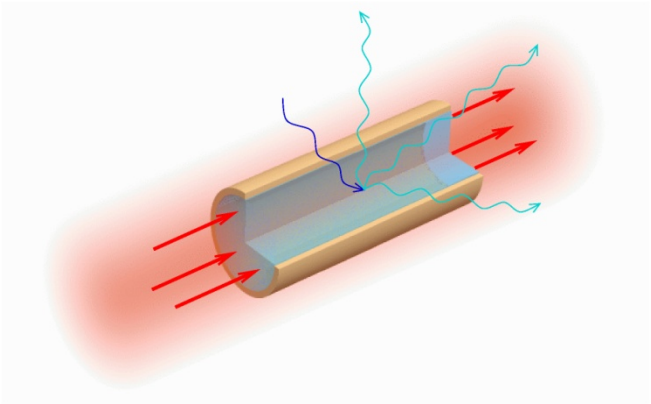
HIHEX: Heavy Ion Heating and Expansion

(HEDgeHOB)



LAPLAS: Laboratory Planetary Sciences

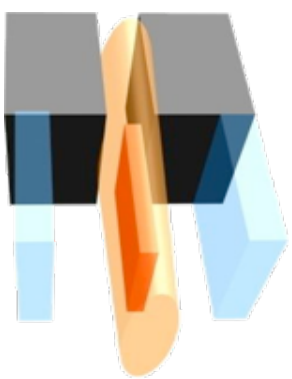
(HEDgeHOB)



WDM: Warm Dense Matter

High Energy Density experiments of HEDgeHOB collaboration

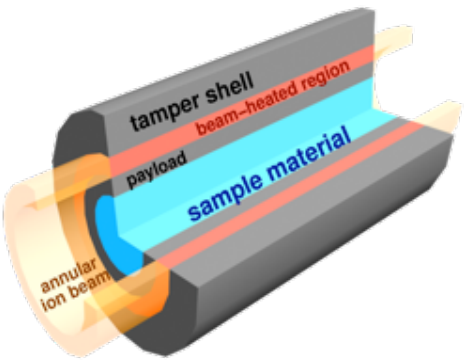
HIHEX
Heavy Ion Heating and Expansion



- uniform quasi-isochoric heating of a large-volume dense target, 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 critical point regions for various materials

LAPLAS
Laboratory Planetary Sciences



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

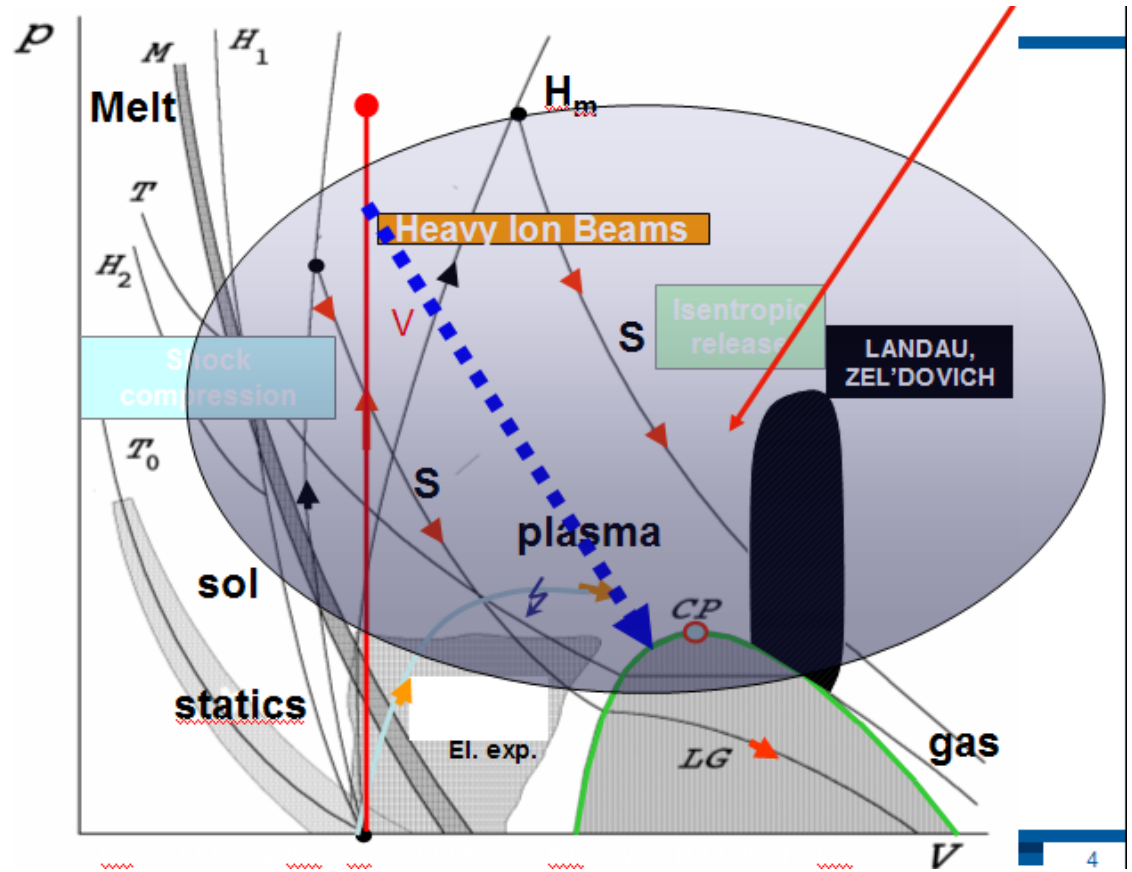
Mbar pressures @ moderate temperatures:
high-density HED states, e.g. hydrogen metallization problem, interior of Jupiter and Saturn

Fundamental properties of matter under extreme conditions

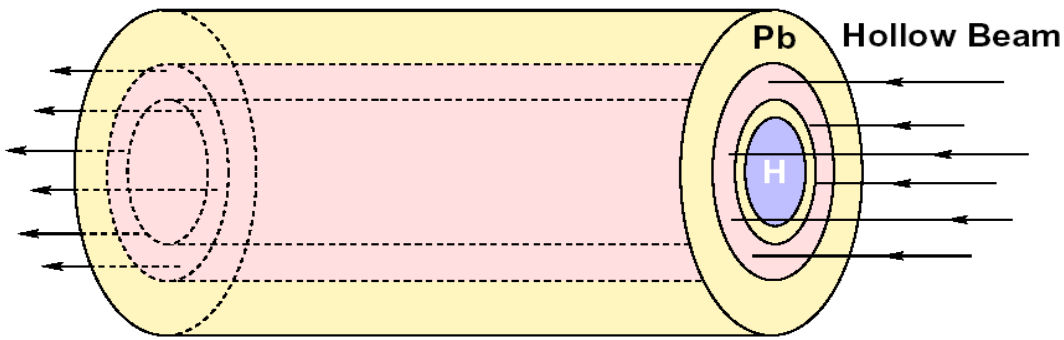
Intense heavy ion beams at FAIR provide unique capabilities for generation and study HED states in matter

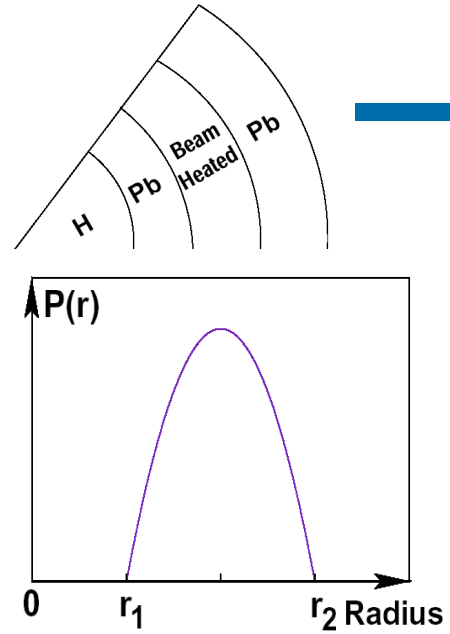
- equation-of-state (EOS) of HED matter
- phase transitions and exotic states of matter
- transport and radiation properties of HED matter
- stopping properties of non-ideal plasma

Isentropic Expansion



Low entropy compression



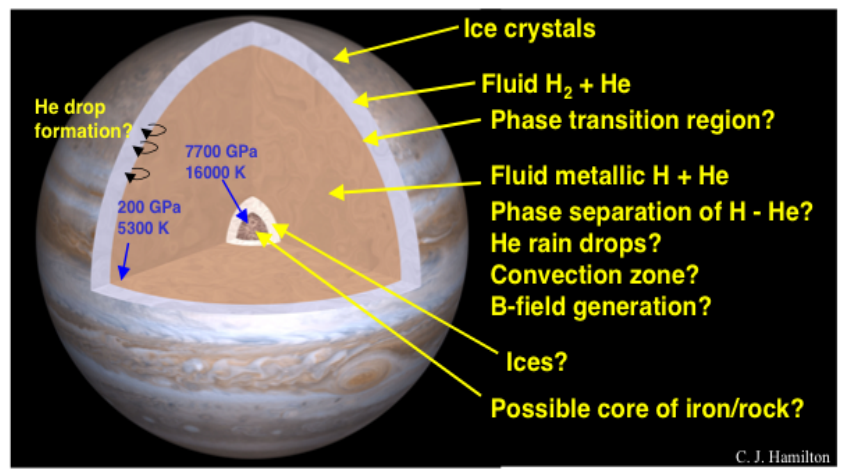


Target Parameters	Beam Parameters
$r_d = 0.4$ mm	2.7 GeV/u Uranium
$r_1 = 0.6$ mm	$N = 0.2 - 1.5 \times 10^{12}$
$r_2 = 2.1$ mm	$\tau = 20$ ns
$r_0 = 3.5$ mm	$E_b = 21 - 155$ kJ

$\rho = 1 - 2$ g/cm^3

P = 2 – 10 Mbar

T = 0.2 – 0.6 eV



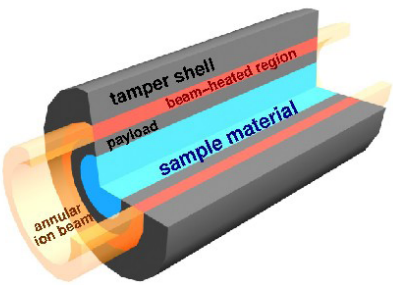
2. LAPLAS [LAboratory PLAnetary Sciences]

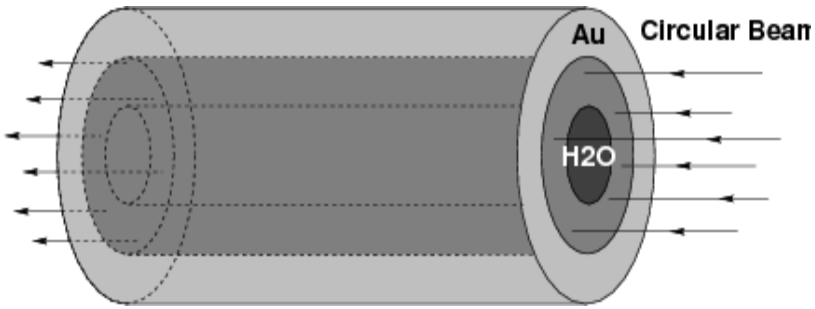
Experimental Scheme: Low entropy compression of a test material like H, D_2 or H_2O, in a multlayered cylindrical target

[Hydrogen Metallization , Planetary Interiors]

N.A. Tahir et al., PRE 64 (2001) 016202; High Energy Density Phsics 2 (2006) 21;

A.R. Piriz et al, PRE 66 (2002) 056403.





Hollow Beam — Au or Pb — Circular beam

Shock reverberates between the cylinder axis and the hydrogen-outer shell interface.

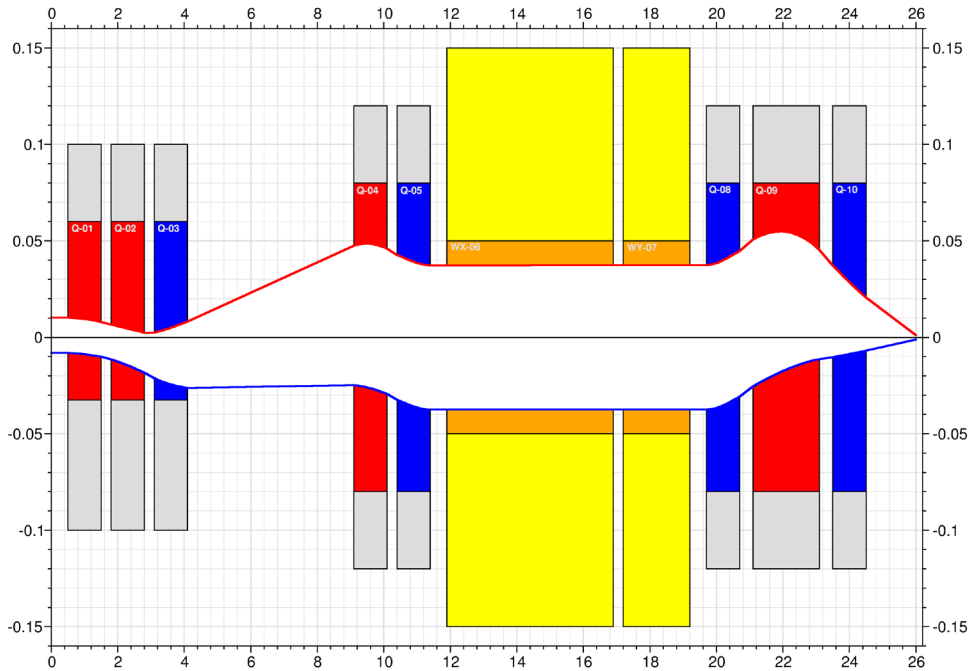
Very high densities, high pressure, higher temperature

Very high ρ (23 g/cc), ultra high P (30Mbar) , low T (of the order of 10 kK).

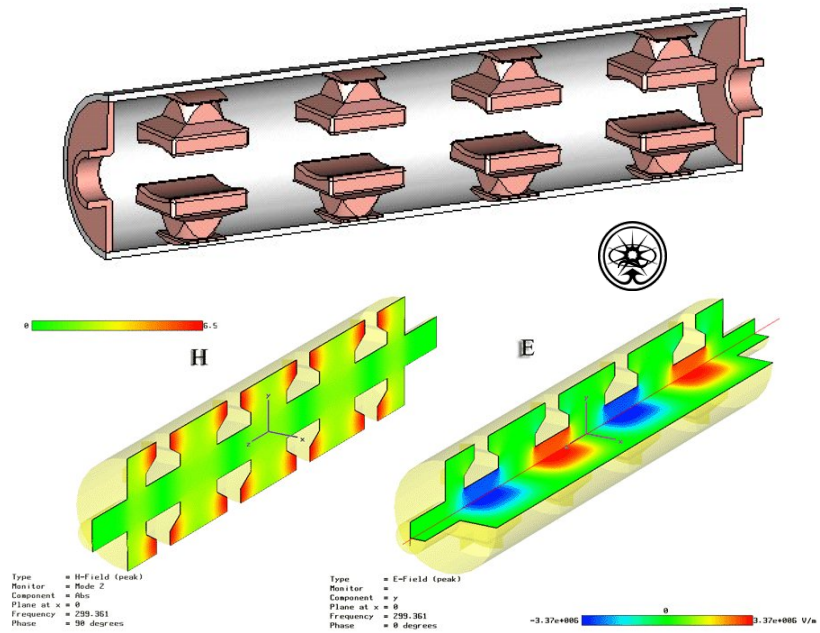
ρ = 1.2 g/cc, P = 11 Mbar, T = 5 ev

P6.1&6.2: Ion optical design of the **LAPLAS** beam line: focusing and RF beam deflector (wobbler), ITEP design.

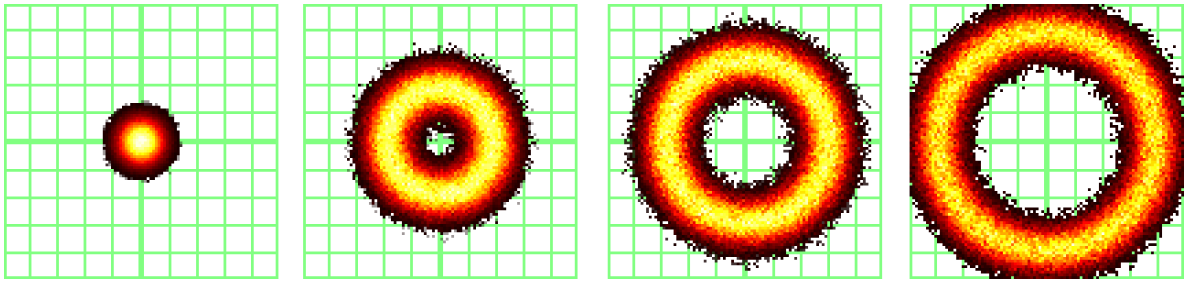
Layout of the **LAPLAS** beam line



Design of rf beam deflector (wobbler)



Transverse beam intensity distribution in the focal spot

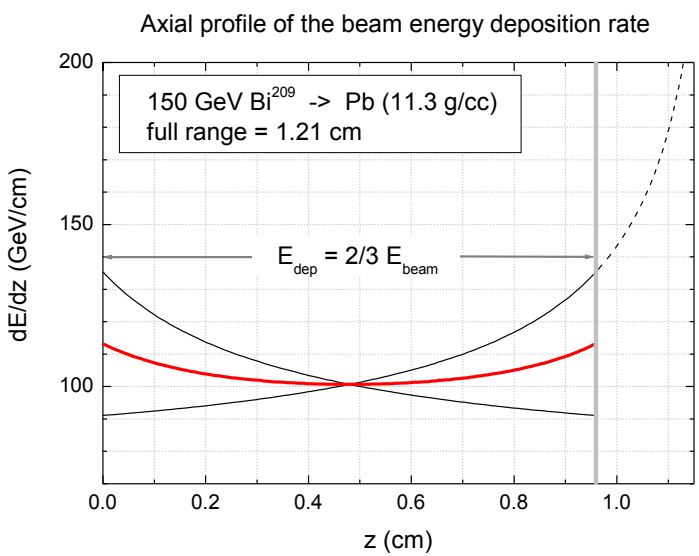


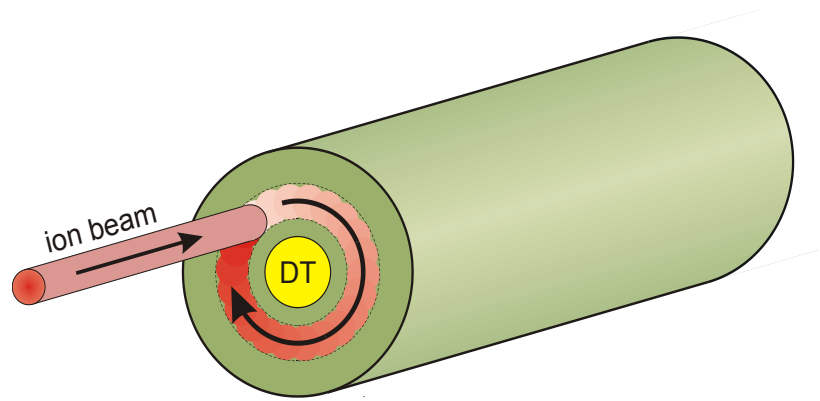
Principal motivation for cylindrical targets

M.Basko et al., HIF 2002

Near-relativistic heavy ions with energies ≥ 0.5 GeV/u become an interesting alternative driver option for heavy ion inertial fusion (D.G. Koshkarev).

Bi ions with energies 100-200 GeV have relatively long ranges of ~7-18 g/cm^2 in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.





Direct drive may become a competitive target option when

- azimuthal symmetry is ensured by fast beam rotation around the target axis,
- axial uniformity is controlled by discarding the Bragg peak, and (possibly) by two-sided beam irradiation,
- a heavy-metal shell (liner) is used to compress the DT fuel.

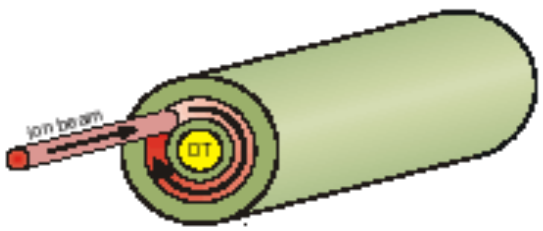
M.Basko *et al.*, HIF 2002

(IAEA-2004) Russian studies of fast ignition using 100 GeV heavy-ion synchrotrons:

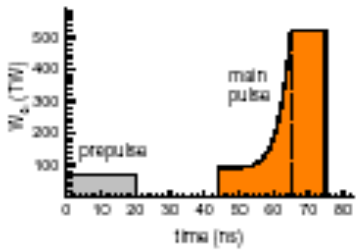
Bi ions with energies 100-200 GeV have relatively long ranges of ~7-18 g/cm2 in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

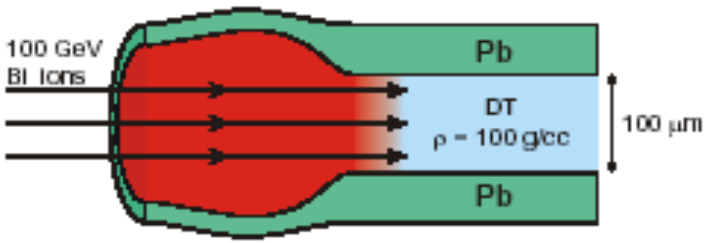


Compression pulse:



- Target compression is accomplished by a separate beam of ions with the same energy of E_i = 0.5 GeV/u.
- Azimuthal symmetry is ensured by fast beam rotation around the target axis (~10 revolutions per main pulse).
- Relative inefficiency of cylindrical implosion is partly compensated for by direct drive.

Ignition and burn propagation



Ignition pulse:

beam energy:	E_{igb} = 400 kJ
pulse duration:	t_{igp} = 200 ps
beam power:	W_{igb} = 2 PW
focal radius:	r_{foc} = 50 μm
irradiation intensity:	I_{igb} = 2.5×10^{19} W/cm^2

2-D hydro simulations (ITEP + VNIIEF) have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder.

An energy gain of **G ≈ 100** can be expected.

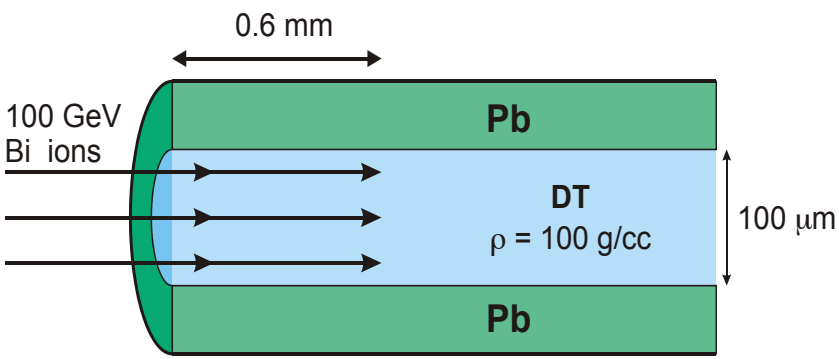
Fast ignition with heavy ions: assembled configuration

M.Basko et al., HIF 2002

With a heavy ion energy ≥ 0.5 GeV/u, we are compelled to use cylindrical targets because of relatively long (≥ 6 g/cm^2) ranges of such ions in matter.

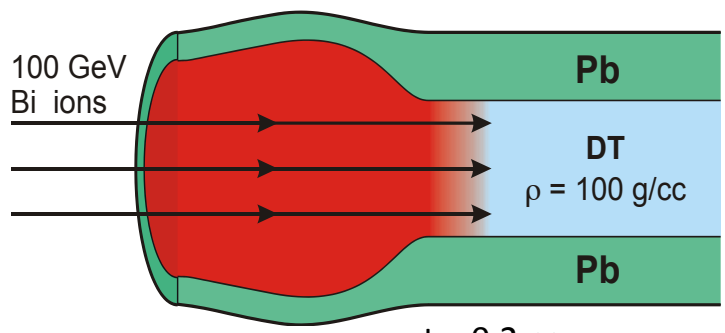
The ion pulse duration of 200 ps is still about a factor 4 longer than the envisioned laser ignitor pulse. For compensation, it is proposed to use a massive tamper of heavy metal around the compressed fuel:

Assembled configuration



t = 0

Ignition and burn propagation



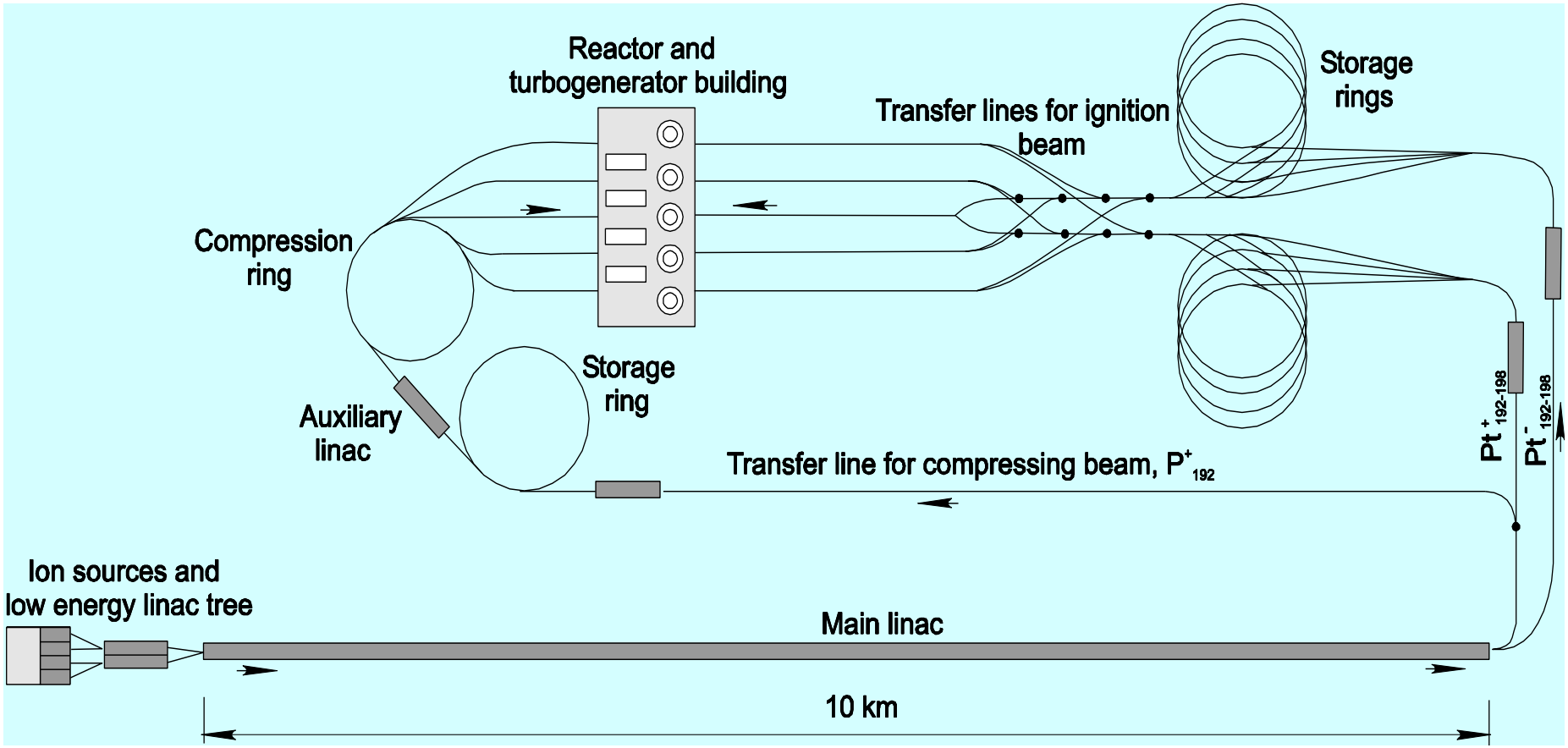
t = 0.2 ns

Fuel parameters in the assembled state: ρ_{DT} = 100 g/cc, R_{DT} = 50 μm, $(\rho R)_{DT}$ = 0.5 g/cm^2.

2-D hydro simulations (ITEP + VNIIEF) have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder!

HI IFE Concept
Ground plan for HIF power plant

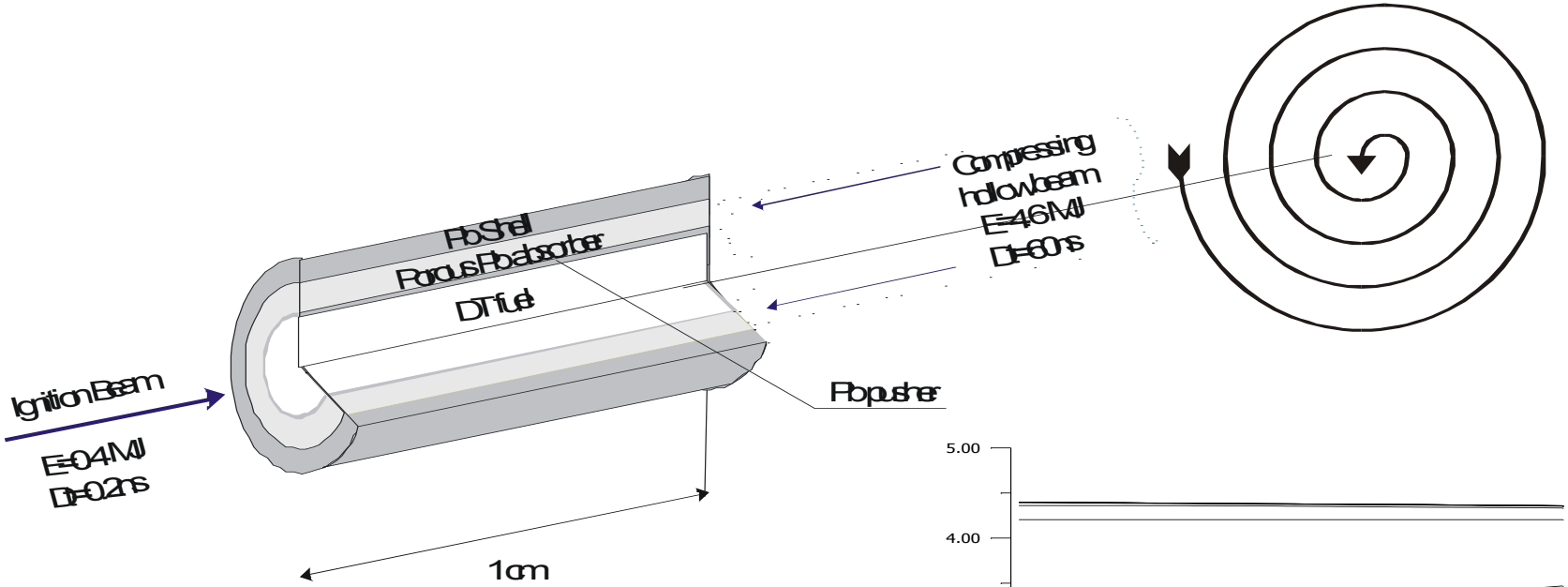
B.Y. Sharkov BY, N.N. Alexeev, M.M. Basko et al., Nuclear Fusion 45(2005) S291-S297.

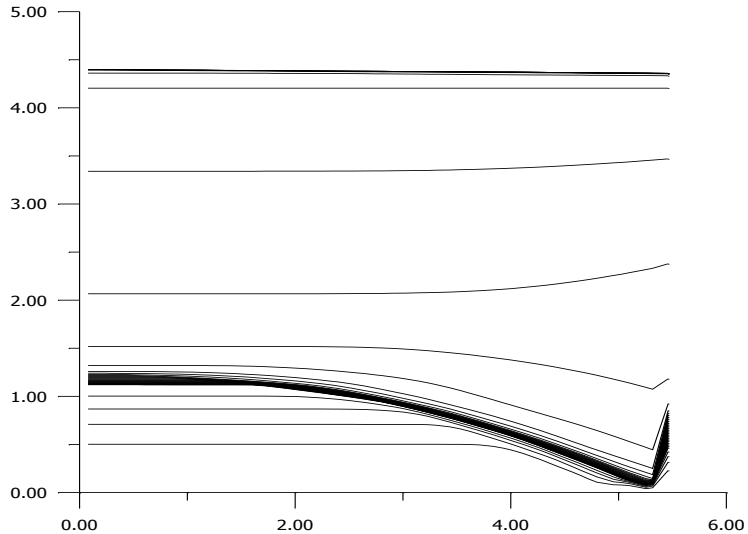


HIGH POWER HEAVY ION DRIVER		
Ions		$Pt^{+,-}_{192,194,196,198}$
Ion energy	(GeV)	100
Compression beam		
Energy	(MJ)	7.1 (profiled)
Duration	(ns)	75
Maximum current	(kA)	1.6
Rotation frequency	(GHz)	1
Rotation radius	(mm)	2
Ignition beam		
Energy	(MJ)	0.4
Duration	(ns)	0.2
Maximum current	(kA)	20
Focal spot radius	(μm)	50
Main linac length	(km)	10
Repetition rate	(Hz)	2x4 (reactor)
Driver efficiency		0.25

CYLINDRICAL TARGET	
DT fuel mass (g)	0.006
Total mass (g)	4.44
Length (mm)	8.0
ρR parameter (g/cm^2)	0.5
Burn fraction	0.39
Gain	~120
Fusion energy (MJ)	750
Energy release partition	
X-ray (MJ)	17
Ion debris (MJ)	153
Neutrons (MJ)	580

Target irradiation by rotating ion beam

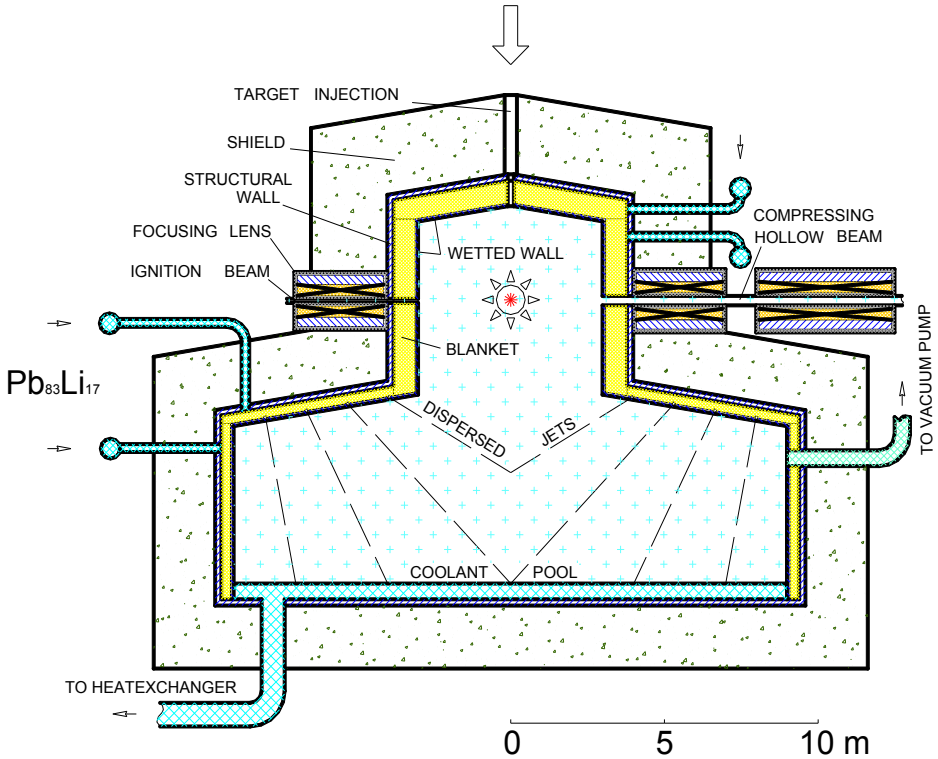




$\rho \geq 100$ g/cm3 ,

$\rho R \geq 0.5$ g/cm2

E = 6.3 MJ (*instead 7.1 MJ*)



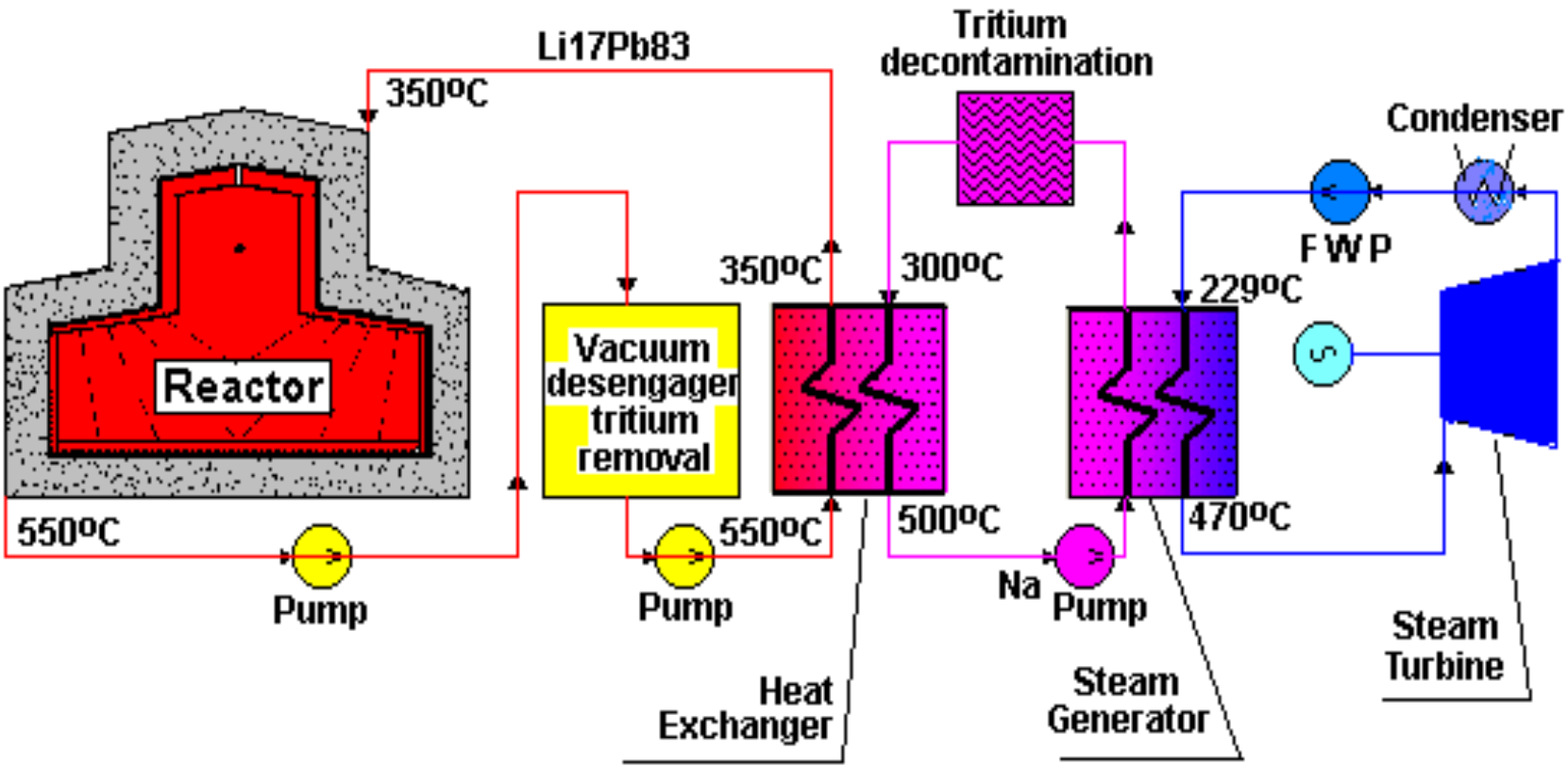
REACTOR CHAMBER FOR FAST IGNITION HEAVY ION FUSION

REACTOR CHAMBER FOR HIF POWER PLANT: wetted first wall design

*Orlov Yu.N., Basko M.M., Churazov M.D. et al., Nuclear Fusion **45 (6)** , 531 – 536, (2005).*

REACTOR CHAMBER CHARACTERISTICS	
Fusion energy per shot (MJ)	750
Repetition rate (Hz)	2
Li/Pb atom density (cm^{-3})	10^{12}
Coolant temperature (°C)	550
Explosion cavity diameter (m)	8
Number of beam ports	2
First wall material	SiC (porous)
Coolant tubes material	V-4Cr-4Ti
Blanket energy multiplication	1.1

HIF Power Plant 1 GW + accelerator 100 GeV Pt+



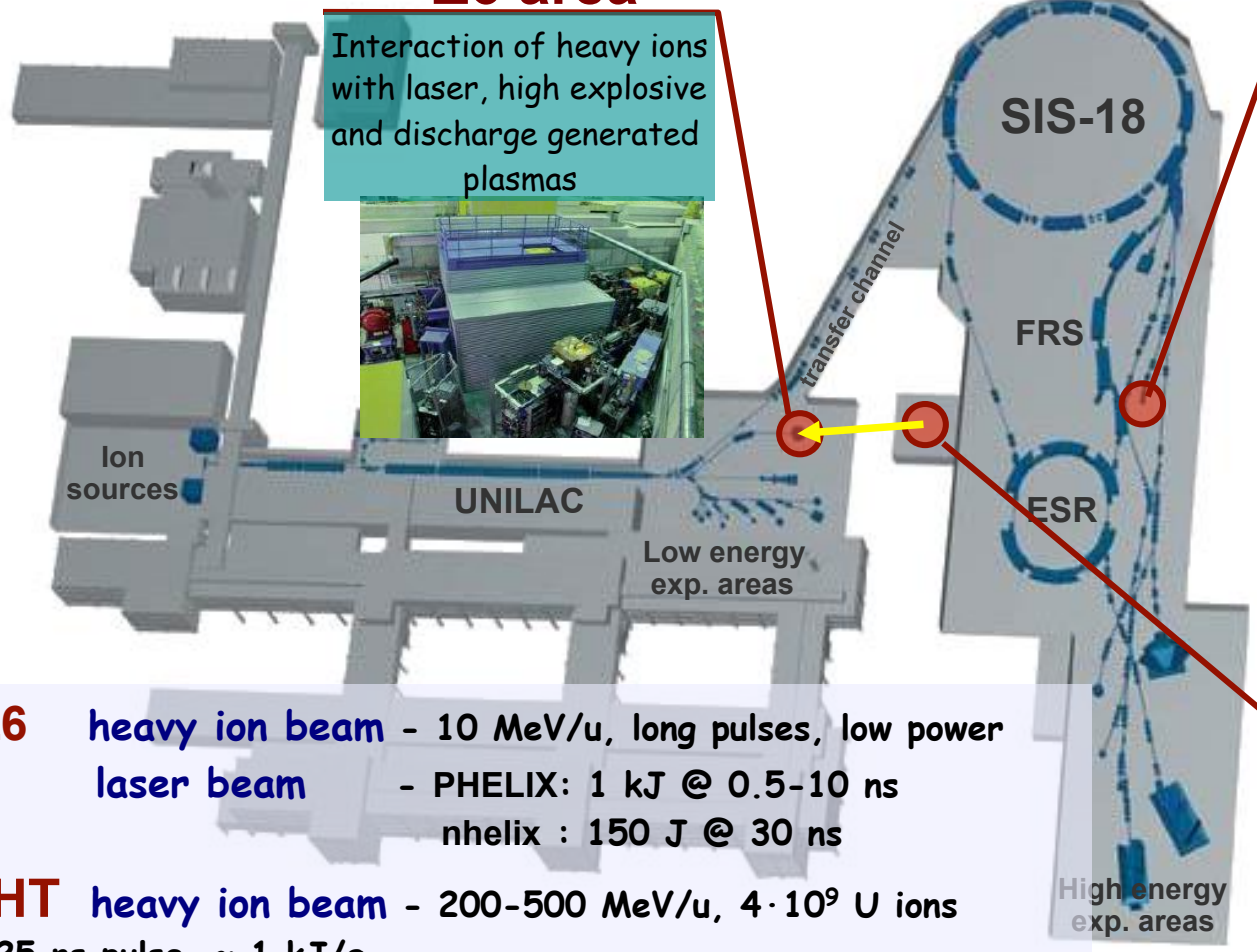
Thermal schematic of FIHIF power plant

- The reactor chamber with a wetted first wall has a minimum number of ports for beam injection.
- A massive target significantly softens the X-ray pulse resulting from the microexplosion.
- A two-chamber reactor vessel mitigates the condensation problem and partly reduces the vapor pressure loading.
- Three loops in the energy conversion system make it easier to optimize the plant efficiency and to develop the thermal equipment.

Present Plasma Physics experimental areas at GSI- Darmstad, Germany

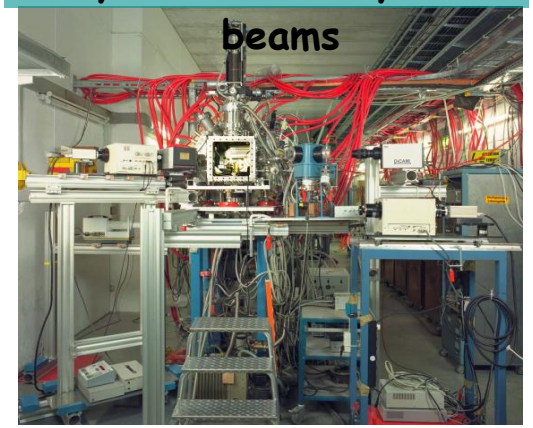
Z6 area

Interaction of heavy ions with laser, high explosive and discharge generated plasmas



HHT area

HED matter generated by intense heavy-ion beams



PHELIX

Petawatt High-Energy Laser for Ion-Beam Experiments

Z6 heavy ion beam - 10 MeV/u, long pulses, low power

laser beam - PHELIX: 1 kJ @ 0.5-10 ns

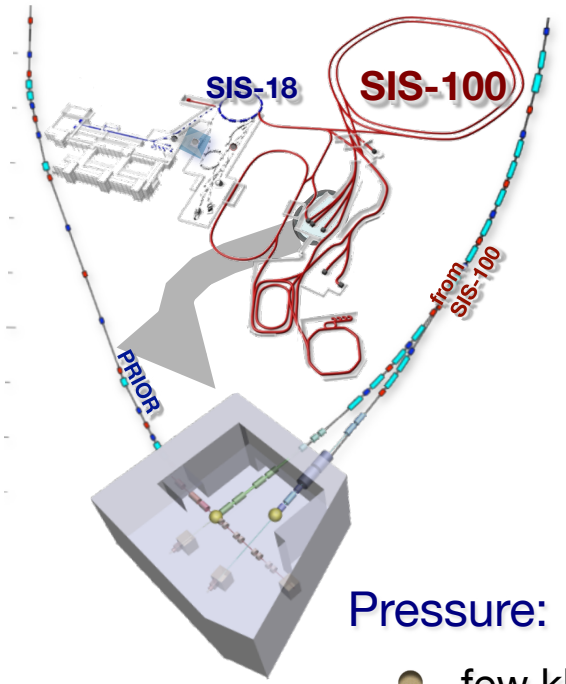
nhelix : 150 J @ 30 ns

HHT heavy ion beam - 200-500 MeV/u, $4 \cdot 10^9$ U ions in 125 ns pulse, ~ 1 kJ/g

Laser beam - PHELIX: 0.5 kJ @ 0.5 ps (PW)

1-5 kJ @ 10 ns

Challenging requirements for beam and target diagnostics in HED Physics experiments:



Density distribution:

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

Temperature:

- 0.2 – 30 eV
- 10 – 20 μm spatial resolution
- 1 – 5 ns time resolution (continuos)

Fast multi-channel pyrometers

Pressure:

- few kbar – few Mbar
- spatial distribution
- 0.5 – 5 ns time resolution

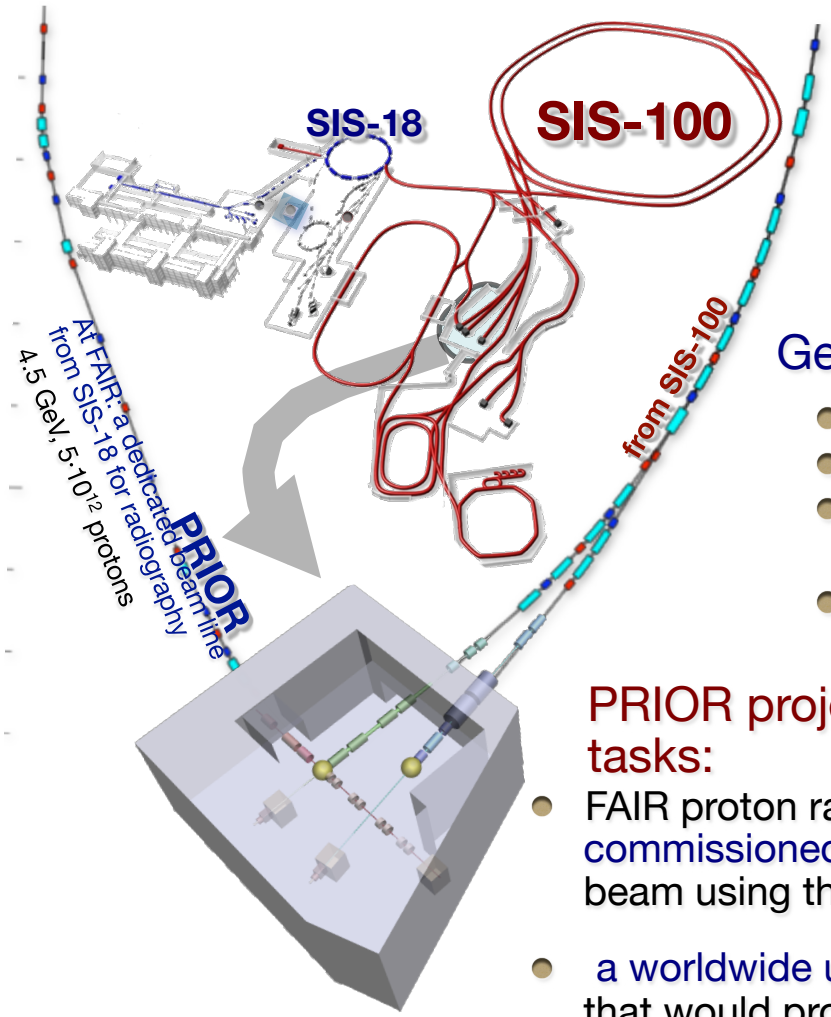
Line-imaging VISARs and displacement interferometers

Intense focused ion beam:

- intensity distribution in the focal spot
- 10 μm spatial resolution
- 1 – 5 ns time resolution

Residual gas fluorescence, etc.

PRIOR – Proton Radiography at FAIR with 4.5 GeV proton beam (collaboration GSI - LANL – ITEP)



- 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:

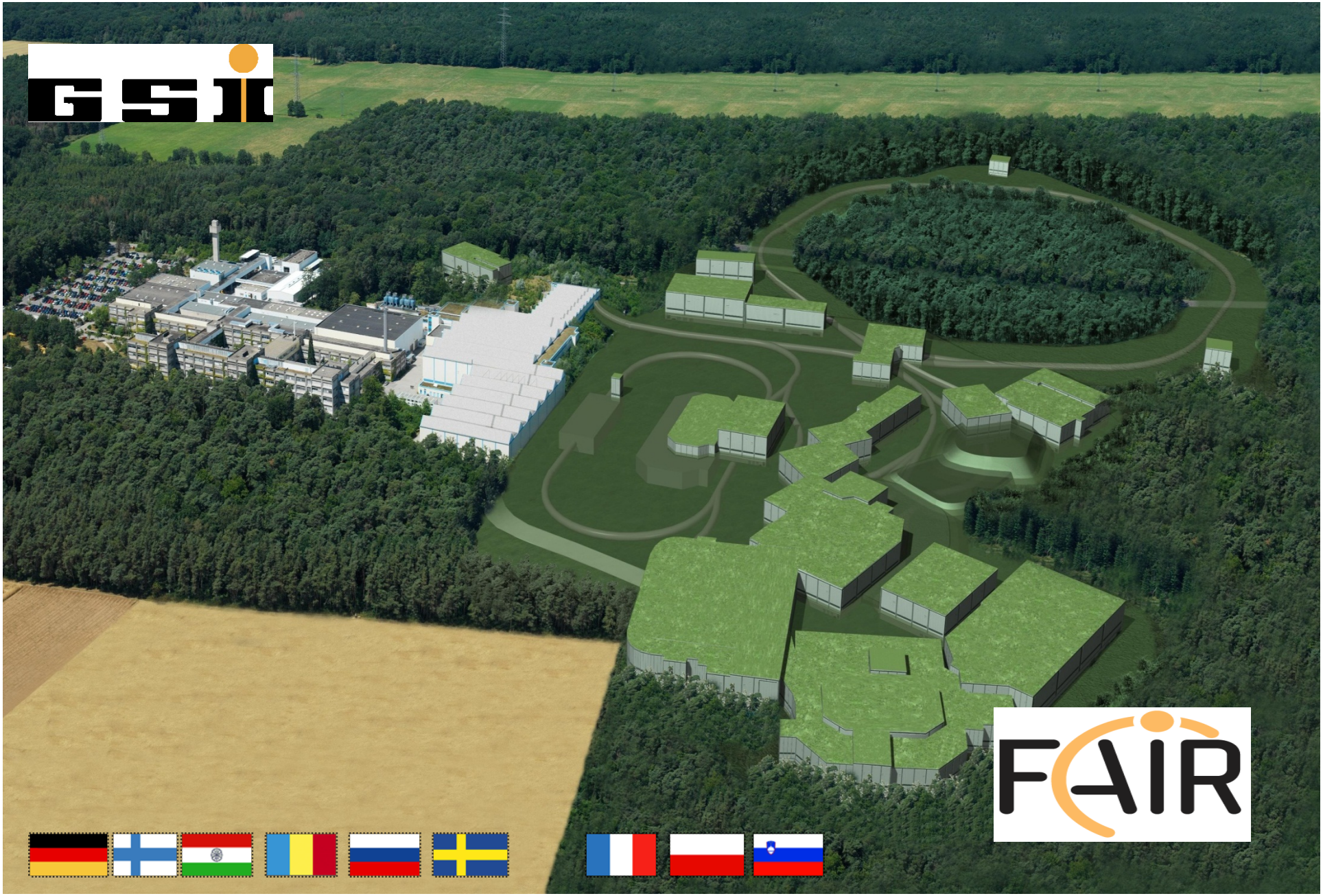
- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets high-spatial resolution (microscopy)
- high density resolution and dynamic range multi-frame capability for fast dynamic events

PRIOR project will accomplish two main tasks:

- FAIR proton radiography system will be designed, constructed and commissioned in full-scale dynamic experiments with 4.5 GeV proton beam using the SIS-18 proton beam,
- a worldwide unique radiographic facility may become operational at GSI that would provide a capability for unparalleled high-precision experiments with great discovery potential at the leading edges of plasma physics, high energy density physics, biophysics, and materials research

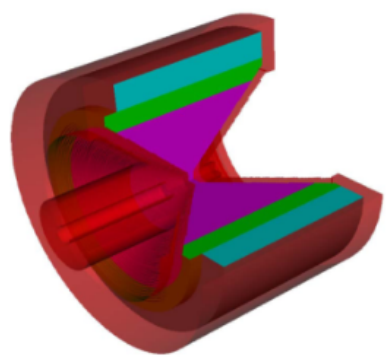
Road Map FAIR Site & Buildings

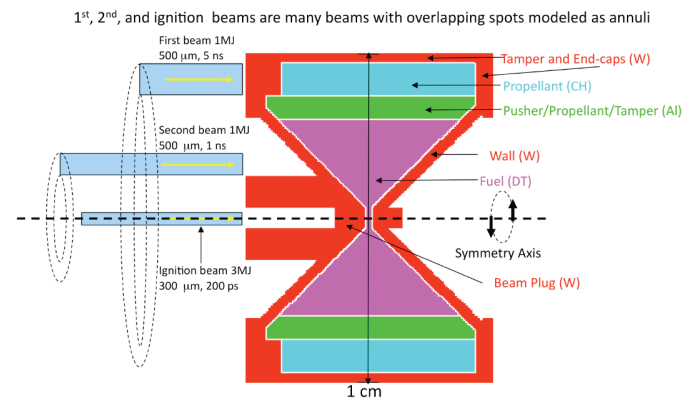
1. Handing in of preplanning documents to hbm
2. Clarification of user requirements Modularized Start Version (MSV)
3. Start revised preplanning for MSV
4. Expected approval of revised planning for MSV
5. Preparation of documents for building permit
6. Expected approval for (partial) building permit
7. Start site preparation (construction roads, clearing trees)
8. Award contracts on civil construction work lot 1 … 4
9. Completion of civil construction work lot 1 … 4
10. Start installation of accelerators and detectors


GSI
FAIR

Summary

1. **The realisation of FAIR has started !!!** Construction of the FAIR facility at Darmstadt will enable to carry out novel and unique experiments on HI IFE
2. **Added value :** demonstration of cylindrical implosion with conversion ratio ~10,
   hollow beam - wobbler technique ~1 GHz
   implosion velocity ~ 2-4 km/s, P ~ 10 Mbar,
3. **Theoretical studies** (simulations + analytic modeling) has shown that an intense heavy ion beam can be employed using very different schemes to study HED physics.
   Work is in progress to investigate more experiment designs.
4. **X-Target @ FAIR**

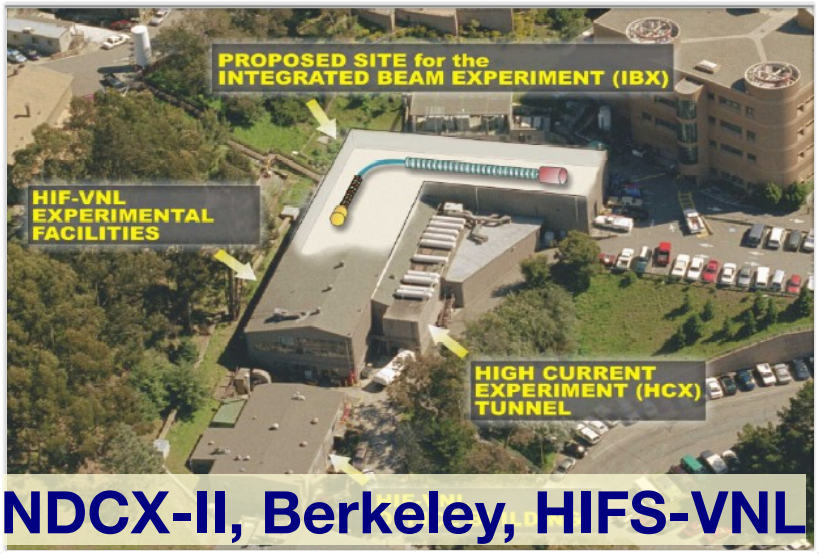




5. Currenet experiments are well in progress aiming at development of new experimental techniques required for FAIR experimental campaign.

FAIR-related exp. activities using HI accelerator facilities and powerful lasers.

Accelerator centers for IFE related HED research with intense HIB



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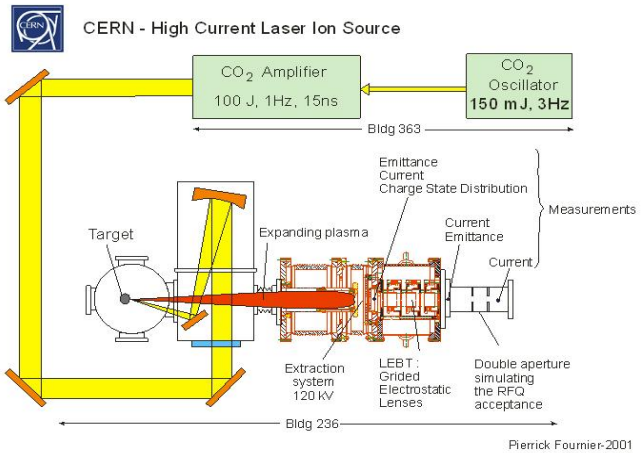
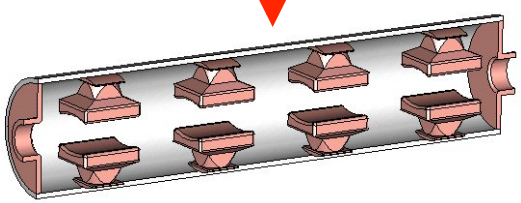
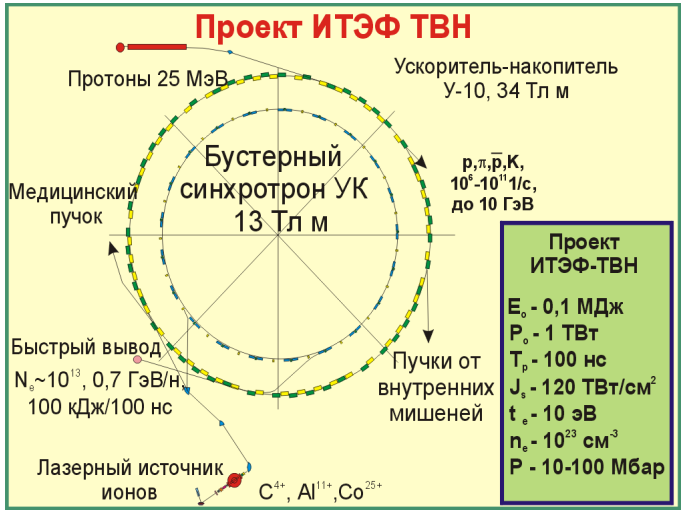
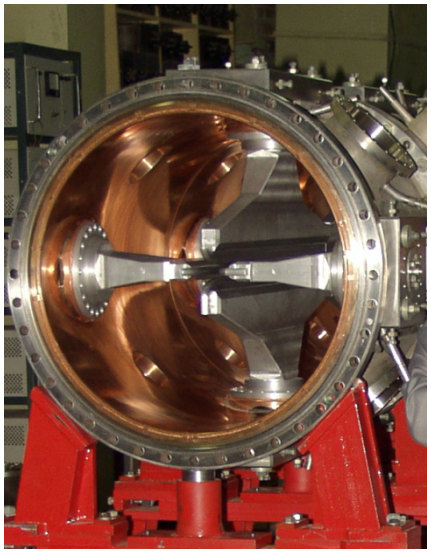
IHED RAS, Russia
Keldysh IAM, RAS, Russia
HZ GSI, Germany
TU-Damstadt, Germany
VNIIEF –Sarov, Russia
Universidad de Castilla - La Mancha, Ciudad Real, Spain

ITEP Solutions

1:Laser ion source

2: RFQ accelerator

3: Non-Liouvillian stacking

4. RF wobbler technique