Beauty of Physics at FAIR

Boris Sharkov

FAIR Scientific Director,
Chairman of the management board

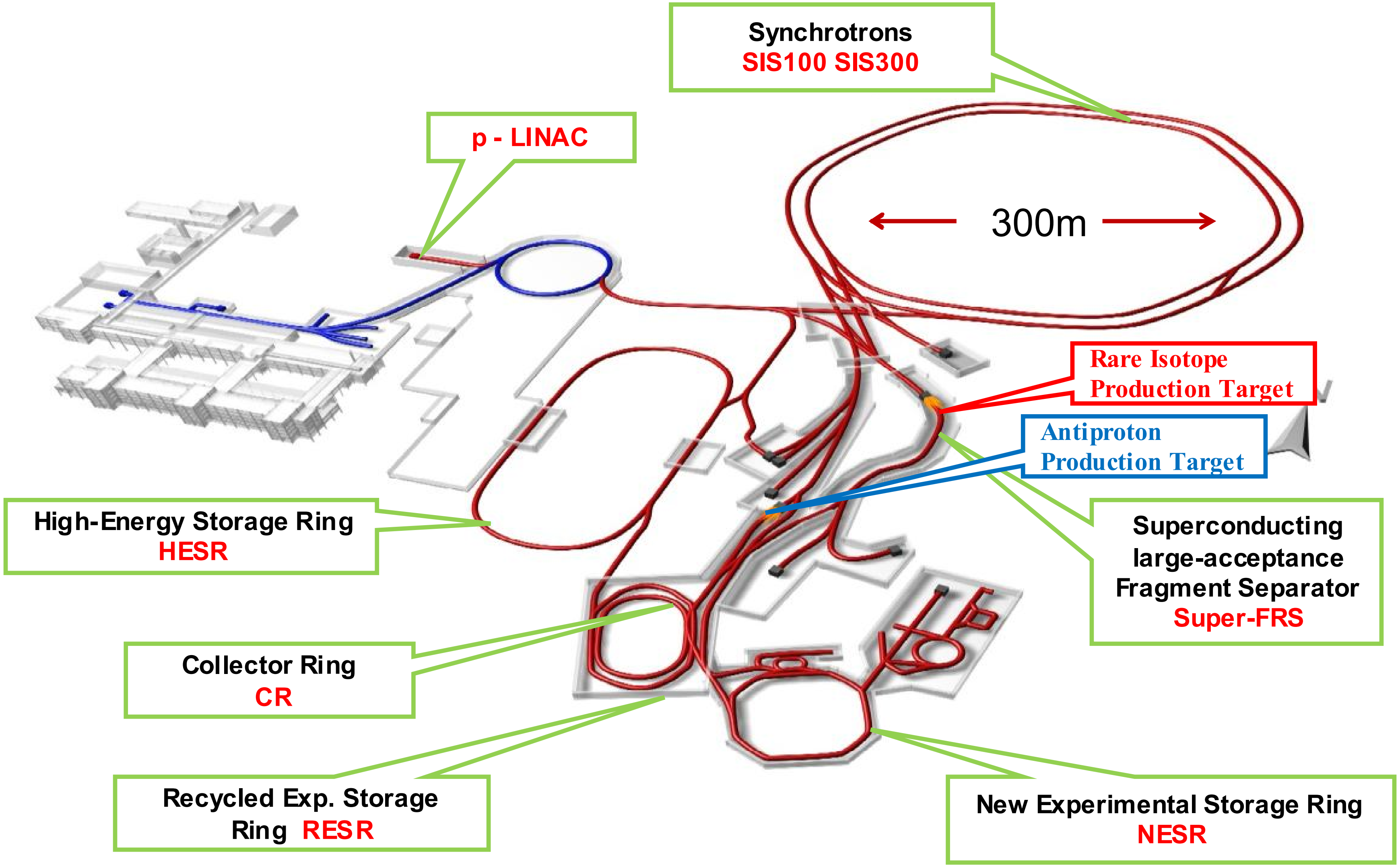
19. 02. 2012. Bekasovo

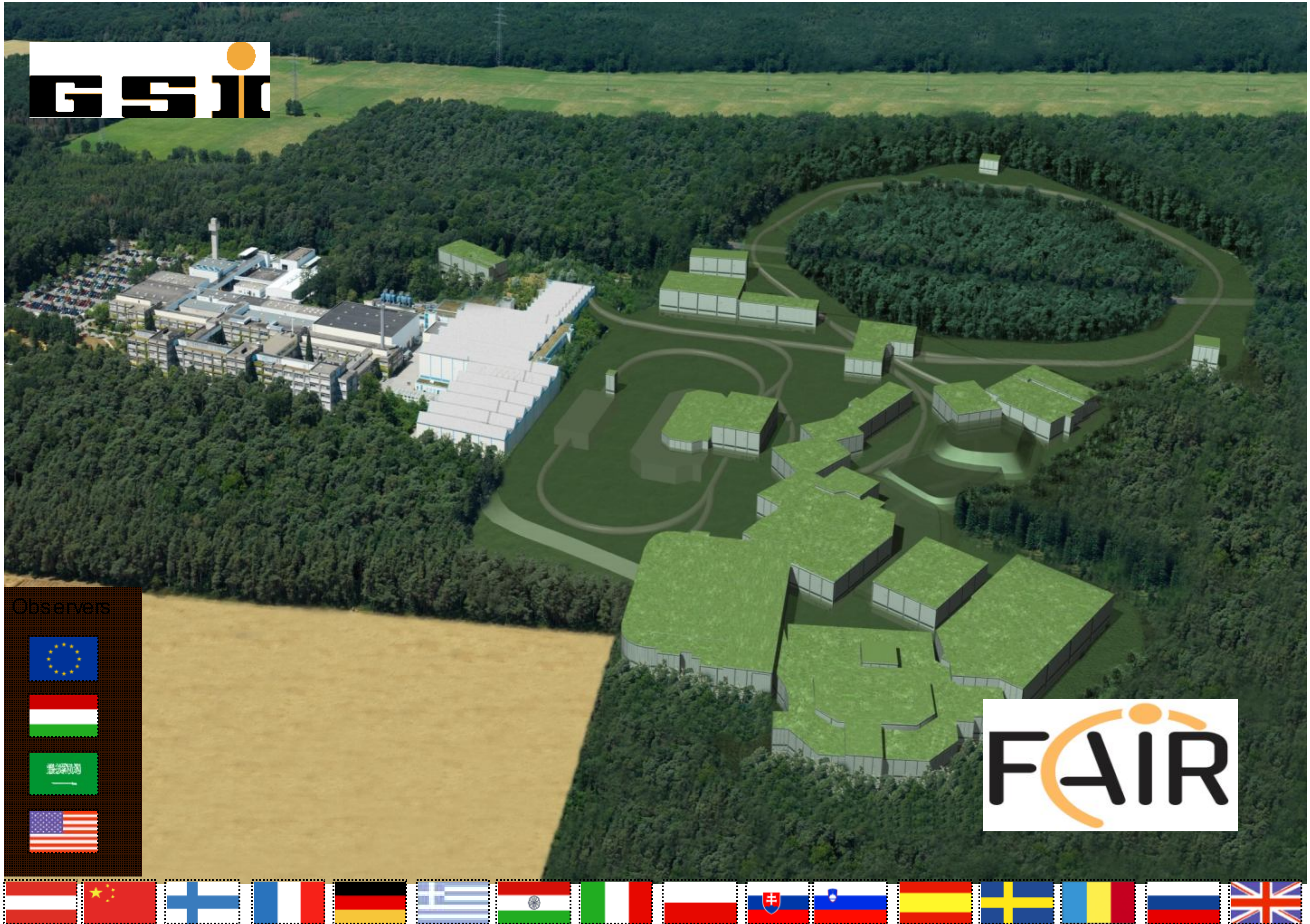
Outline

1. International FAIR
2. Research at FAIR
3. 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
6. Summary

Facility for Antiproton and Ions Research –
the light tower of the ESFRI Roadmap

New accelerator systems to be constructed in Darmstadt





Austria China Finnland France Germany Greece India Italy Poland Slovakia Slovenia Spain Sweden Romania Russia UK

04.10.2010 Castle Biebrich, Wiesbaden
Signing Ceremony of FAIR international Convention

Finland, France, Germany, India, Poland, Romania, Russia, Slovenia and Sweden

The present Main Project: FAIR – the intensity frontier

Added value

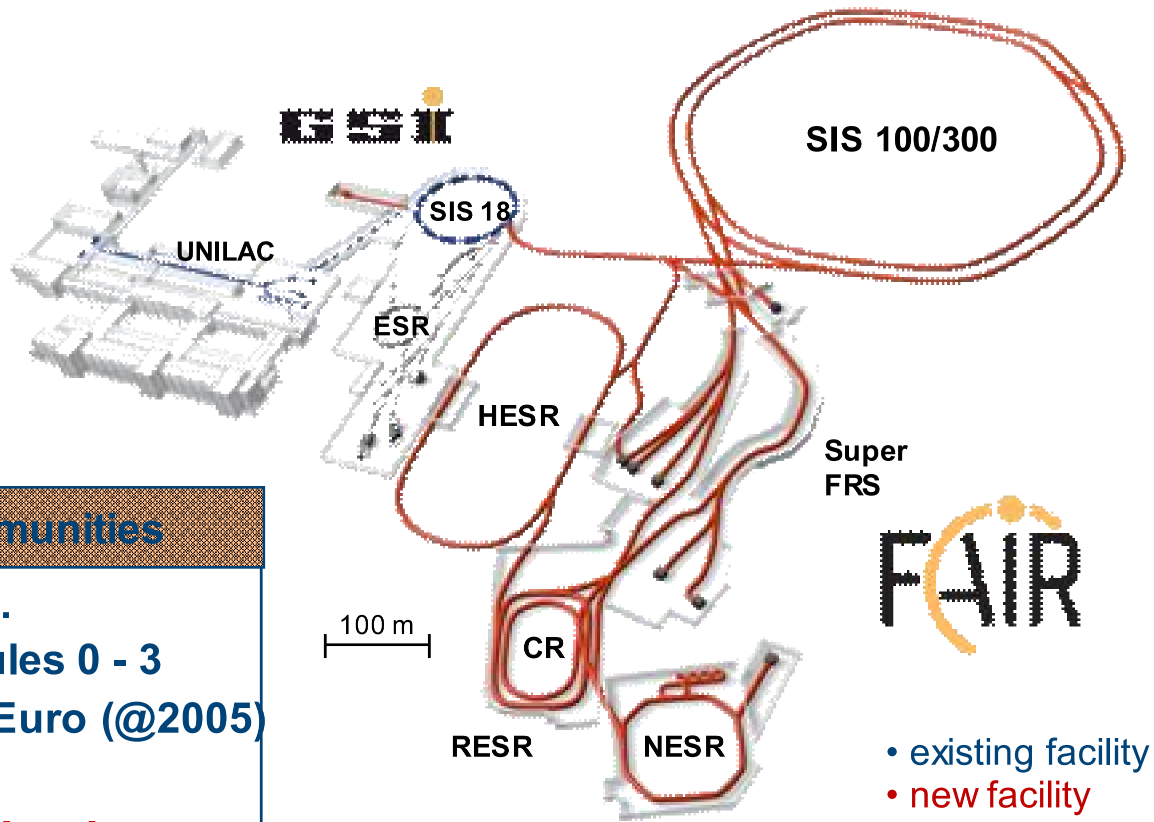
- § Beam intensity by a factor of 100 - 10000
- § Beam energy by a factor of 20
- § Anti-matter beams
- § Unique beam quality
- § Parallel operation

Construction, cost, scientific communities

- § **Construction in modules 0 – 6, …**
- § **Modularized Start Version: Modules 0 - 3**
  Construction cost: 1.027 Billion Euro (@2005)
- § **Scientific Pillars:**

- **APPA:** Atomic Physics, **Plasma Physics**, Applic.
- **CBM:** Compresed Baryonic Matter
- **NuSTAR:** Nucl Structure & Astrophysics
- **PANDA:** Hadron Structure & Dynamics

In total: 2500 – 3000 Users



Funding (Construction)

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

Development of Project Staging

2003	**Recommendation by WissenschaftsRat – FAIR Realisation in three stages**						
2005	**Entire Facility** **Baseline Technical Report**						
2007	**Phase A**						**Phase B** SIS300
2009	**Module 0** SIS100	**Module 1** expt areas CBM/HADES and APPA	**Module 2** Super-FRS fixed target area NuSTAR	**Module 3** pbar facility, incl. CR for PANDA, options for NuSTAR	**Module 4** LEB for NuSTAR, NESR for NuSTAR and APPA, FLAIR for APPA	**Module 5** RESR nominal intensity for PANDA & parallel operation with NuSTAR and APPA	**Module 6** SIS300

Modularized Start Version

Financial Constrains

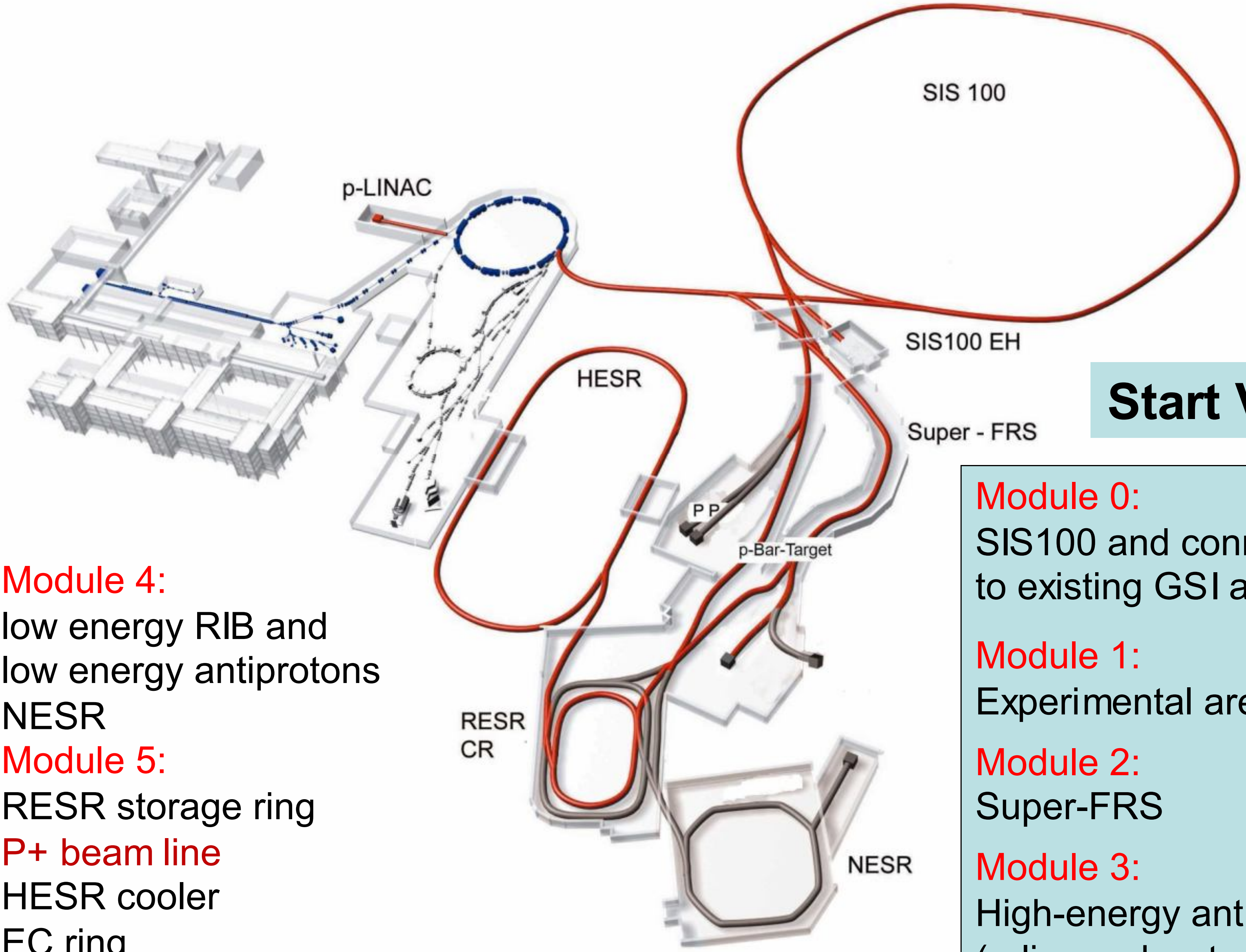
Cost of Modularized Start Version = 1027 M€

Firm funding commitments of FAIR Partners = 1026,5 M€

Modularized Start Version secures a swift start within the current funding commitments

Basic criteria of new FAIR construction scenario:

The Modularized Start Version should enable realization of outstanding forefront research program to <u>all four</u> scientific communities of FAIR



Start Version

Module 0:
SIS100 and connection
to existing GSI accel.

Module 1:
Experimental areas CBM,APPA

Module 2:
Super-FRS

Module 3:
High-energy antiprotons
(p-linac, pbar-target, CR,
HESR)

Module 4:
low energy RIB and
low energy antiprotons
NESR

Module 5:
RESR storage ring

P+ beam line
HESR cooler
EC ring

FAIR – new international research laboratory to explore the nature of matter in the Universe

The main research thrust of FAIR focuses on the
structure and evolution of matter
on both a **microscopic and a cosmic scale**

Scientific Pillars:

- **APPA:** Atomic Physics, **Plasma Physics**, Applic.
- **CBM:** Compressed Baryonic Matter
- **NuSTAR:** Nucl Structure & Astrophysics
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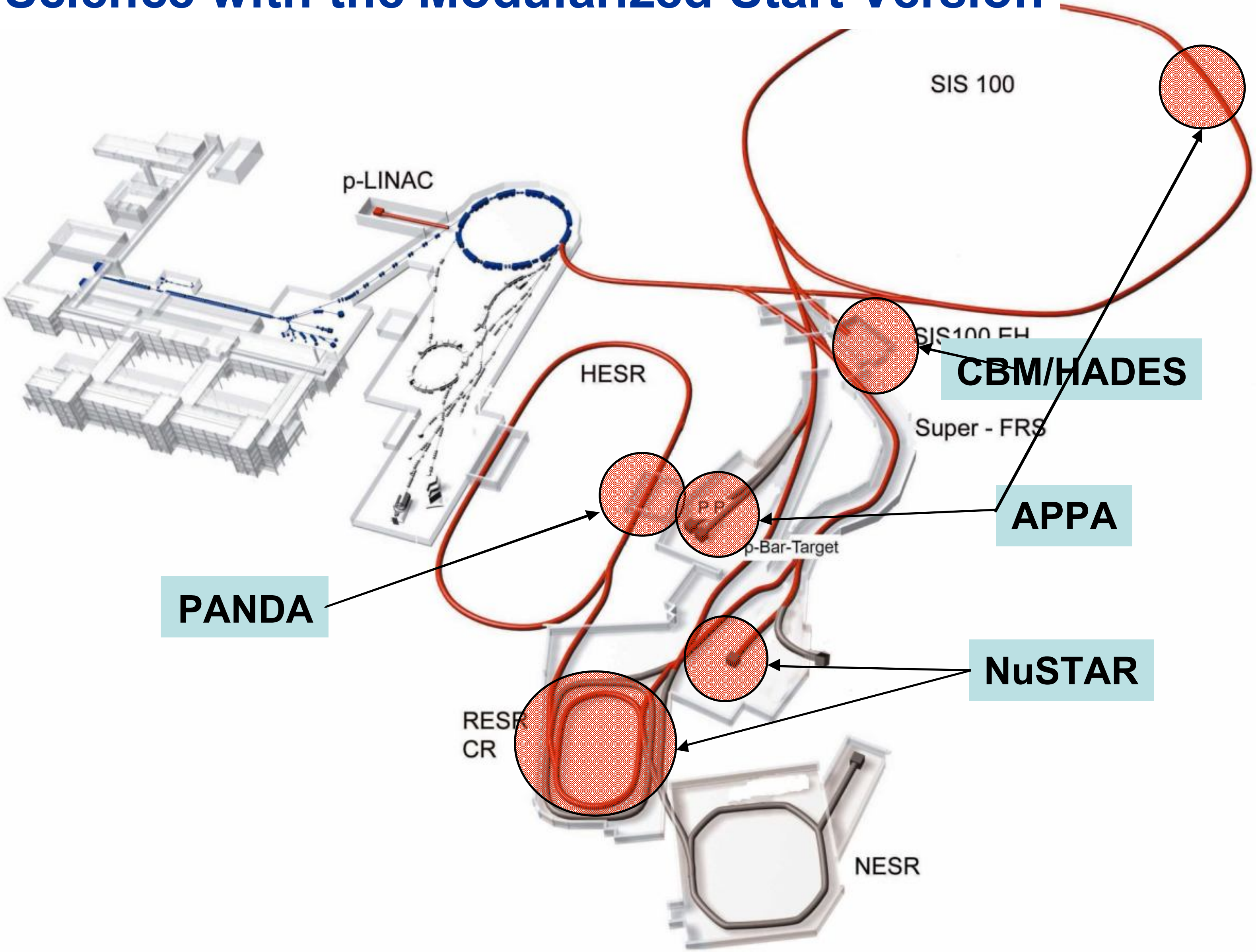
In total: 2500 – 3000 Users

Science with the Modularized Start Version



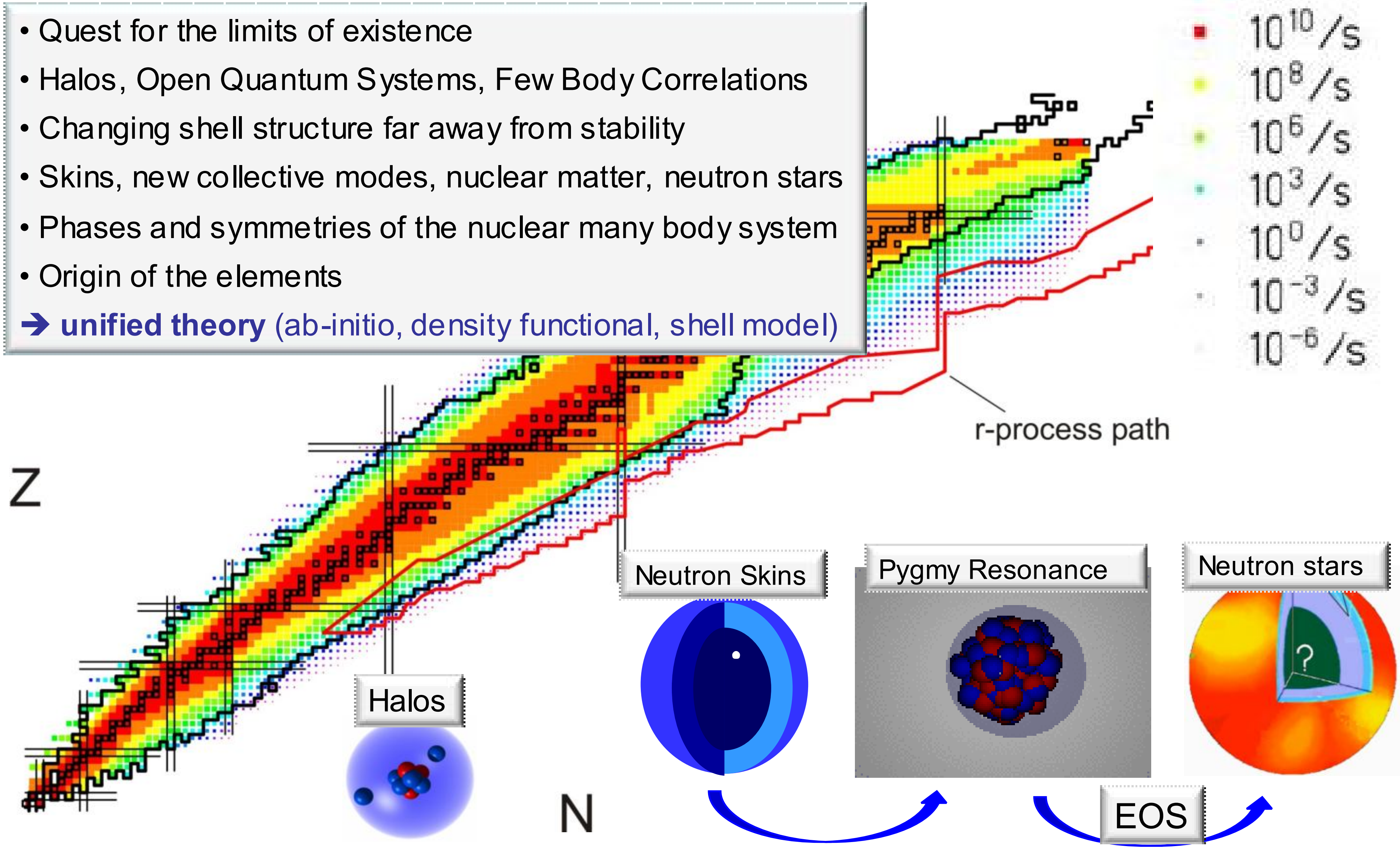
Nuclear STructure, Astrophysics and Reactions

> 800 members from 37 countries and 146 institutions

Central Topics for NuSTAR at FAIR *How are nuclei made?*

- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

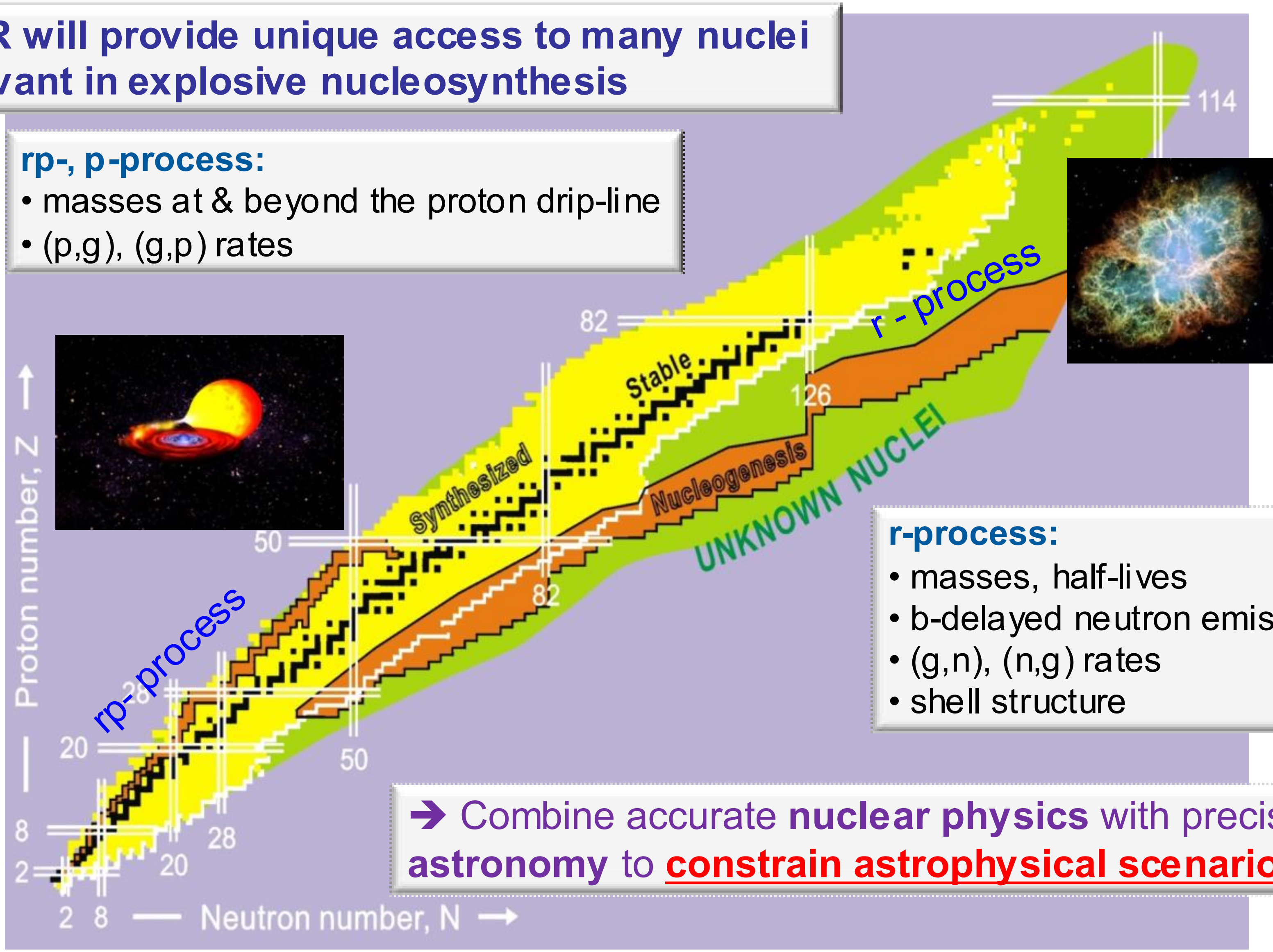
➔ **unified theory** (ab-initio, density functional, shell model)



Nuclear Astrophysics at FAIR

FAIR will provide unique access to many nuclei relevant in explosive nucleosynthesis

rp-, p-process:
- masses at & beyond the proton drip-line
- (p,g), (g,p) rates

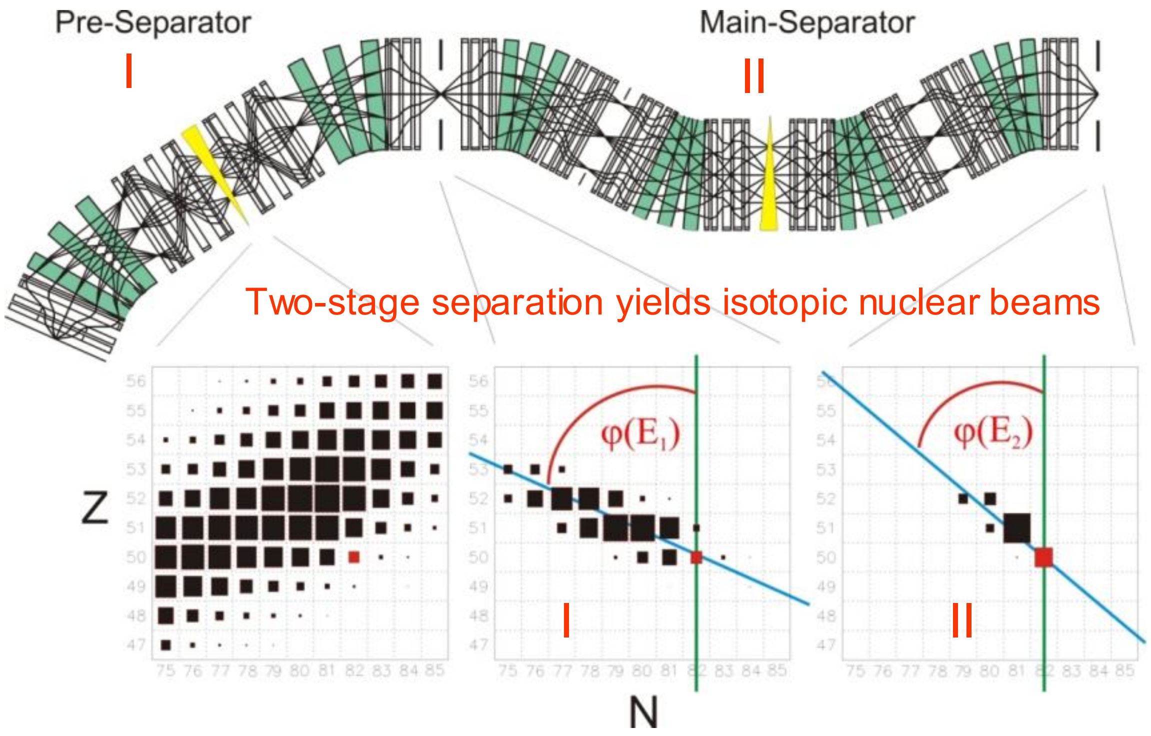


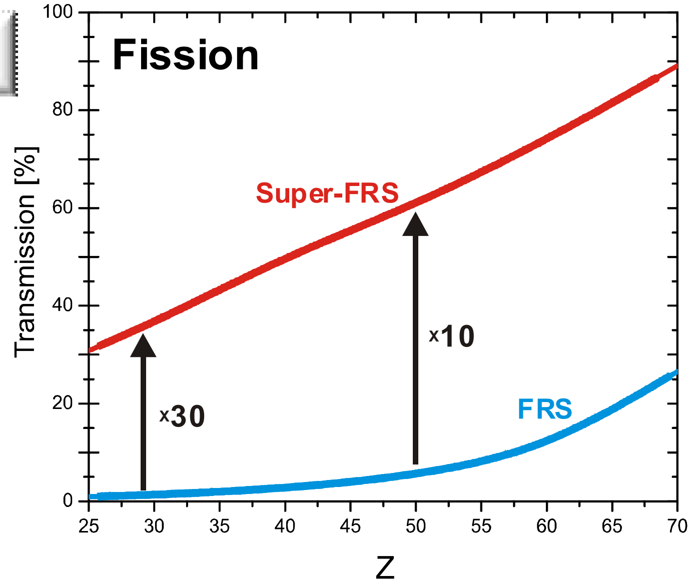
r-process:
- masses, half-lives
- b-delayed neutron emission
- (g,n), (n,g) rates
- shell structure

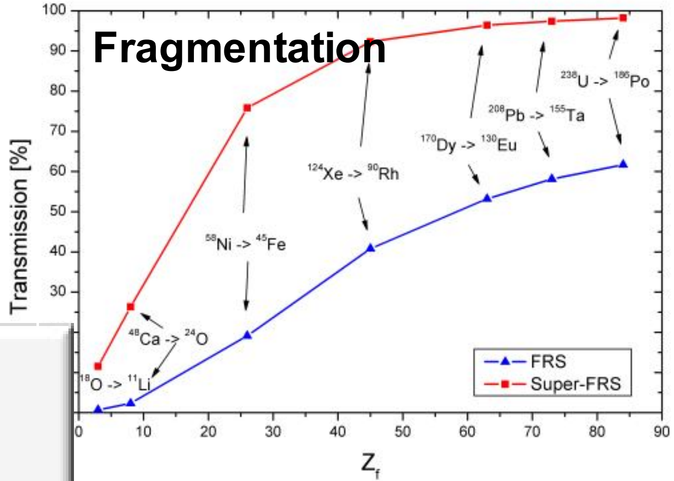
➔ Combine accurate **nuclear physics** with precision **astronomy** to <u>**constrain astrophysical scenarios**</u>

The Super-FRS

Central instrument for the NuSTAR program!!

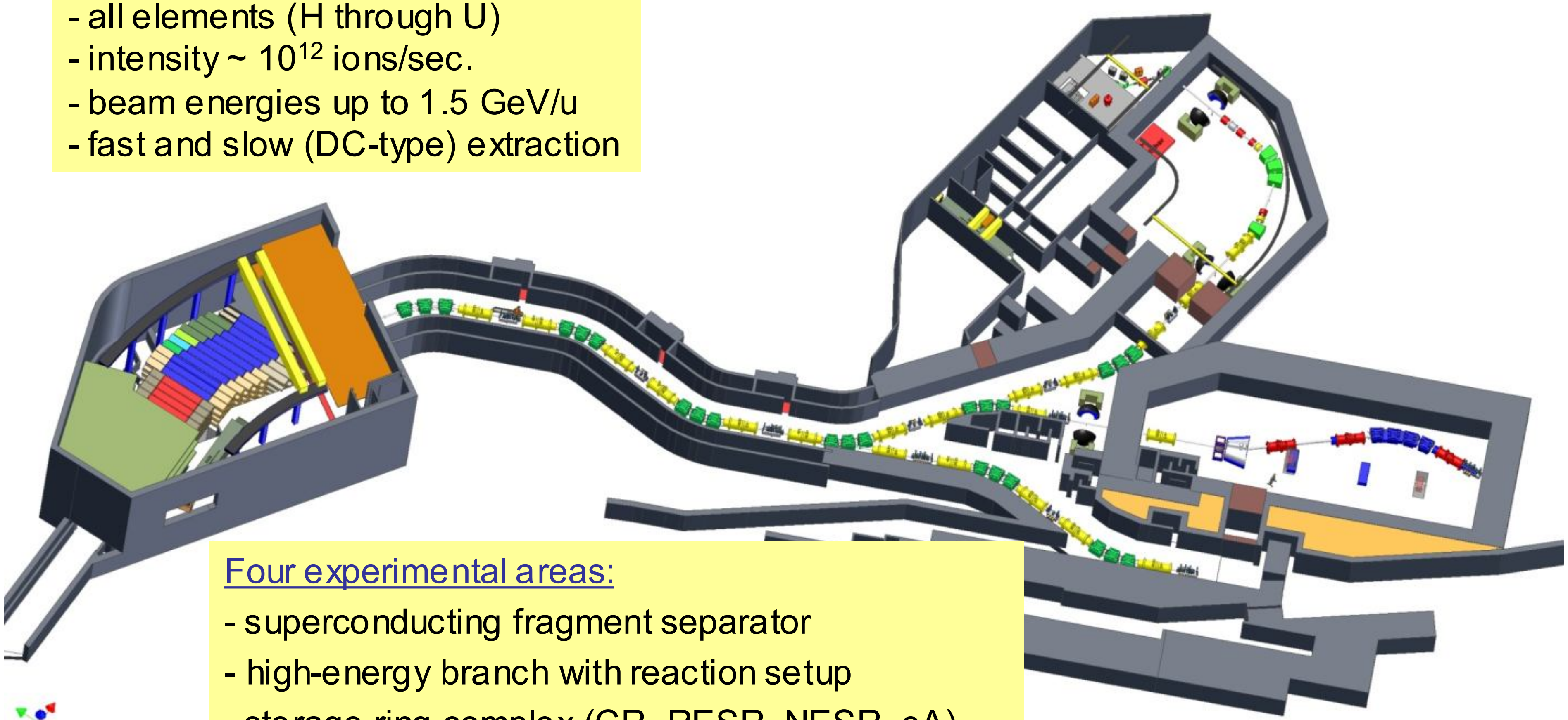






- High acceptance for projectile fragments and fission products
- Two-stage separation absolutely needed for clean beams
- **More than one order of magnitude transmission gain relative to FRS**

The NUSTAR experimental facilites at FAIR

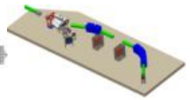
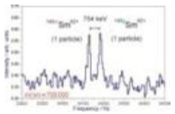


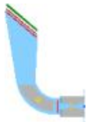
Important beam parameters:
- all elements (H through U)
- intensity ~ 10^{12} ions/sec.
- beam energies up to 1.5 GeV/u
- fast and slow (DC-type) extraction

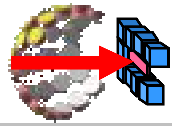
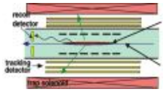
Four experimental areas:
- superconducting fragment separator
- high-energy branch with reaction setup
- storage-ring complex (CR, RESR, NESR, eA)
- low-energy branch with energy focusing and re-acceleration

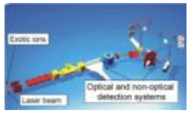
Complementarity of NUSTAR experiments

Super-FRS | R3B | ILIMA | EXL | ELISE | AIC | HISPEC/ DESPEC | exo+ pbar | MATS | LASPEC



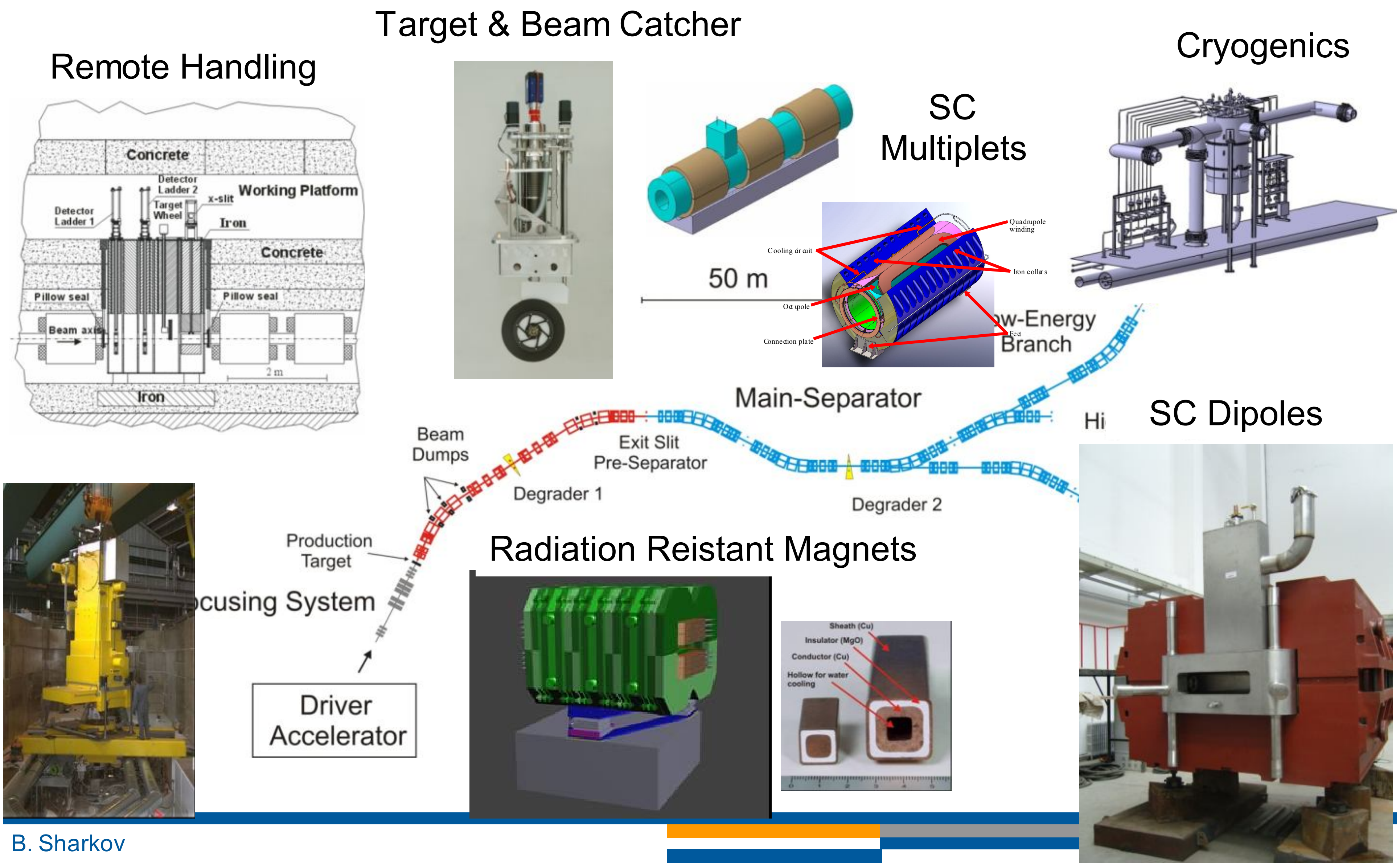


	Super-FRS	**R3B**	**ILIMA**	**EXL**	**ELISE**	**AIC**	**HISPEC DESPEC**	**exo+pbar**	**MATS**	**LASPEC**
Masses			bare ions, mapping study				Q-values, isomers		dressed ions, highest precision	
Half-lives	ps…ns-range		bare ions, s…h				dressed ions, µs…s			
Matter radii	interaction x-sect	matter radii		matter densitiy distributions		matter radii from absorption		nuclear periphery		
Charge radii					charge density distribution					mean square radii
Single-particle structure	high resolution, angular momentum	complete kinematics, neutron detection		low momentum transfers			high-resolution spectroscopy			

- Highest intensity and transmission
- "High" energy (unambigous identification)
- World-wide unique storage-ring complex
- Exotic nuclei **and** antiprotons
- Complementary instruments, cutting-edge technology

- New isotopes (r-nuclides)
- Neutron radioactivity, neutron dripline
- Modification of shell structure, new excitation modes
- Unexpected observations and phenomena

Technical Challenges: contributions by partner countries



panda The Collaboration

At present 410 physicists from 53 institutions in 16 countries

Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, IIT Chicago, Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow, TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, KTH Stockholm, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien

High precision beams of Antiprotons

..allow in collisions with protons and nuclei the formation of

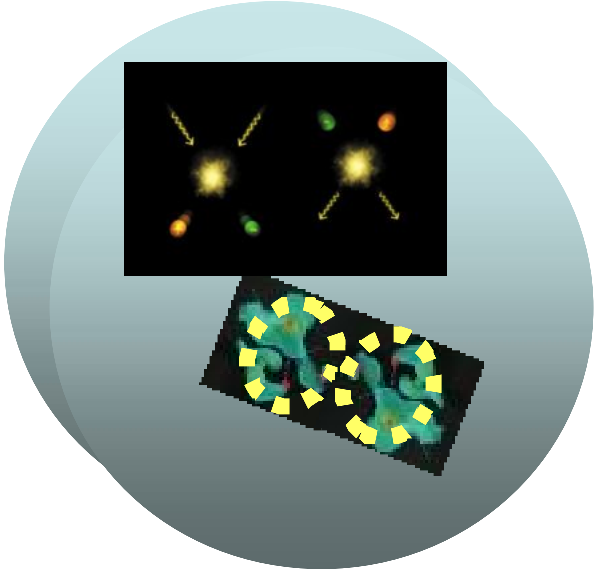
- pairs of sub-nuclear particles and their antiparticles
- high precision measurements of sub-nuclear masses and lifetimes

..allow at zero velocity the production of ***antihydrogen atoms and molecules***, the antimatter of hydrogen, and studies of, e.g.,

- gravity acting on ***antimatter***
- validity of our physics laws for ***antimatter***

Þ ***At FAIR: 100 times more abundant than at CERN***

Structure and fundamental properties of anti-matter

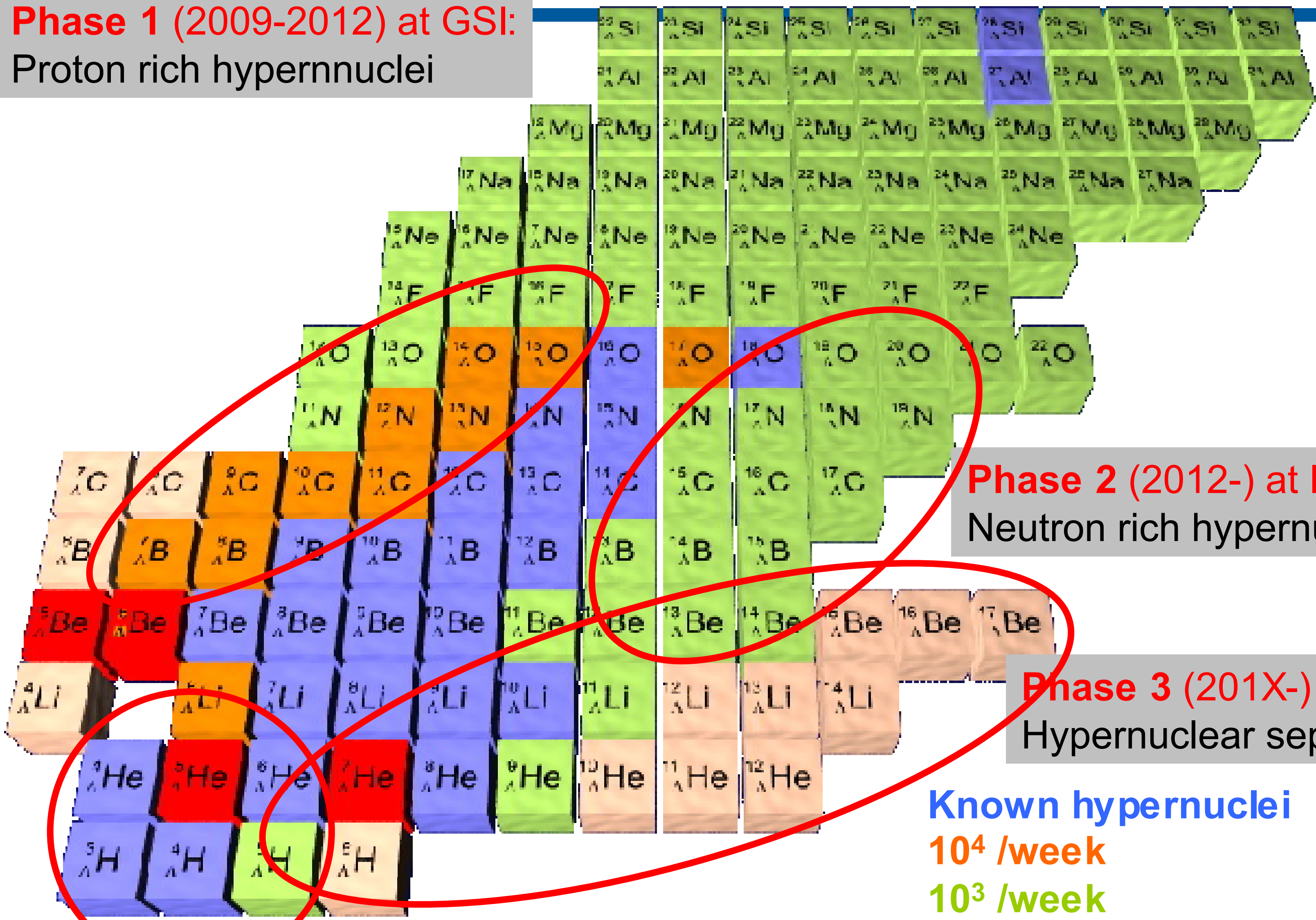


Scientific program (Highlights)

- Charmonium (ccbar)/open charm (c+other non c-quark) spectroscopy
- Non-pertubative QCD dynamics
- Nucleon Structure via electro-magnetic processes

Hypernuclear landscape with HypHI

Phase 1 (2009-2012) at GSI:
Proton rich hypernnuclei



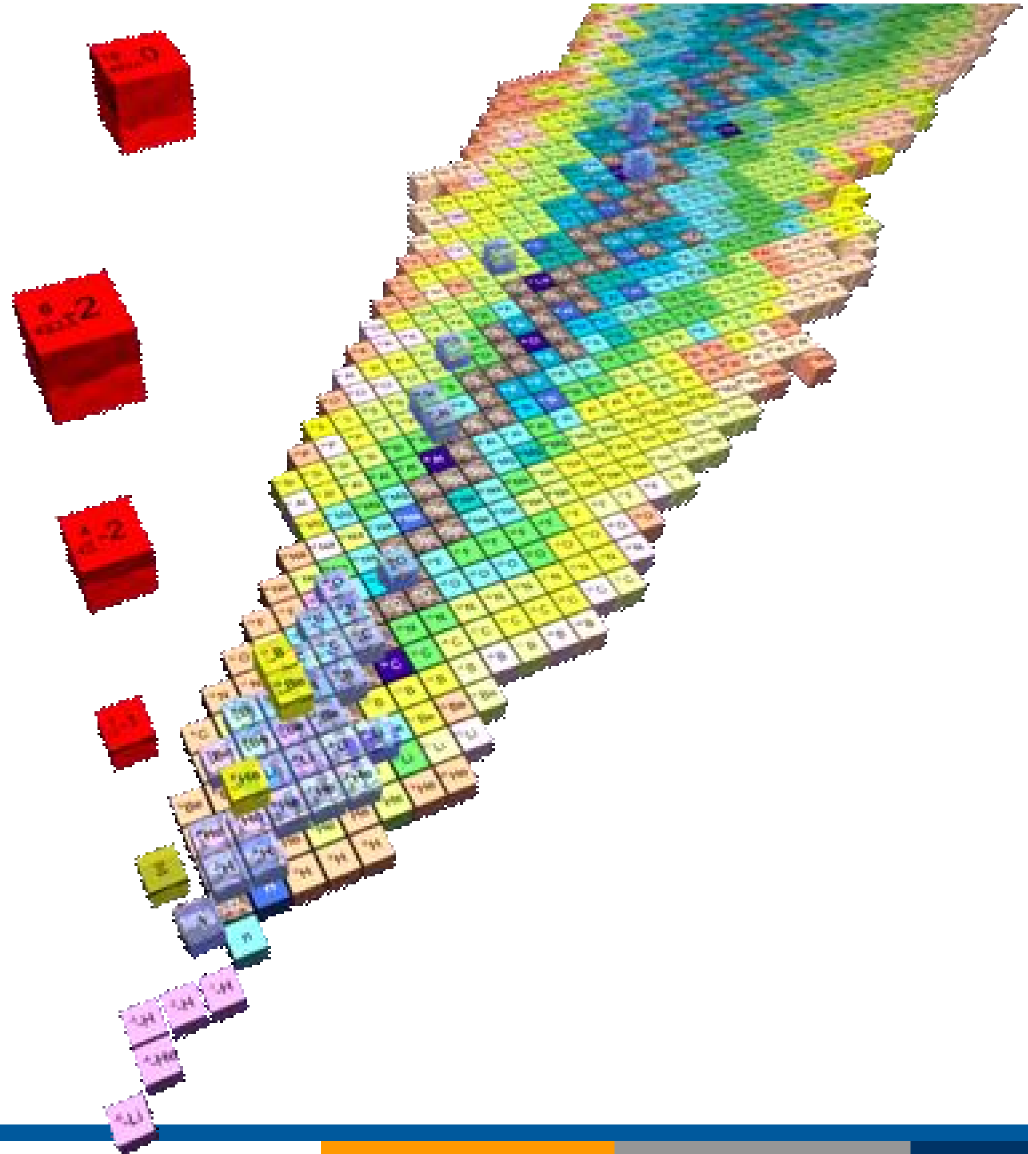
Phase 2 (2012-) at R3B/FAIR:
Neutron rich hypernuclei

Phase 3 (201X-) at FAIR:
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

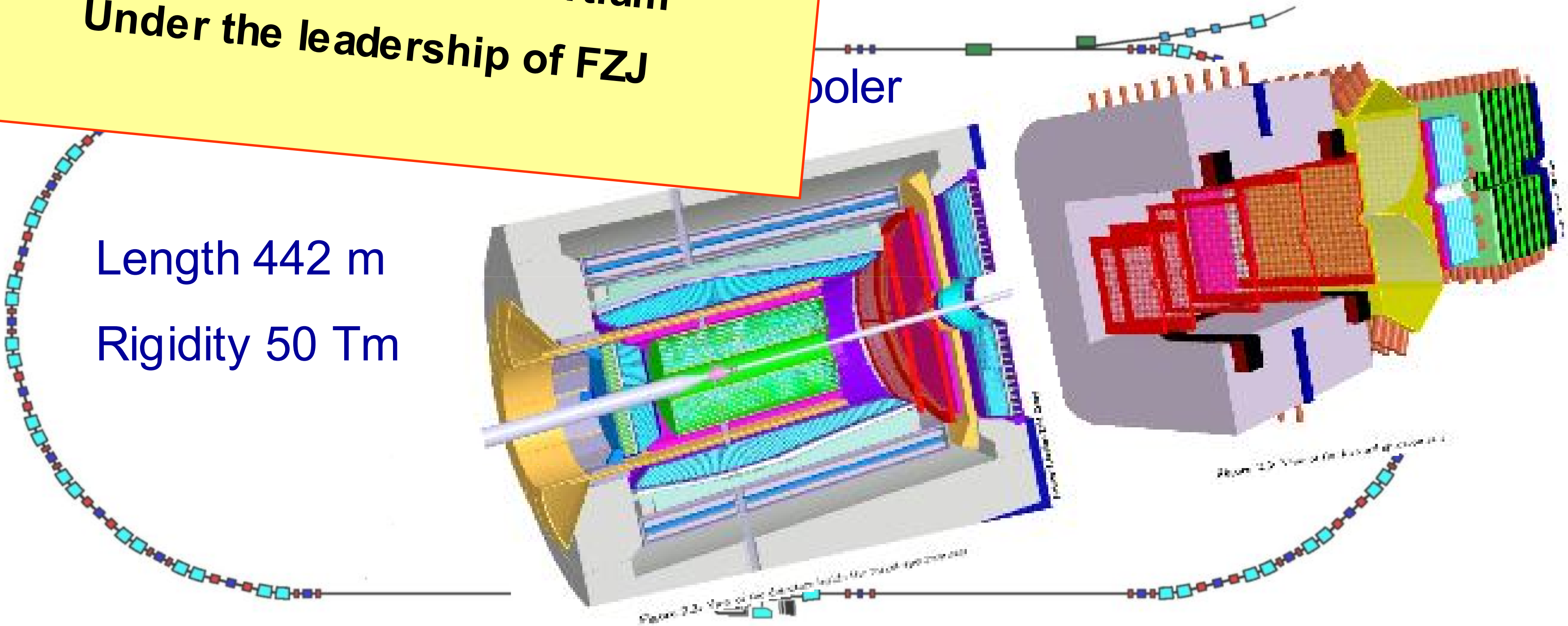
Phase 0 (2009) at GSI:
Light hypernuclei

Exploring strange dimensions for the nuclear chart: Hyperon Clusters



HESR and PANDA

Working on planning and design of HESR performed by the consortium Under the leadership of FZJ



4π detector **PANDA Detector**

The CBM Collaboration: 55 institutions, 450 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Norway:
Univ. Bergen

India:
Aligarh Muslim Univ.
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Germany:
Univ. Heidelberg, P.I.
Univ. Heidelberg, KIP
Univ. Heidelberg, ZITI
Univ. Frankfurt IKF
Univ. Frankfurt, FIAS
Univ. Münster
FZ Dresden
GSI Darmstadt
Univ. Wuppertal

Poland:
Jag. Univ. Krakow
Warsaw Univ.
Silesia Univ. Katowice
AGH Krakow

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest
Univ. Bucharest

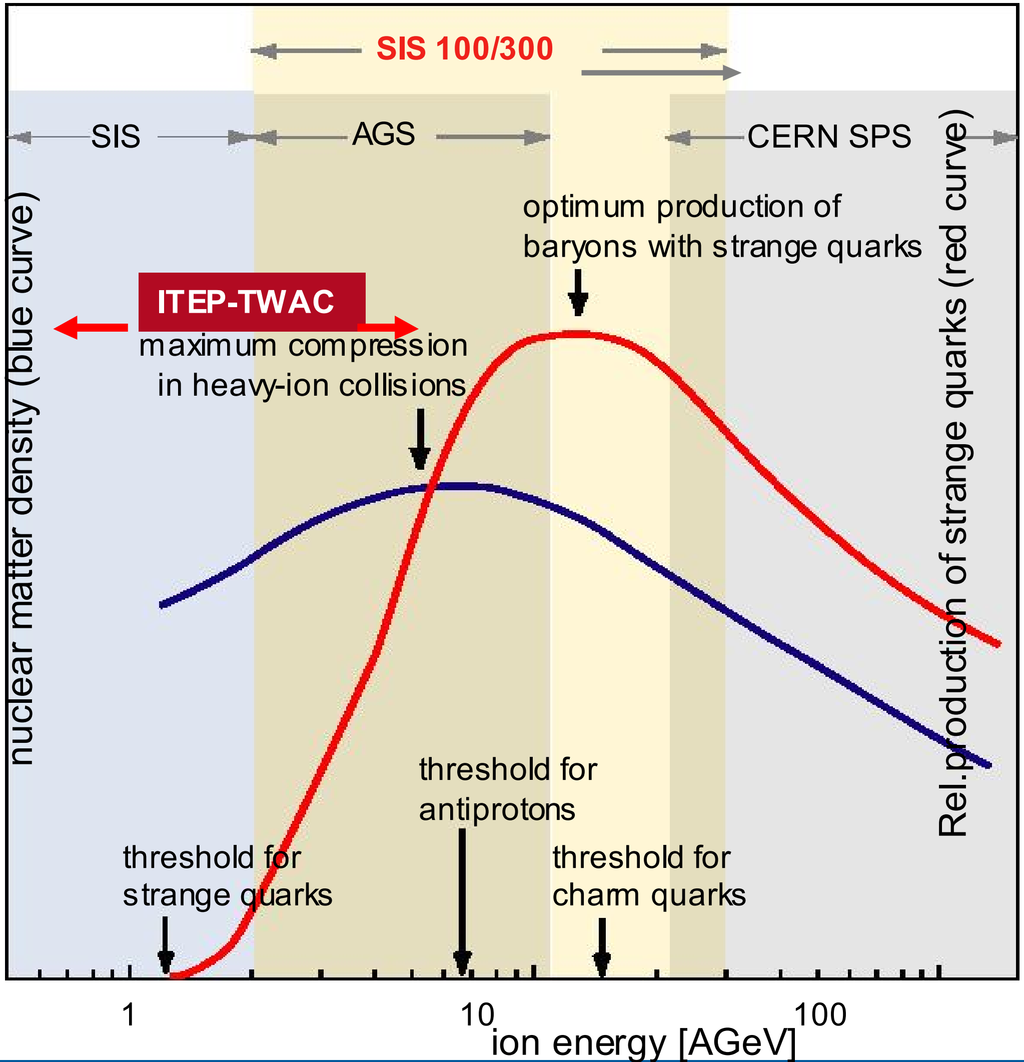
Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

Relativistic Nuclear Physics

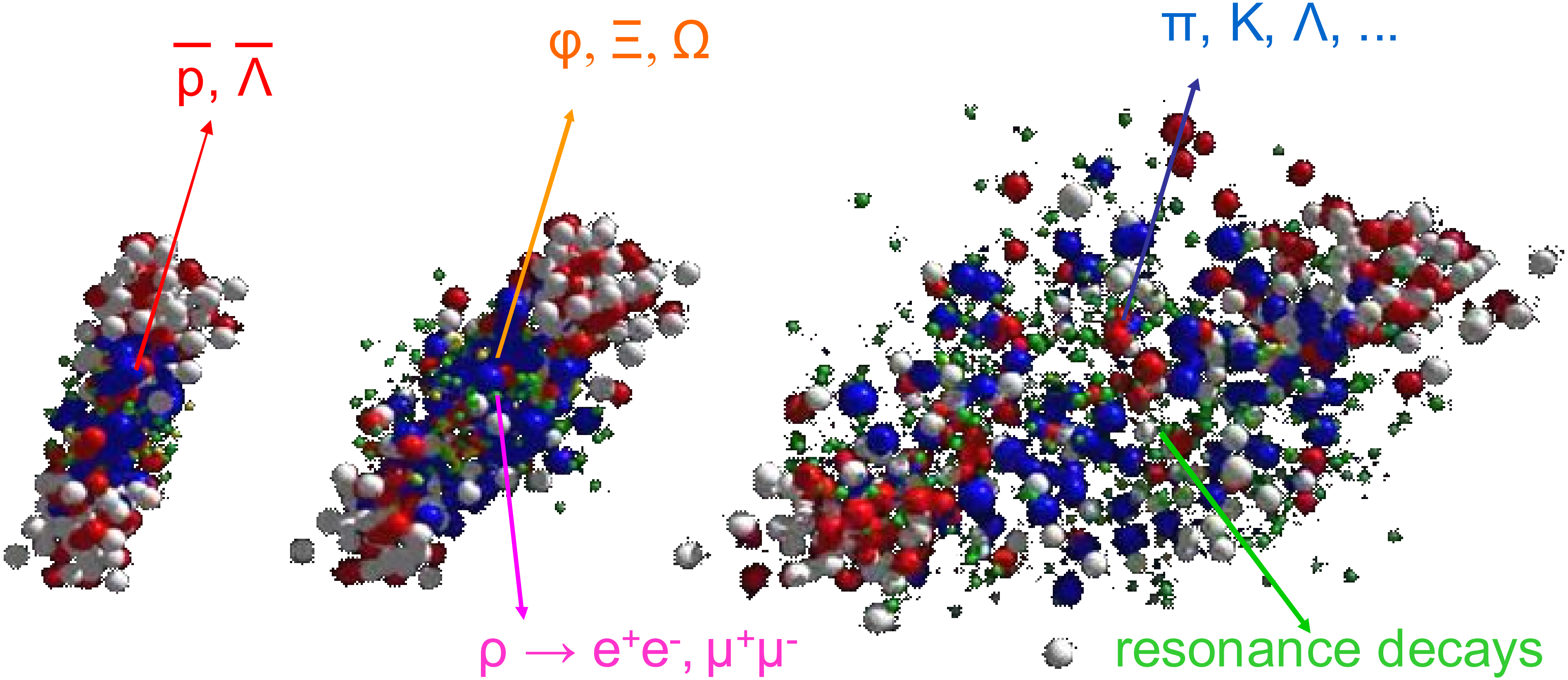
Studies of hadronic matter at high densities

Motivation for NN collisions at 2-40 AGeV



The evolution of the fireball

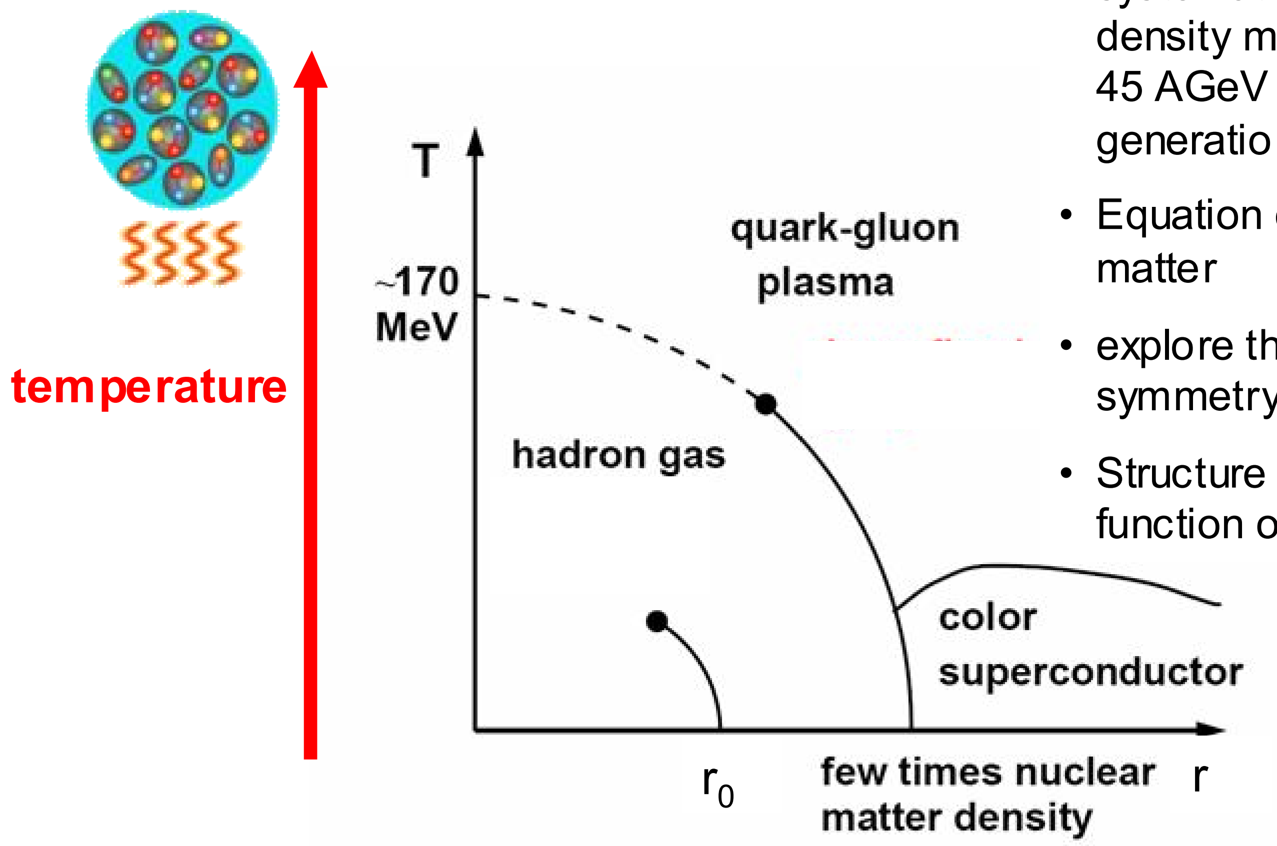
Au+Au collision at 10.7 A GeV from UrQMD



... using multistrange particles: equation of state at high baryon densities

Phasediagram of strongly interacting matter

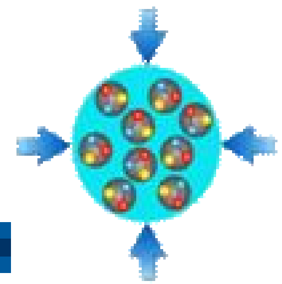
Fundamental questions of QCD



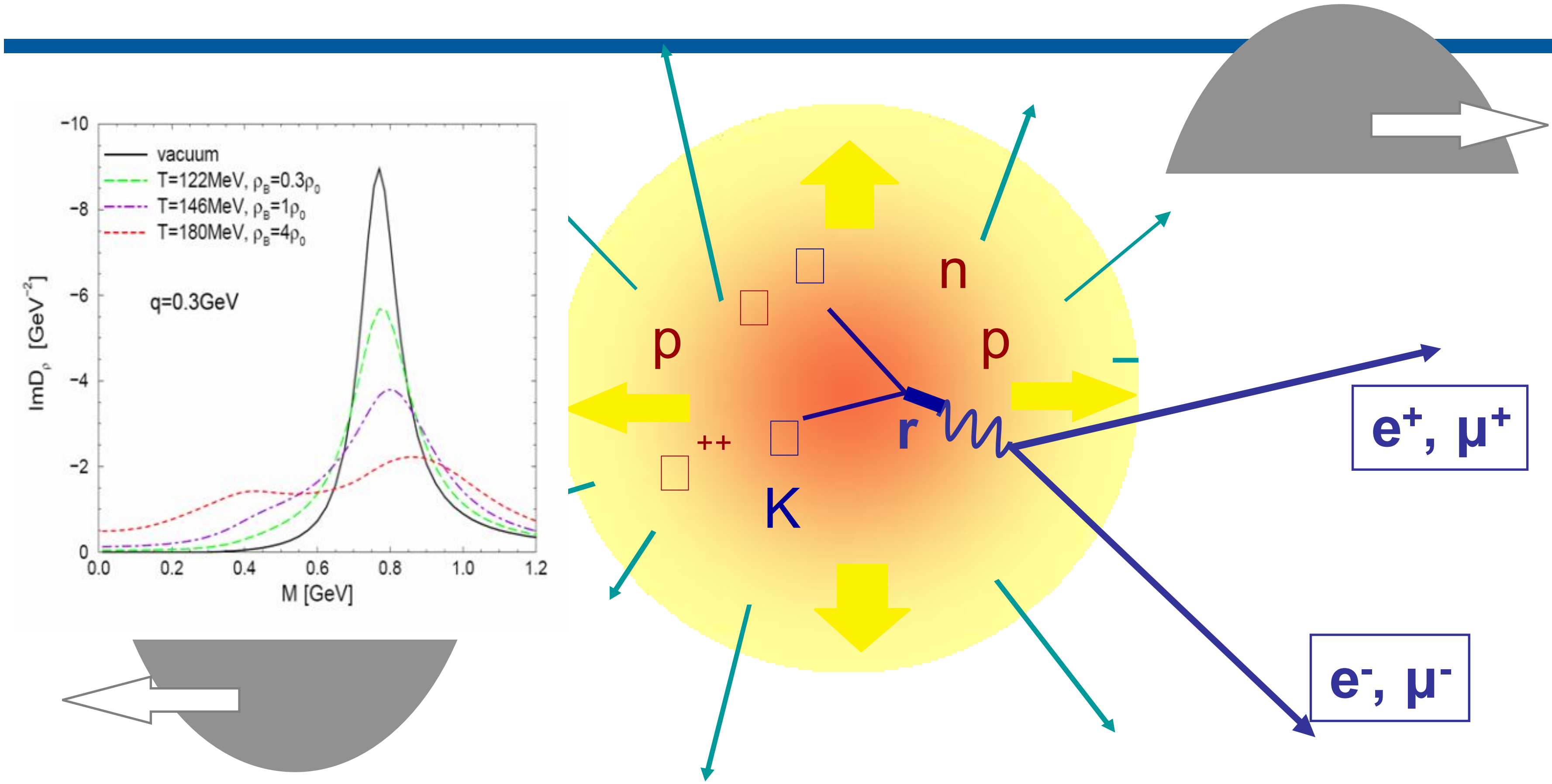
CBM and HADES at SIS 100 and SIS 300

- systematic exploration of high baryon density matter in A+A collisions from 2 – 45 AGeV beam energy with 2nd generation experiments
- Equation of state of strongly interacting matter
- explore the QCD phase diagram, chiral symmetry restauration
- Structure of strongly interacting matter as function of T and r_B?

address with heavy-ion collisions **pressure**



Looking into the fireball ...



… using penetrating probes: short-lived vector mesons decaying into electron-positron pairs

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

Plasma Physics

- Interior of massive planets like Jupiter

  ..do we understand the interior of planets?

- Warm and dense plasmas

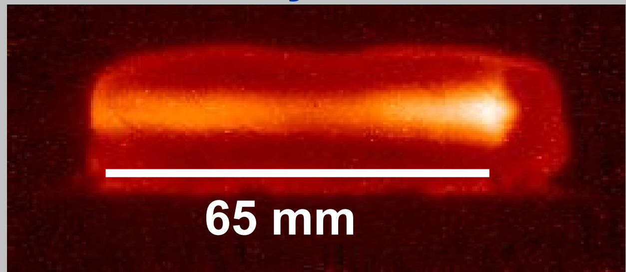
  ...Equation of State, transport properties, etc.,

- Energy production through Inertial Confinement Fusion:

  ..do we understand the basic physics problems?

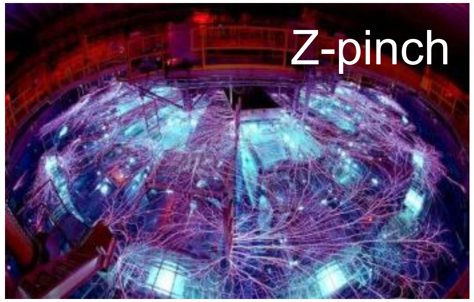
The uniqueness of heavy ion beams compared to other techniques (Laser, Z-pinch)

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



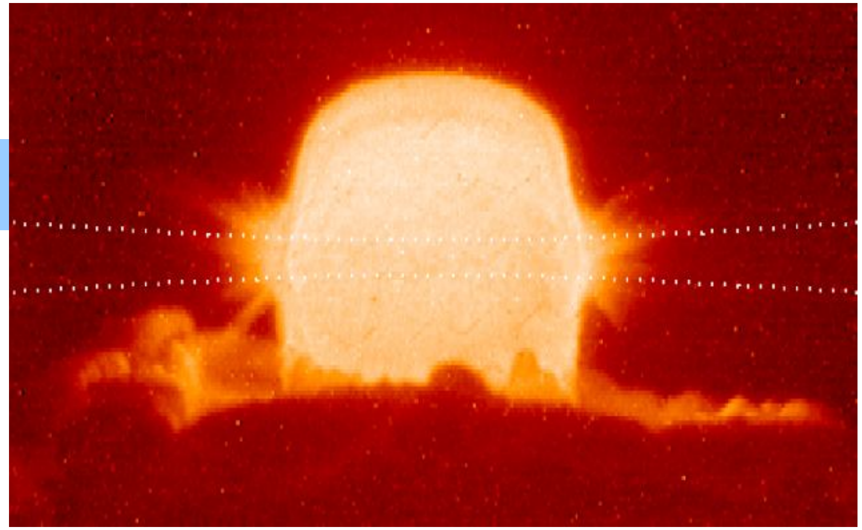
Already within module 1: Compared to GSI, FAIR will provide an ***intensity and energy density increase by a factor of 100.***

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

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

$$E_s = (1.6 \cdot 10^{-19}) \cdot \frac{dE/\rho dx}{\pi \cdot r^2} \cdot N \left[J/g\right]$$

$$dE/dx \sim -\rho \frac{Z_{эф}^2}{E_i} \ln \Lambda$$



Intense Heavy Ion Beams

large volume of sample (N mm3)
fairly uniform physical conditions
high entropy @ high densities
extended life time

<u>HI : high entropy states of matter - without shocks !</u>

Intense particle beams are a novel, very efficient tool to study HEDP and WDM:

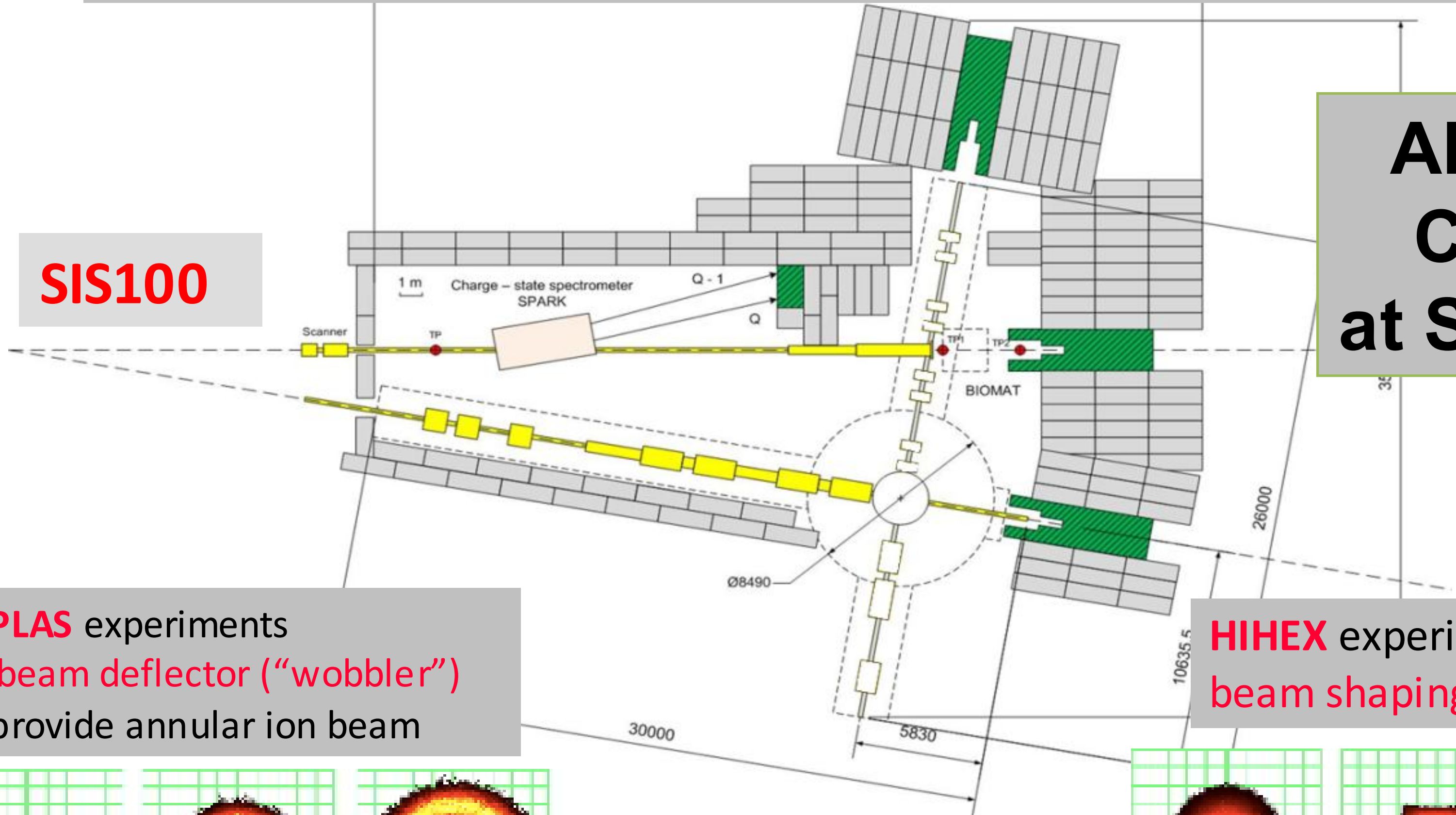
[N.A. Tahir et al. PRE 60 *(1999) 4715;*
PRE 61 *(2000) 1975; PRE* 62 *(2000) 1224; PRE* 63 *(2001) 016402;*
PRE 63 *(2001) 036407; PRB* 67 *(2003) 184101].*

Main Advantages of Ion Beams are:

- High repetition rate, high coupling efficiency
- Large sample size [mm^3 cm^3]
- Fairly uniform physical conditions (no sharp gradients)
- Precise knowledge of energy deposition in the sample
- Long life times
- Any target material can be used
- Unrivaled flexibility (Generate HED matter by isochoric heating as well as by shock compression)

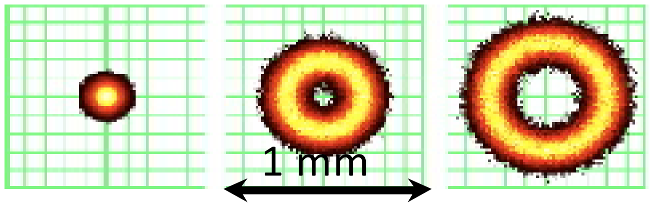
Plasma Physics beam line at SIS100

SIS-100: One beam line with replaceable elements:

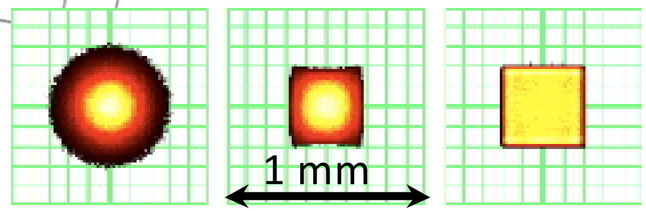


LAPLAS experiments
RF beam deflector ("wobbler")
to provide annular ion beam

HIHEX experiments
beam shaping system



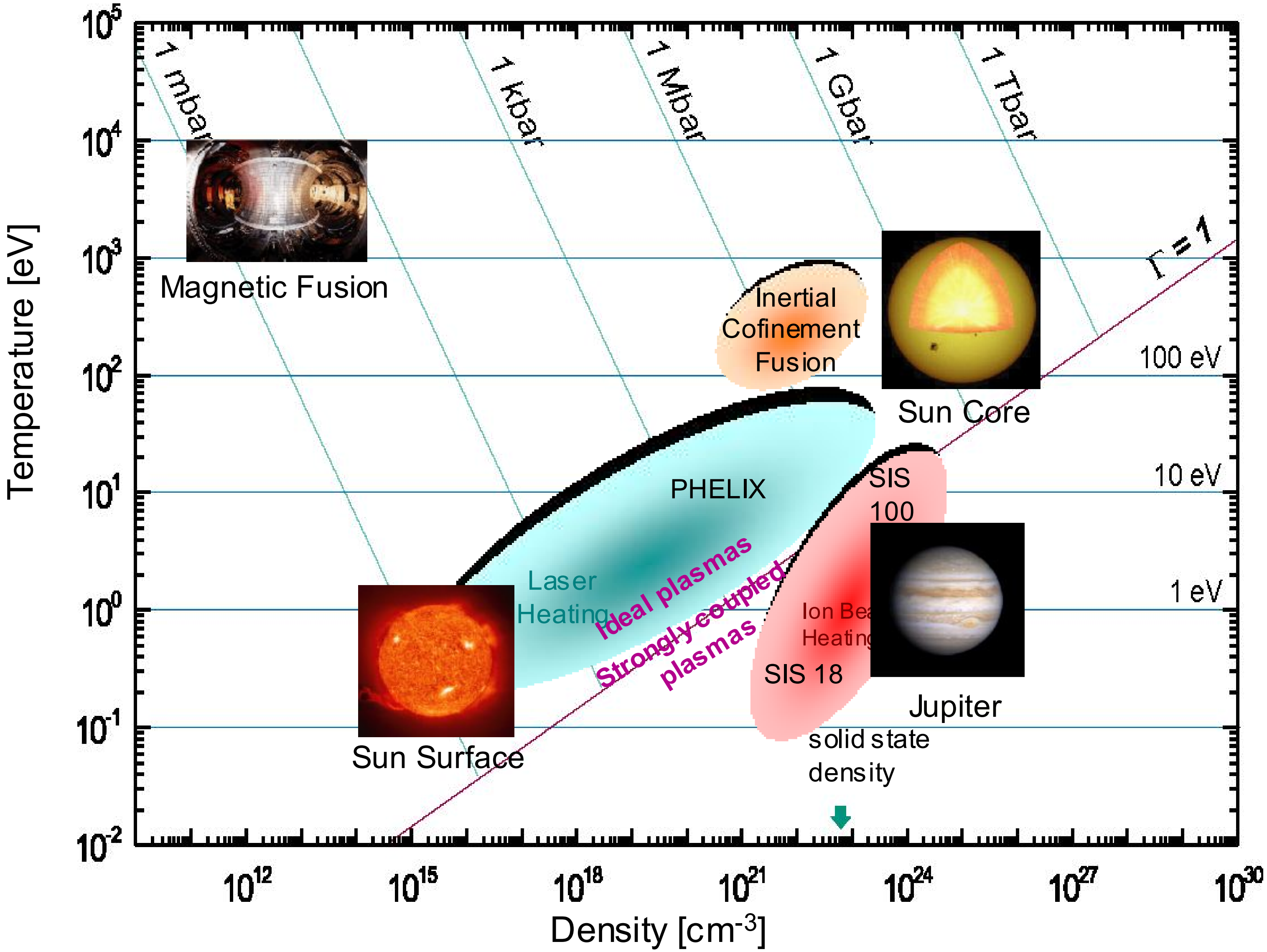
Transverse distributions of beam intensity at focal plane for LAPLAS



Transverse distributions of beam intensity at focal plane for HIHEX

Plasma Physics with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures



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	10-20 eV	

only available at FAIR

Plasma Physics

- Interior of massive planets like Jupiter

  ..do we understand the interior of planets?

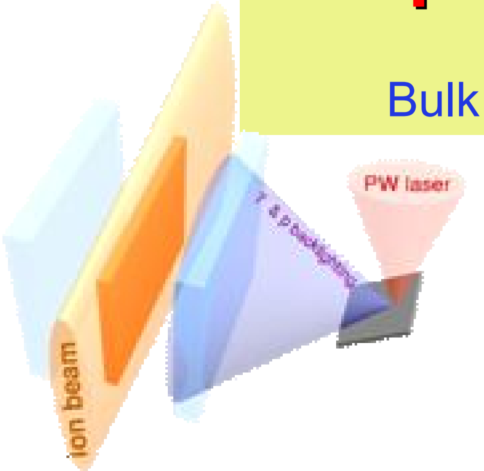
- Warm and dense plasmas

  ...Equation of State, transport properties, etc.,

- Energy production through Inertial Confinement Fusion:

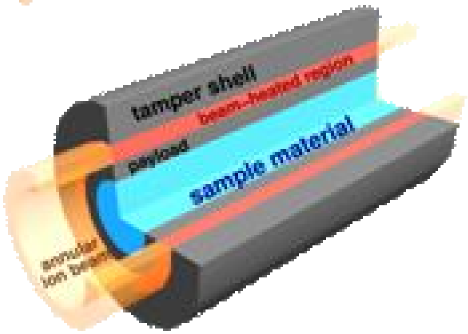
  ..do we understand the basic physics problems?

Proposed experiments on Plasma Physics
with highly Bunched Beams
Bulk matter at very high pressures, densities, and temperatures



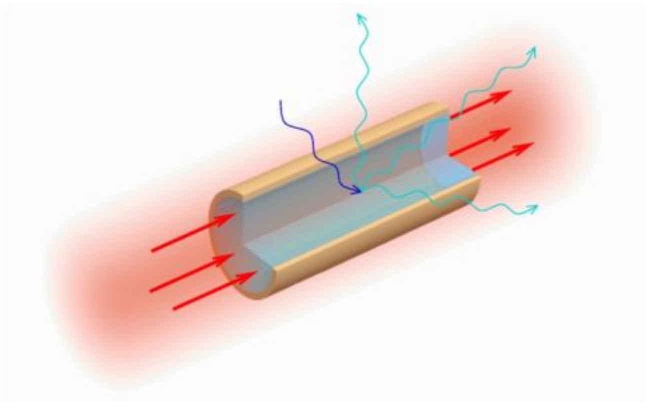
HIHEX: Heavy Ion Heating and Expansion

(HEDgeHOB)



LAPLAS: Laboratory Planetary Sciences

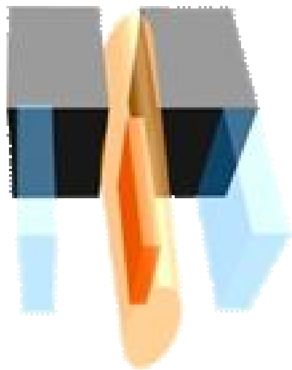
(HEDgeHOB)



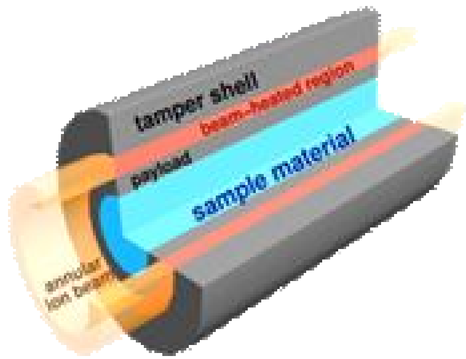
WDM: Warm Dense Matter

High Energy Density experiments of HEDgeHOB collaboration

HIHEX	**LAPLAS**
Heavy Ion Heating and Expansion	*Laboratory Planetary Sciences*



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



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

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

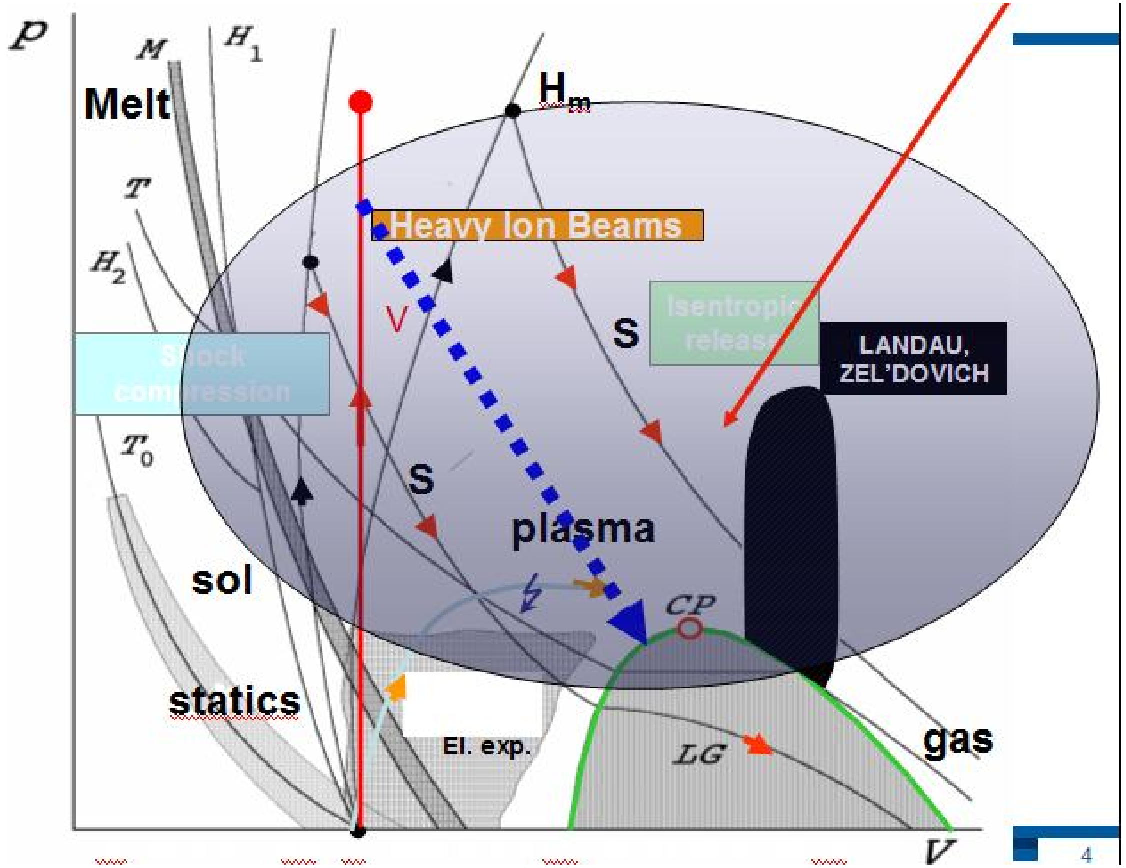
Mbar pressures @ moderate temperatures:
high-density HED states, e.g. hydrogen metallization problem, interior of Jupiter and Saturn

Fundamental properties of matter under extreme conditions

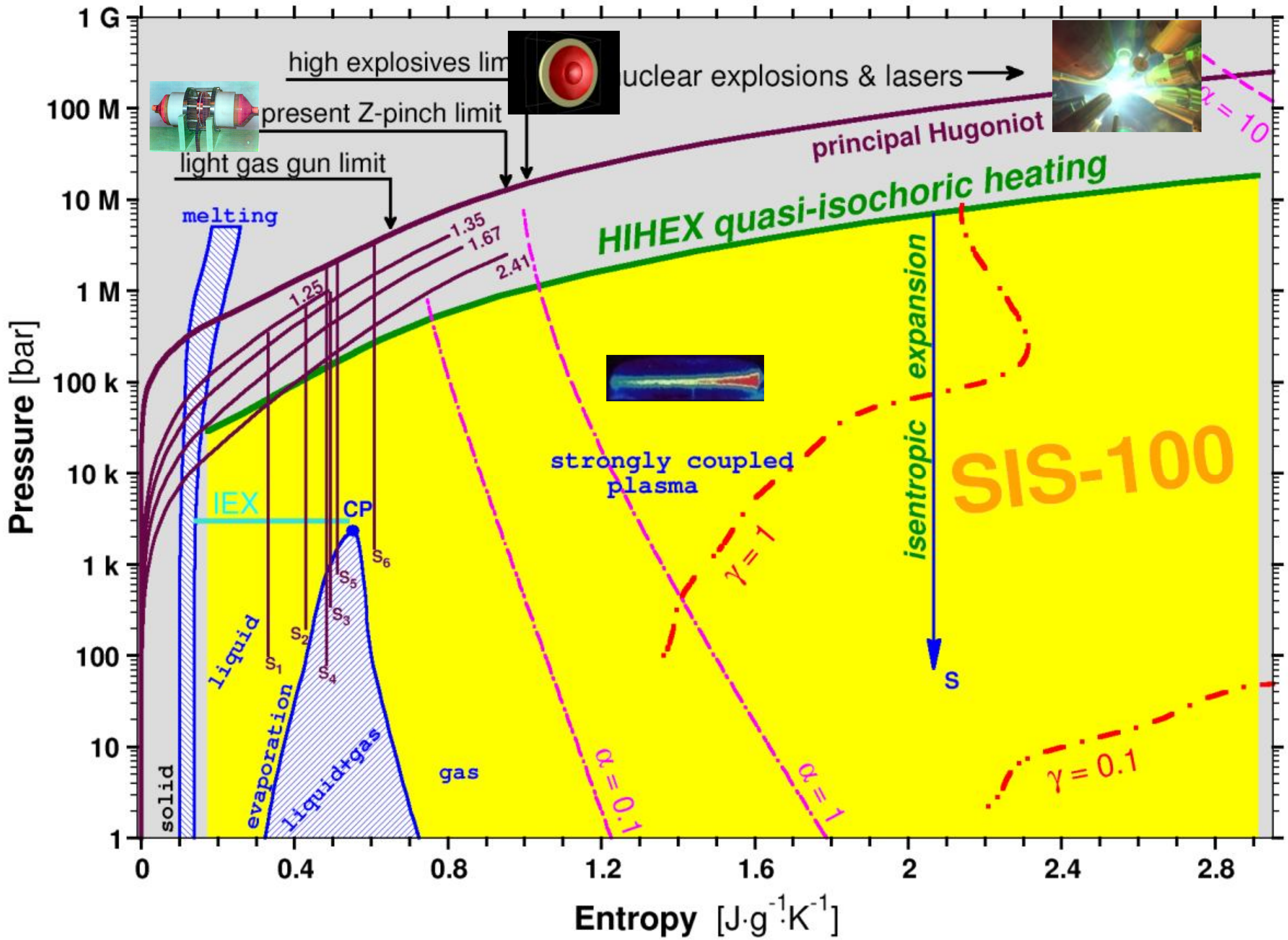
Intense heavy ion beams at FAIR provide unique capabilities for generation and study HED states in matter

- 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



"Terra Incognita" regions of the phase diagram accessible in **HEDgeHOB** experiments at FAIR



D.H.H. Hoffmann, V.E. Fortov et al. Phys. Plasmas 9 (2002) 3651.

Critical Parameters of Some Metals

I.V. Lomonosov and V.E. Fortov

	T_c (K)	P_c(kbar)	r_c(g/cm^3)
Aluminum	6390	4.45	0.86
Copper	7800	9.00	2.28
Gold	8500	6.14	6.10
Lead	5500	2.30	3.10
Niobium	19200	11.1	1.70
Tantalum	14550	7.95	3.85
Tungsten	13500	3.10	2.17
Beryllium	8600	2.00	0.40

ISOCHORIC HEATING TECHNIQUE

1. HIHEX [Heavy Ion Heating and Expansion]

.

This technique involves isochoric and uniform heating of matter by an intense ion beam and the heated material is allowed to expand isentropically.

Expanded Hot Liquid

Two Phase Liquid-Gas Region

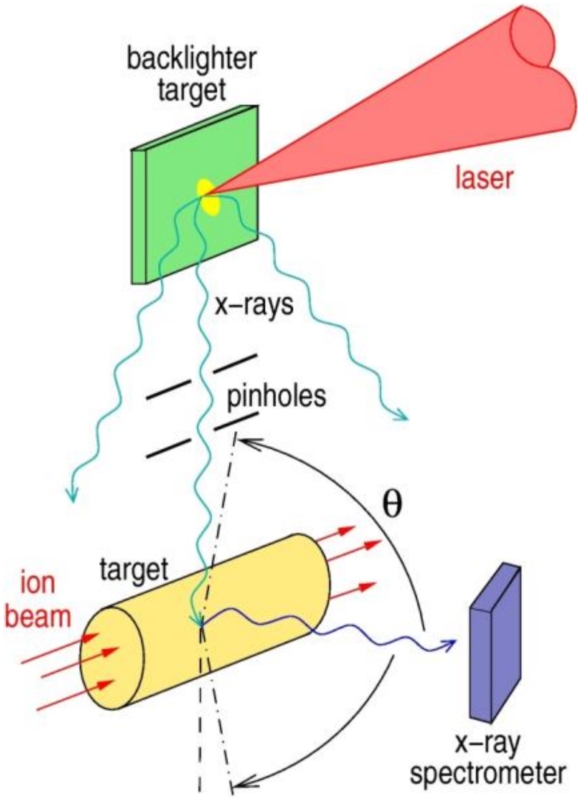
Critical Parameters

Strongly Coupled Plasma

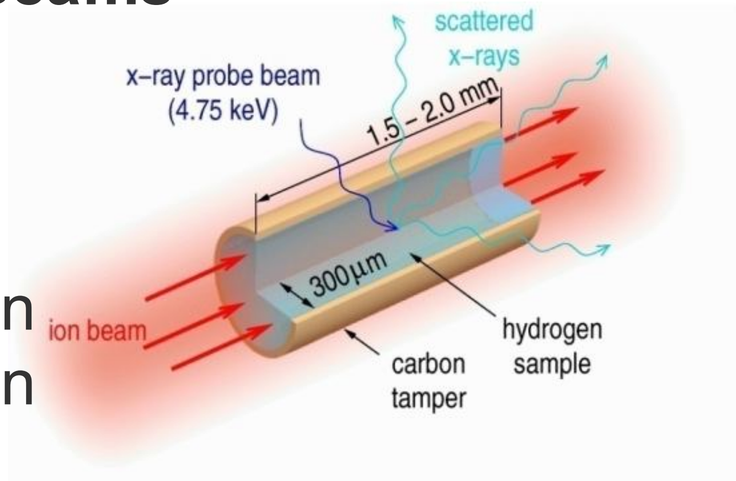
N.A. Tahir et al., Phys. Rev. Lett. 95 (2005) 035001

WDM collaboration – Atomic physics in dense environments

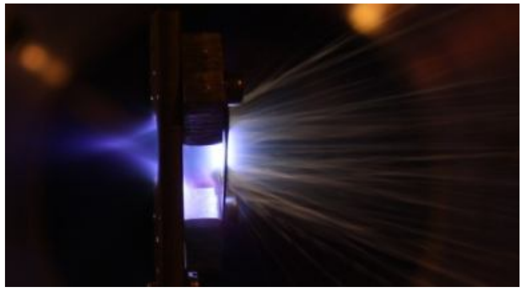
WDM produced by Intense Heavy Ion Beams and probed by Intense Laser Beams



Unique combination of intense heavy ion beam driven experiments
+
Laser driven diagnostics

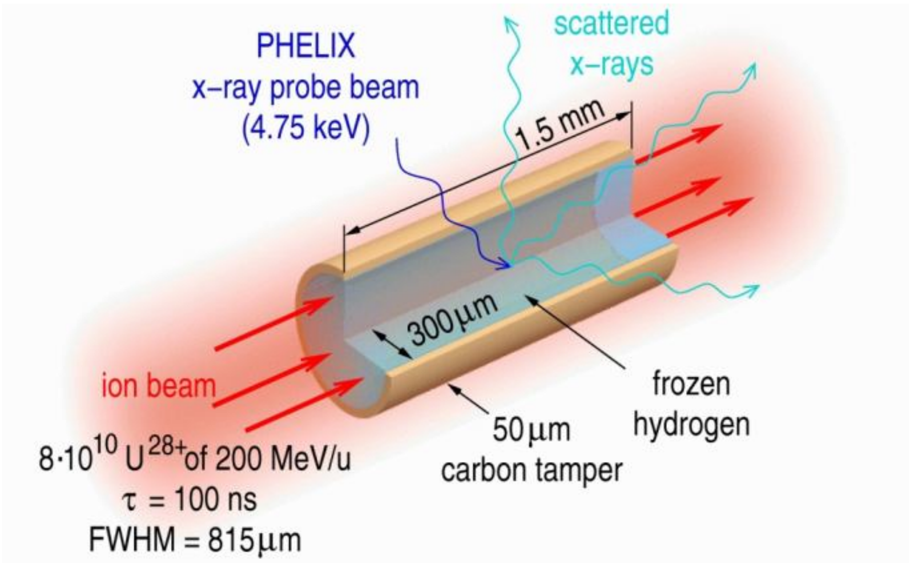


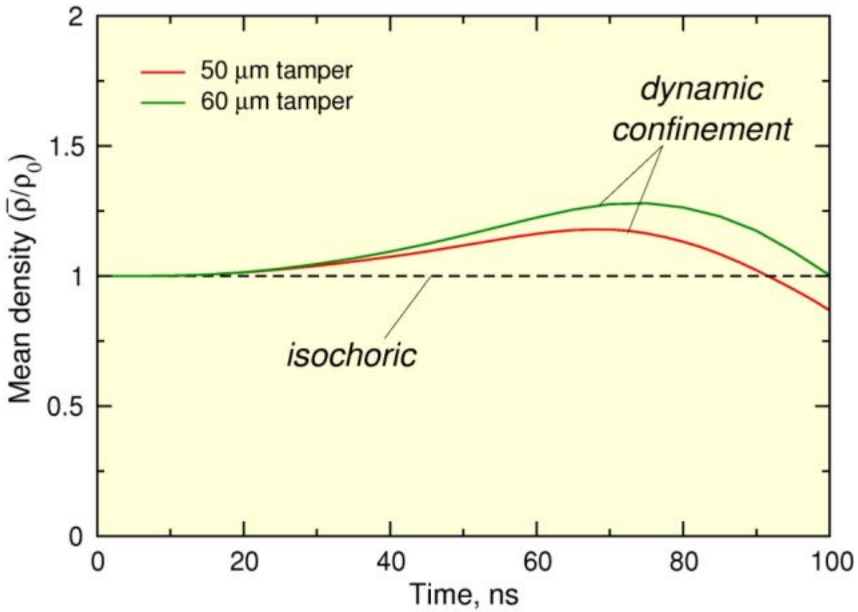
High Power Laser PHELIX



Dynamic confinement of targets heated quasi-isochorically with heavy ion beams

A. Kozyreva[1], M. Basko[2], F. Rosmej[3], T. Schlegel[1],
A. Tauschwitz[3] and D.H.H. Hoffmann[1,3]





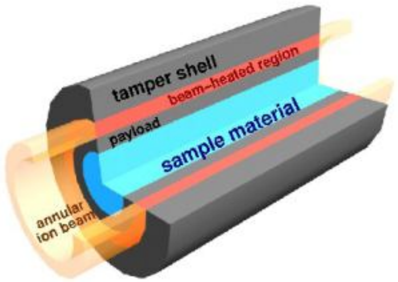
Target: Solid (cryogenic) hydrogen
For isochoric heating in at ε = 130 kJ/g → T = 0.64 eV (Warm Dense Matter regime)

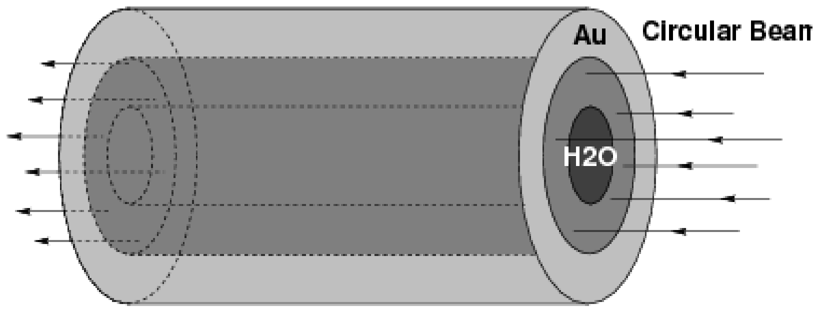
2. LAPLAS [LAboratory PLAnetary Sciences]

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

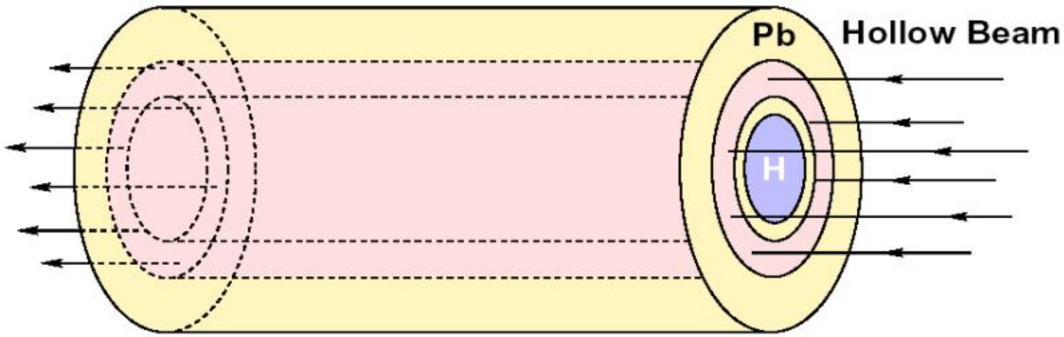
Shock reverberates between the cylinder axis and the hydrogen-outer shell interface.

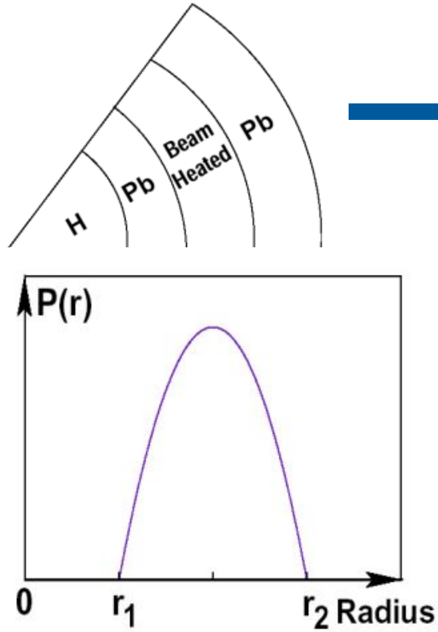
Very high densities, high pressure, higher temperature

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

□ = 1.2 g/cc, P = 11 Mbar, T = 5 ev

Low entropy compression





Target Parameters

$r_d = 0.4$ mm

$r_1 = 0.6$ mm

$r_2 = 2.1$ mm

$r_0 = 3.5$ mm

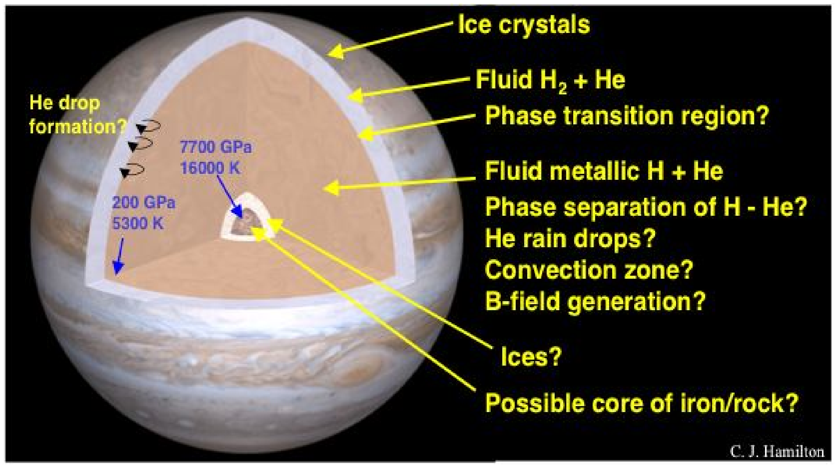
Beam Parameters

2.7 GeV/u Uranium

$N = 0.2 - 1.5 \times 10^{12}$

$\tau = 20$ ns

$E_b = 21 - 155$ kJ



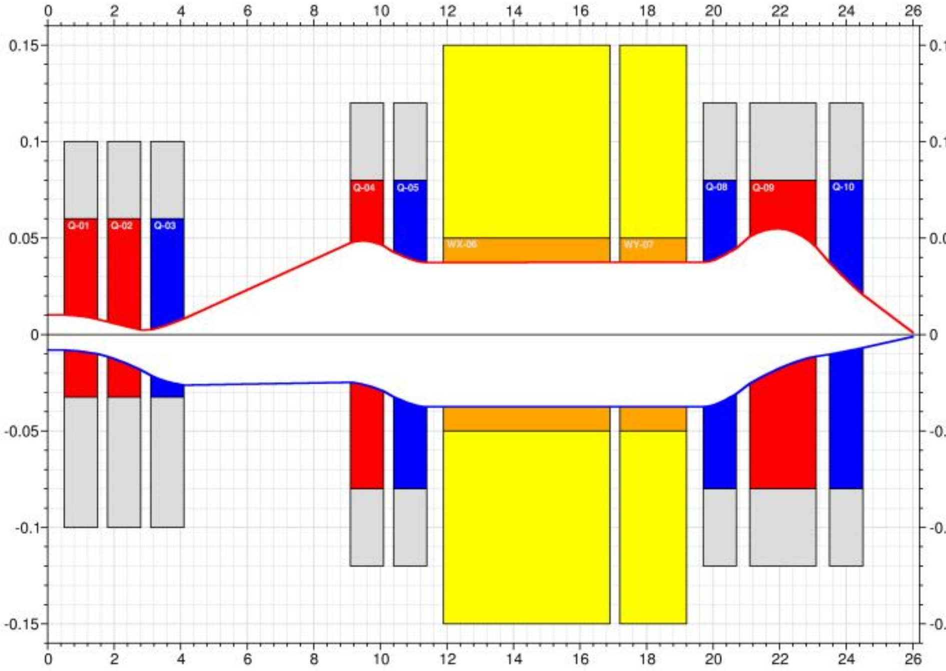
$\rho = 1 - 2$ g/cm^3

$P = 2 - 10$ Mbar

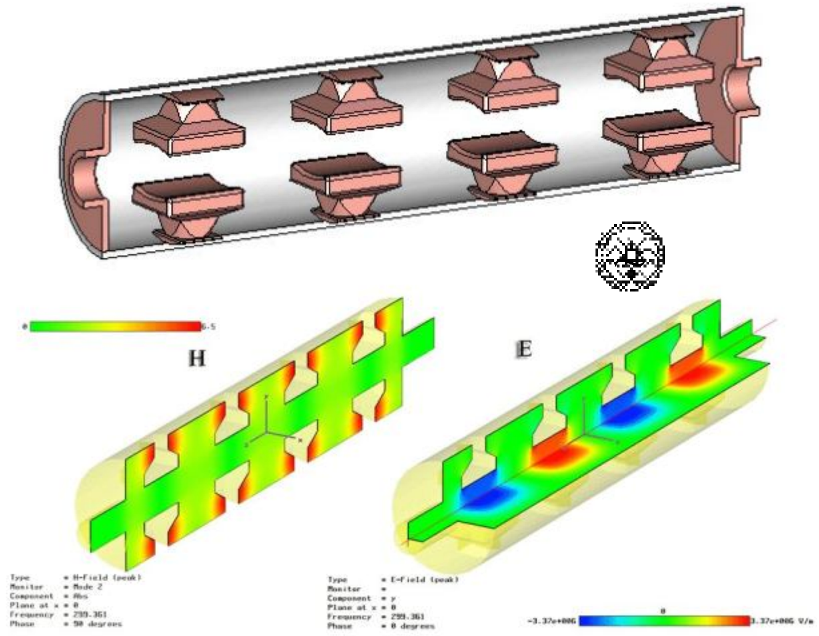
$T = 0.2 - 0.6$ eV

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

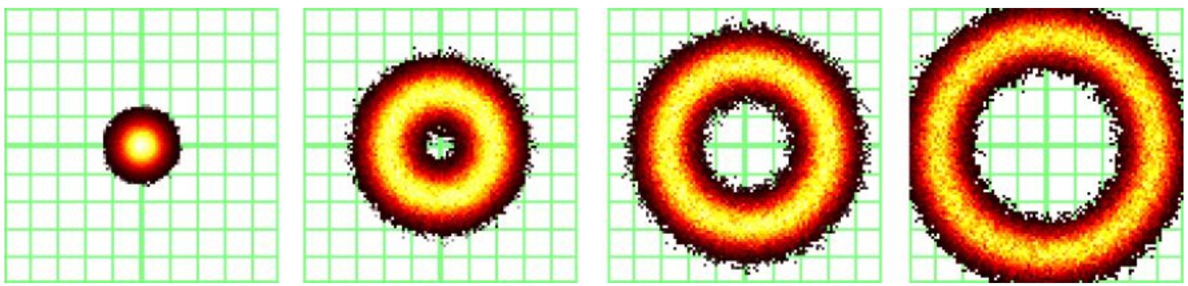
Layout of the **LAPLAS** beam line



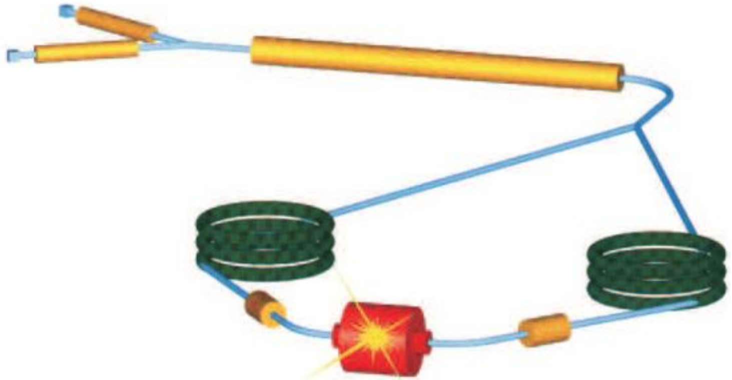
Design of rf beam deflector (wobbler)



Transverse beam intensity distribution in the focal spot



Basic motivations for HI IFE



- Intrinsic efficiency $\eta G > 10$.
- High repetition rate ~1 - 10 Hz
- Reliability / durability to last billions of shots
- Final focusing magnets tolerant to neutrons and target debris
- Compatibility of beams to propagate through the poor vacuum of fusion chamber
- Effective beam-target coupling
- Mature driver technology

A.W.Mashke 1979

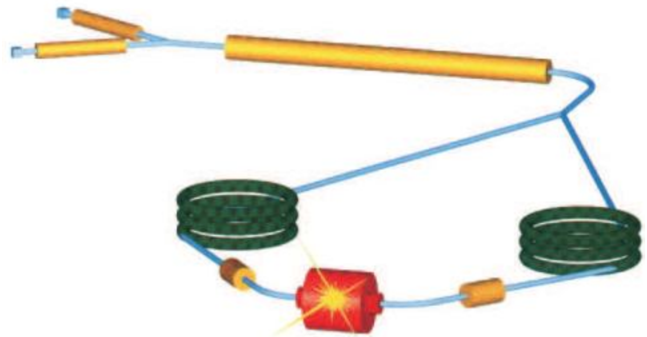
Consideration of HIFE leads to special driver - and - target combinations

Drivers
determined by target requirements

Targets
tailored specifically for accelerators

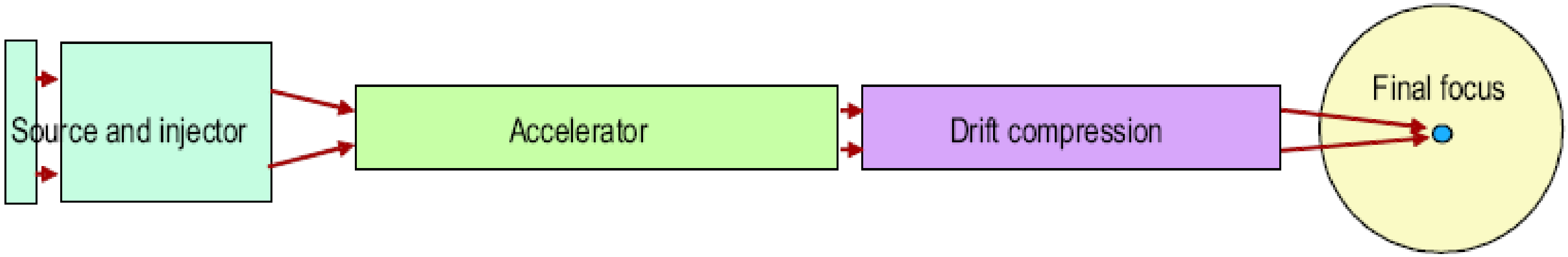
Challenging aspect : short pulse length < 10ns – i.e. 10E4 compression
small focal spot ~ 1-2 mm
@ large distance ~ 5 m

Two complimentary accelerator scenarios as potential IFE drivers :



1. **The RF linac & storage ring approach**
   – *HIBALL, HIBALL-II (R.Bock 1984, GSI Darmstadt)*
   - *ITEP-Moscow (Koshkarev, V.Imshennik, P.Zenkevich -1987)*

2. **The induction linear accelerator concept** – *US (LBNL, LLNL, Princeton)*

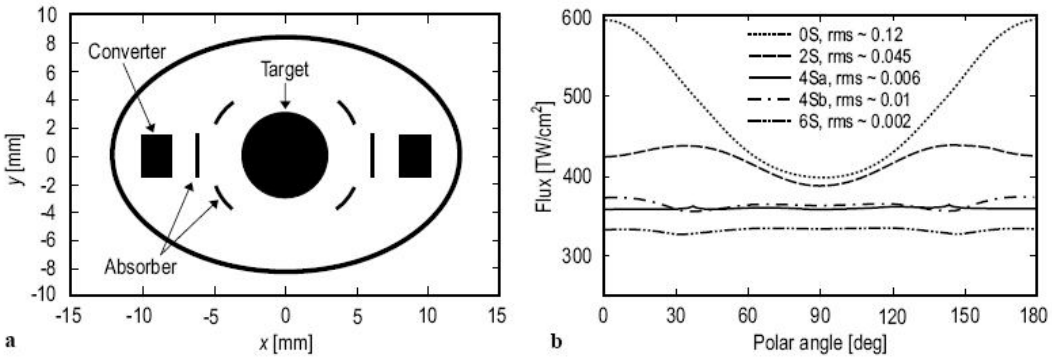


Heavy ion targets with hydrodynamic ignition

Indirect drive option is considered to be feasible for heavy ion targets in the hydrodynamic ignition mode.

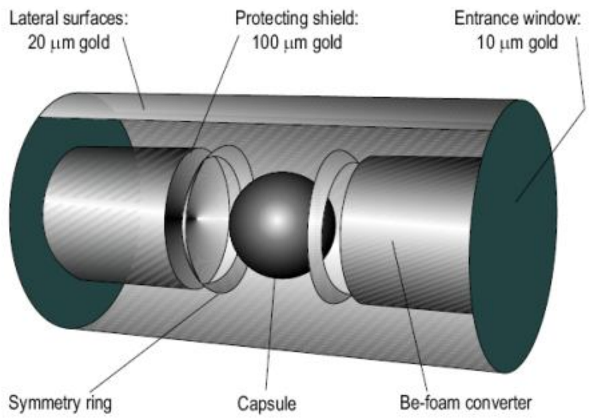
The fusion capsule can be similar to those of laser-driven hohlraums

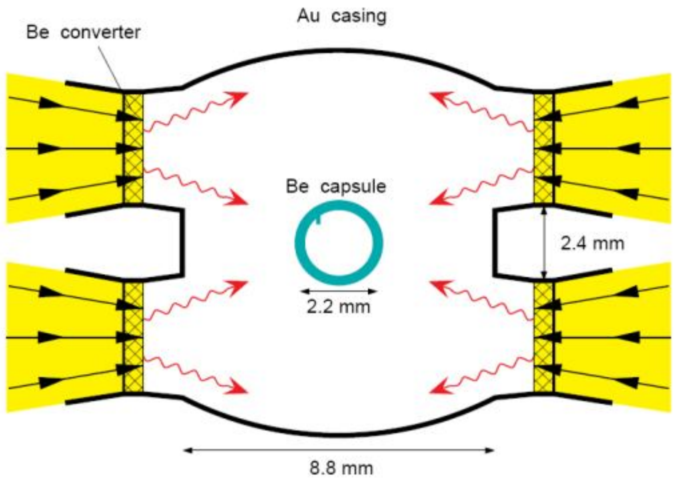
J.Maruhn 1997



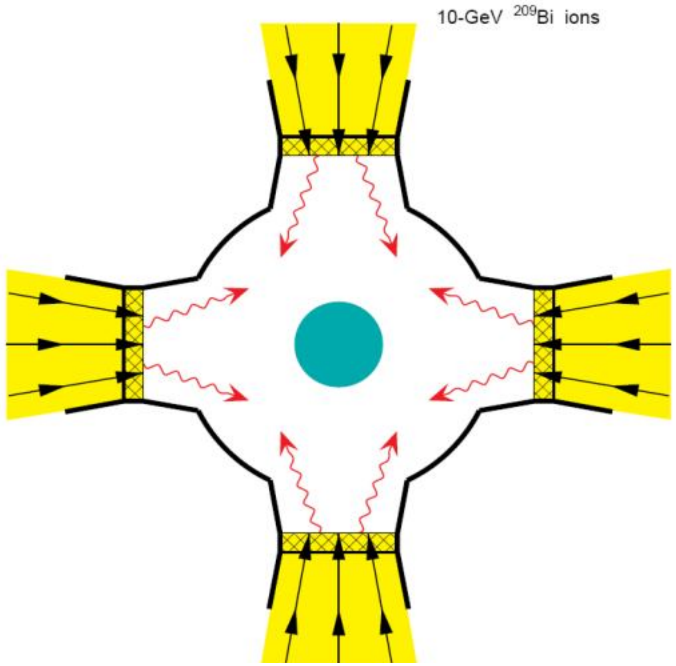
R.Ramis 1998

2 converters
3 MJ/6 ns





"Russian" target
M.Basko, V.Vatulin 1997
8 (10) converters 1.7 mm each,
Energy deposiion 4.5 MJ/6ns

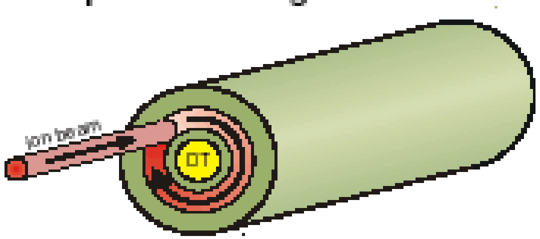


(IAEA-2004) Russian studies of fast ignition using 100 GeV heavy-ion synchrotrons:

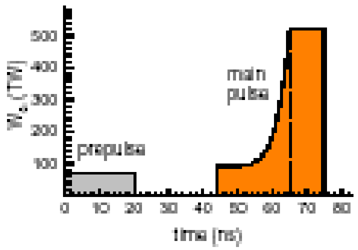
Bi ions with energies 100-200 GeV have relatively long ranges of ~7-18 g/cm2 in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

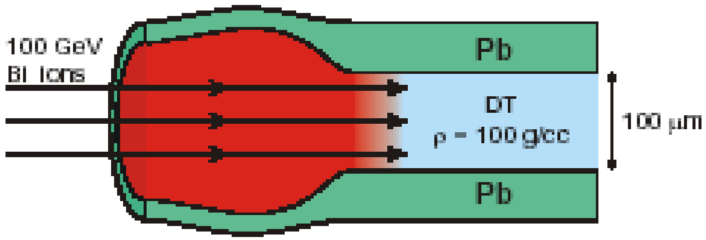


Compression pulse:



- 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:	$I_{igb} = 2.5 \times 10^{19}$ W/cm²

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.

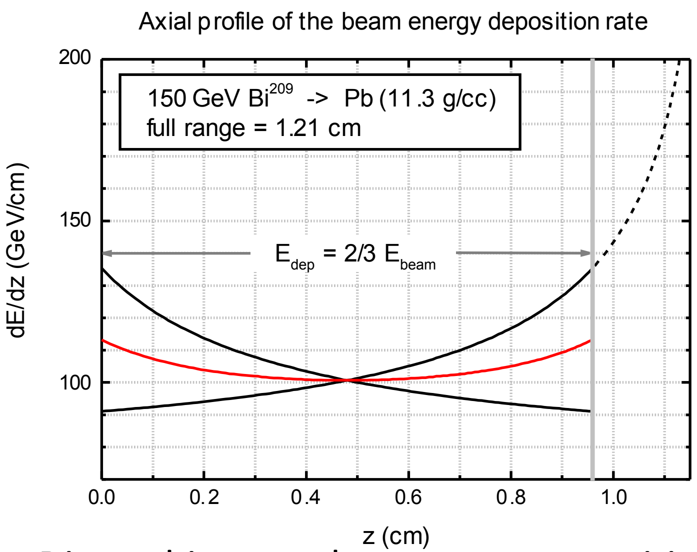
An energy gain of $G \approx 100$ can be expected.

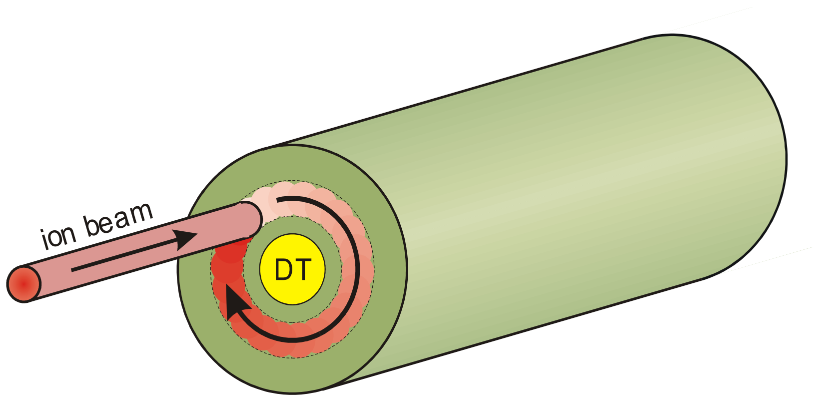
Principal motivation for cylindrical targets

M.Basko et al., HIF 2002

Near-relativistic heavy ions with energies ≥ 0.5 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/cm² 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.

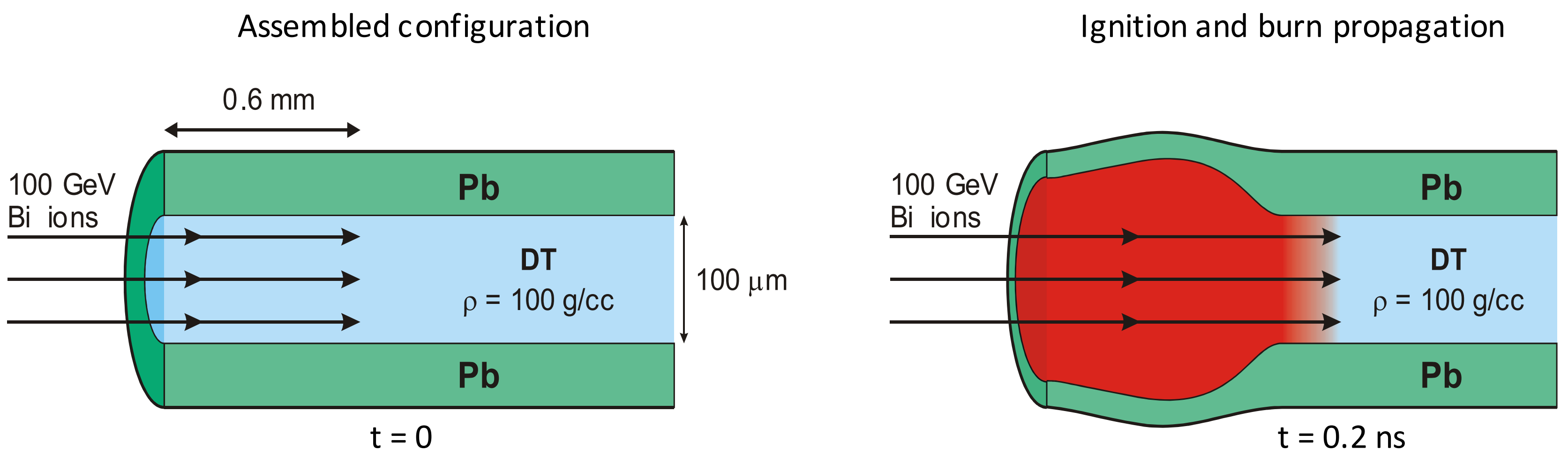
M.Basko *et al*., HIF 2002

Fast ignition with heavy ions: assembled configuration

M.Basko et al., HIF 2002

With a heavy ion energy $\geq$ 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:

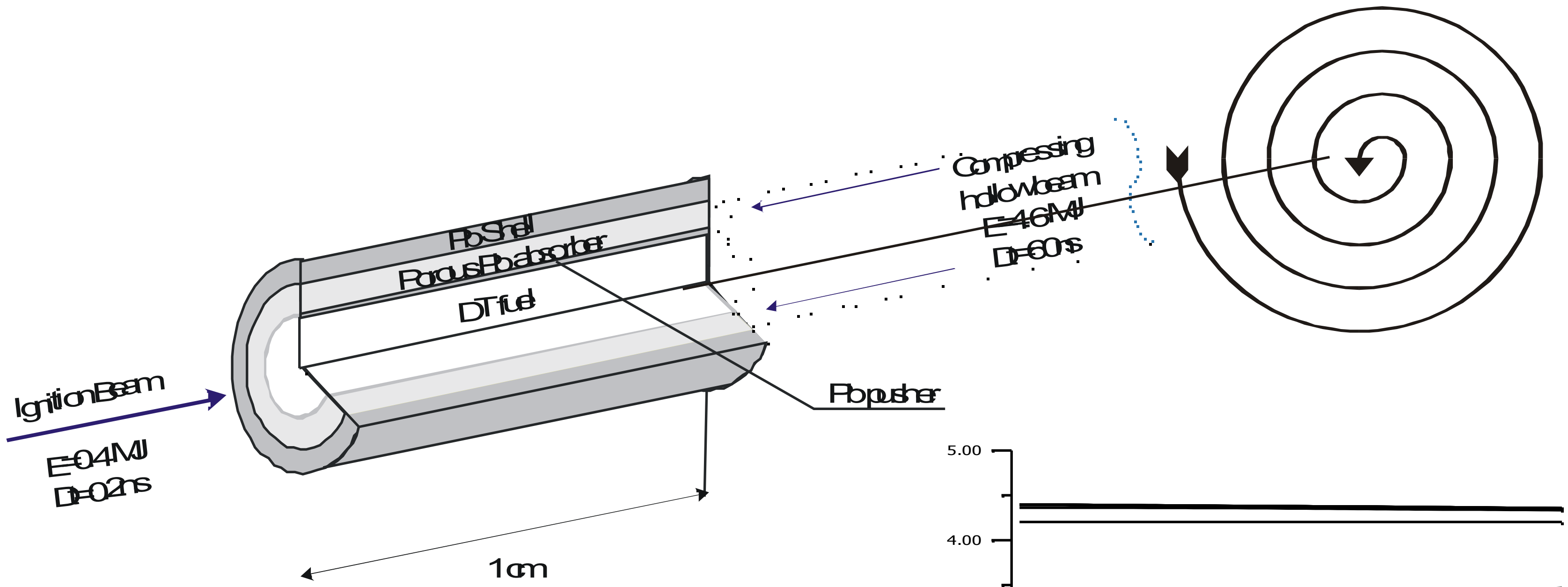


Fuel parameters in the assembled state: ρ_{DT} = 100 g/cc, R_{DT} = 50 μm, $(\rho R)_{DT}$ = 0.5 g/cm^2.

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!

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

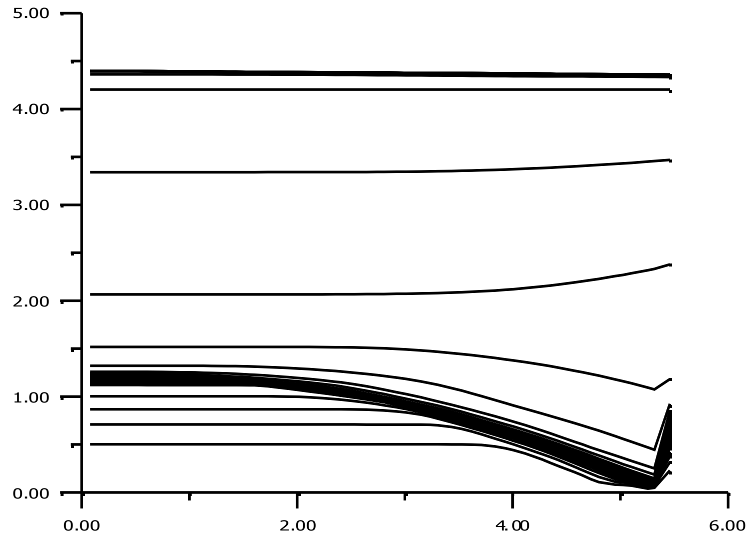
Target irradiation by rotating ion beam



$\rho \geq 100$ g/cm3 ,

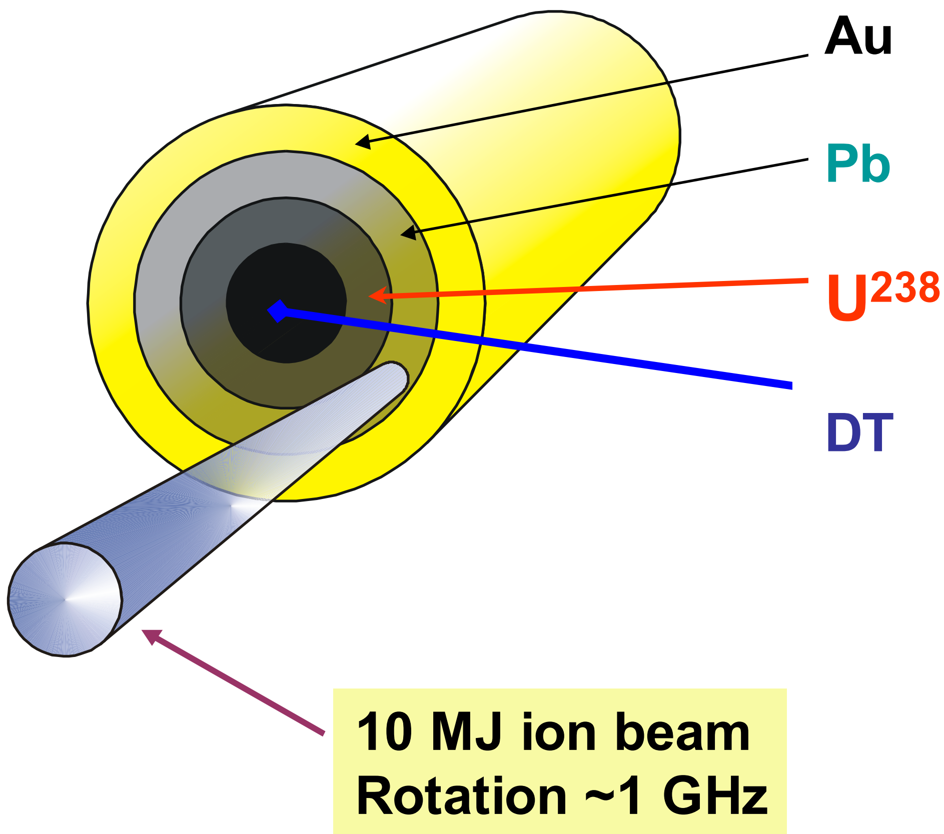
$\rho R \geq 0.5$ g/cm2

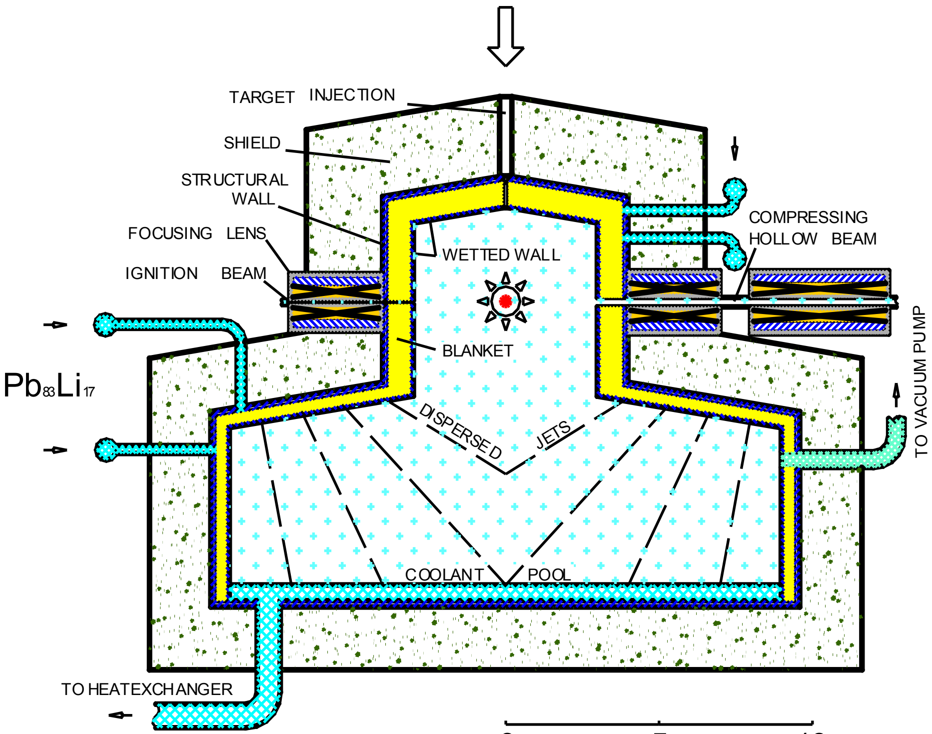
E = 6.3 MJ (*instead 7.1 MJ*)



Fusion – Fission - Fusion

- **10 MJ Heavy Ion Driver -> directly driven cylindrical target**
- **Cylindrical implosion of DT fuel -> DT-neutrons generation**
- **DT-neutrons -> fission of U_{238} pusher material**
- **Better confinement, additional compression of DT**
- **Burn fraction & energy gain enhancement**





REACTOR CHAMBER FOR FAST IGNITION HEAVY ION FUSION

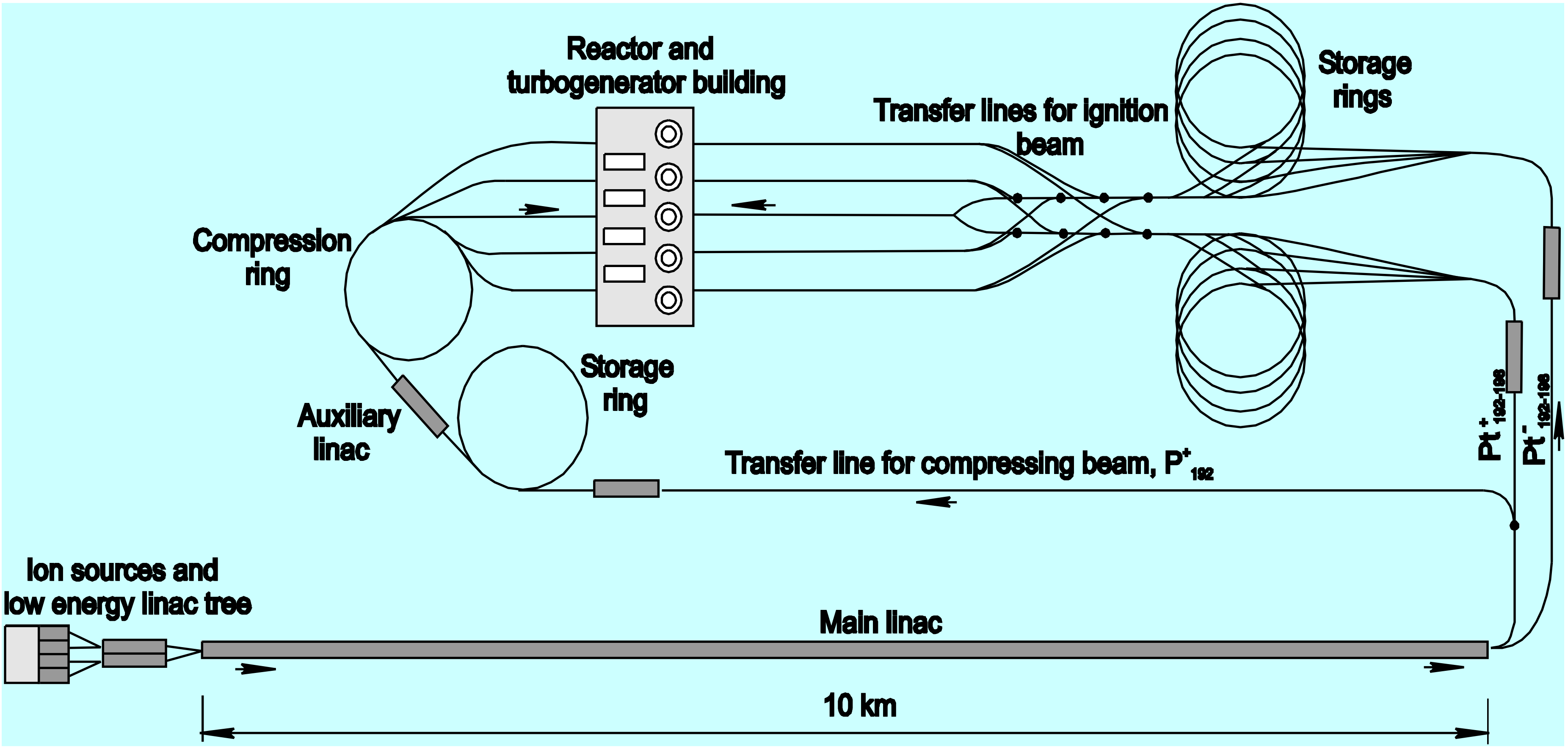
REACTOR CHAMBER FOR HIF POWER PLANT: wetted first wall design

*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 (^oC)	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

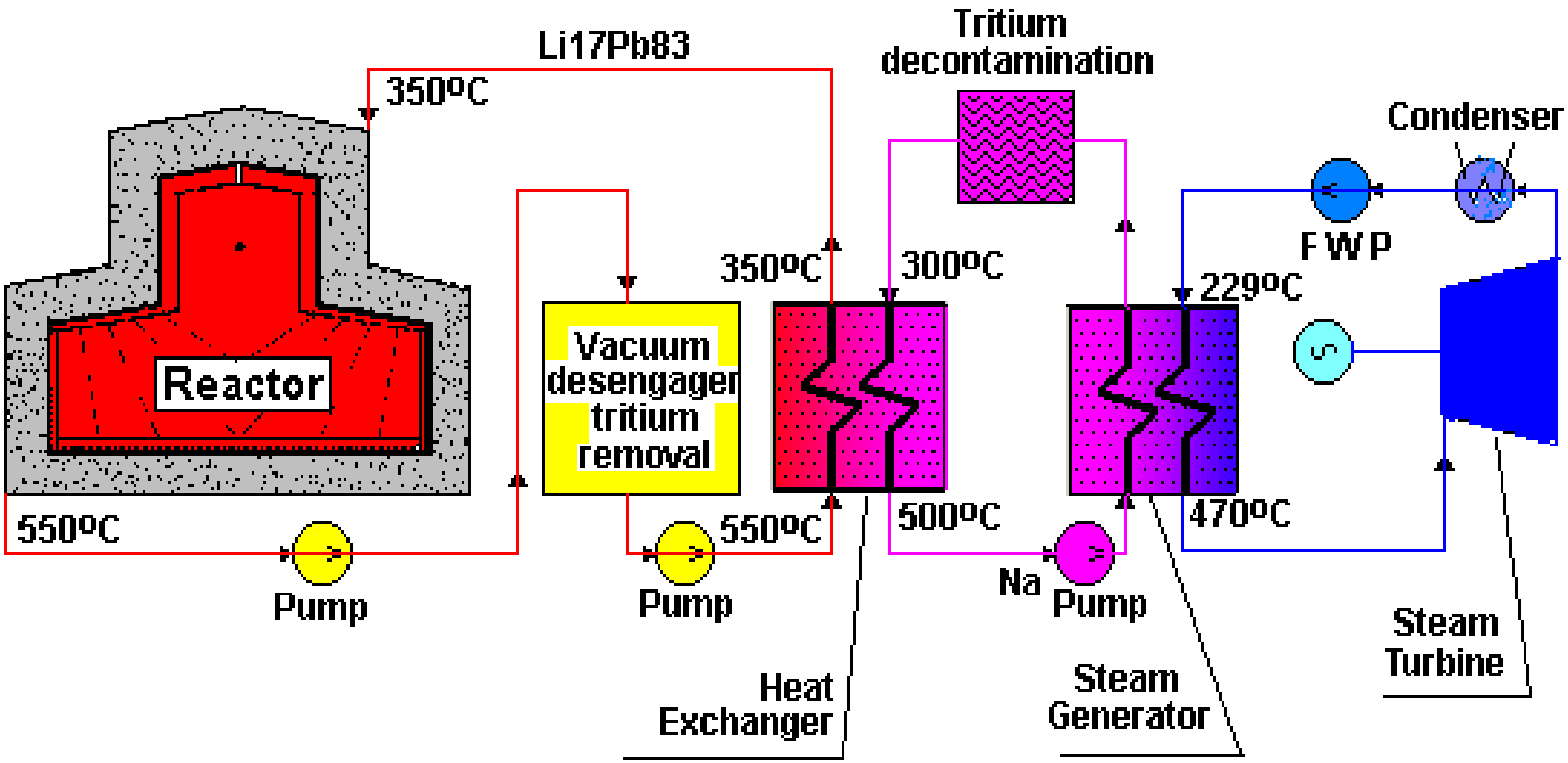
HI IFE Concept
Ground plan for HIF power plant

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

HIF Power Plant 1 GW + accelerator 100 GeV Pt+

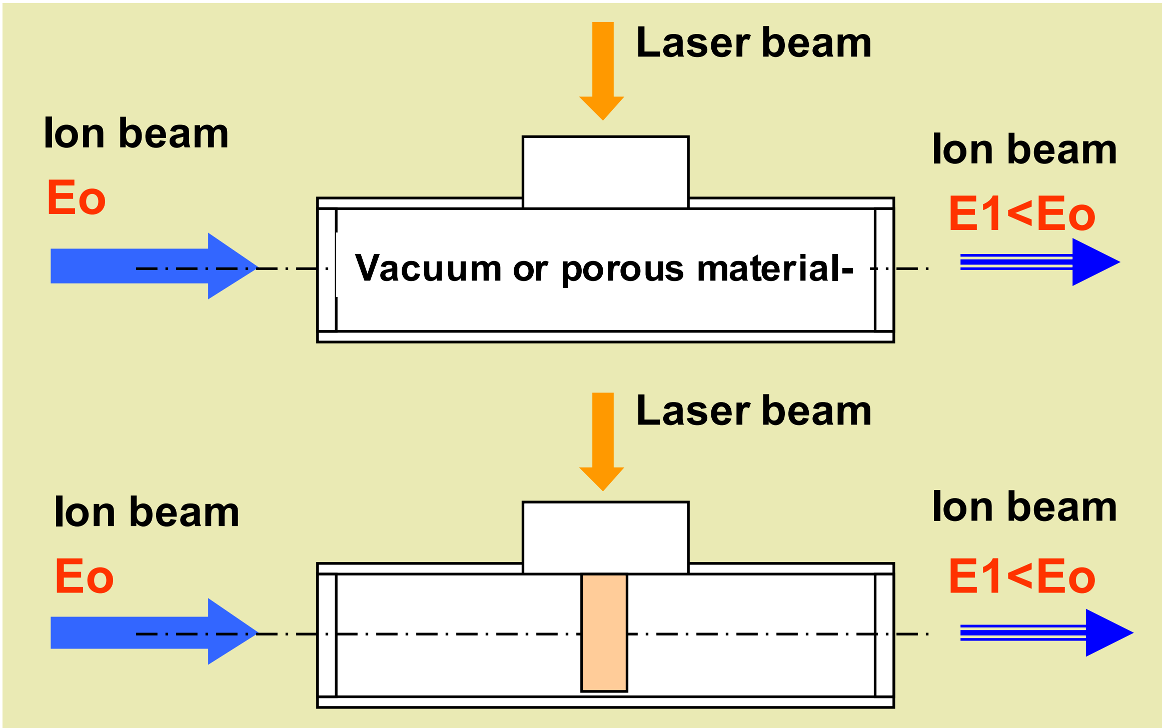


Thermal schematic of FIHIF power plant

- 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.

Indirect target design for investigation of ion stopping in plasma targets (V. Vatulin, VNIIEF,1999)

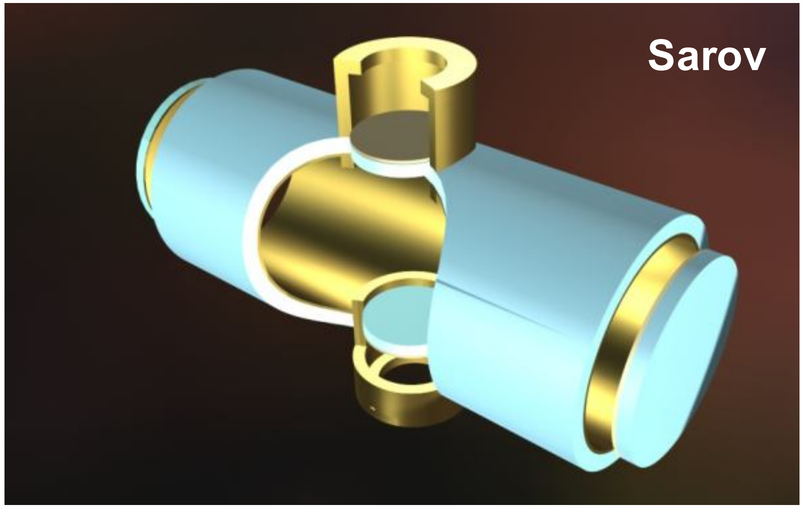
In order to get clear experimental evidence of temperature effect on ion stopping in dense plasma, it is desirable that the target density is uniform and $\rho \cdot l$ *target* conserved going from cold to plasma target. It is also very important to determine plasma parameters accurately.

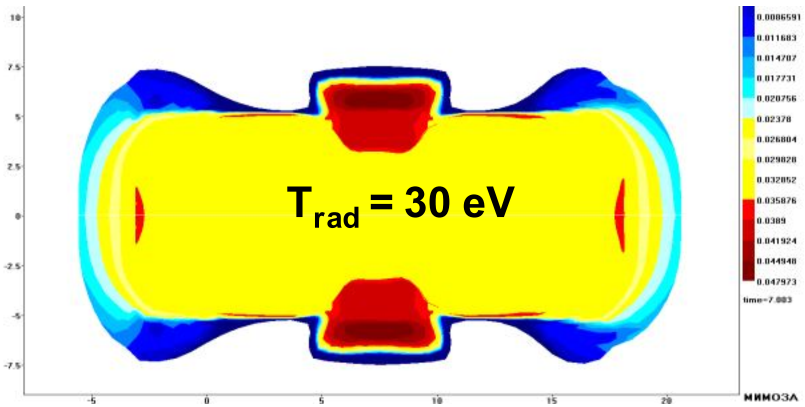


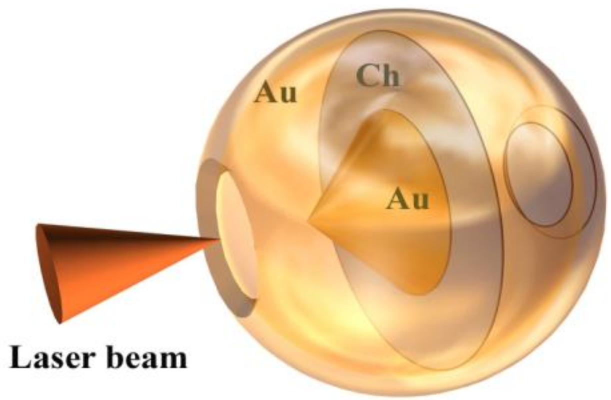
E1/Eo=?

X-rays generated by Phelix laser heat the main volume of the target.

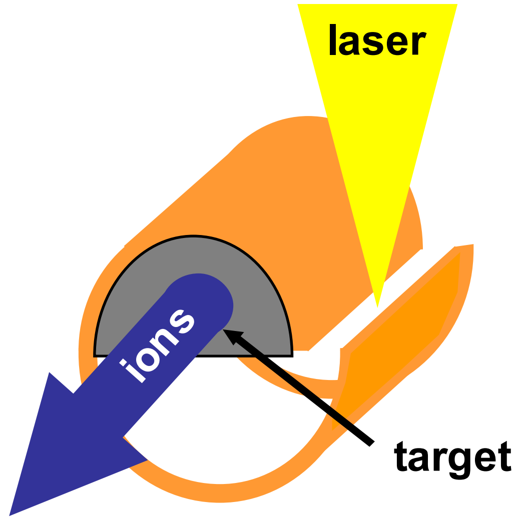
Various design of Hohlraum targets





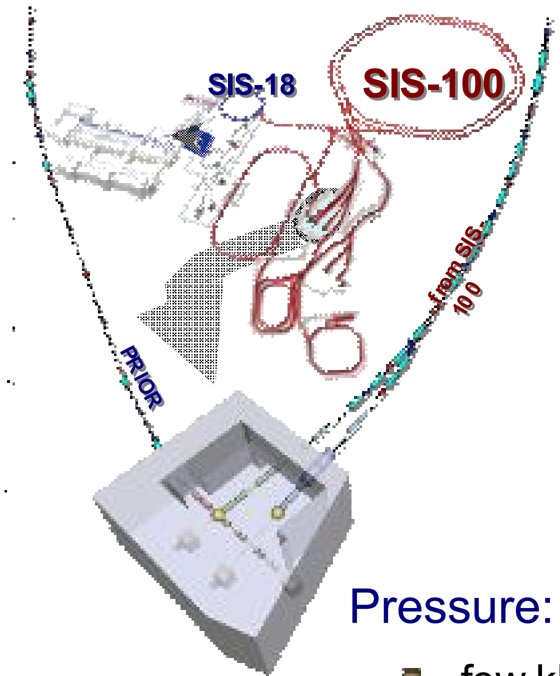


Type of Asterix target as x-ray source for Hohlraum target (GSI proposal)



Numerical simulations: Y.Belyakov et al., Sarov
Maruhn, Frankfurt
Basko, Moscow

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 – 20 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

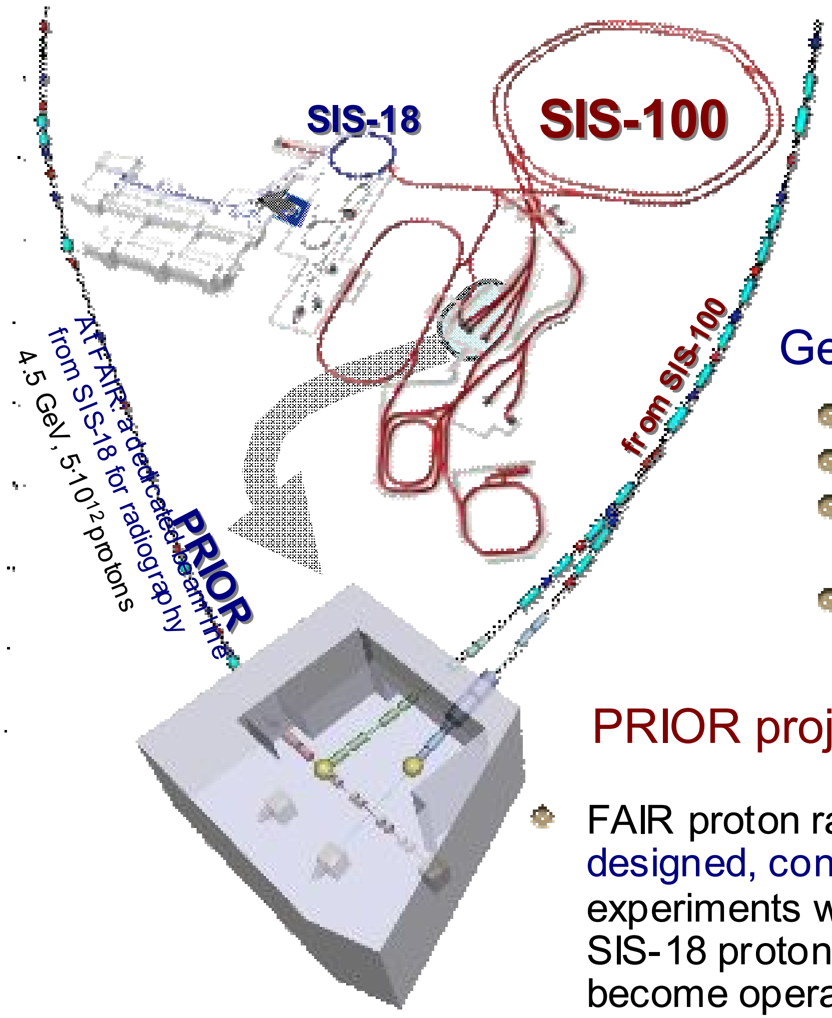
Line-imaging VISARs and displacement interferometers

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 (Moscow)



- 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 magnetshigh spatial resolution (microscopy)
- high density resolution and dynamic rangemulti-frame capability for fast dynamic events

PRIOR project will accomplish two main tasks:

- FAIR proton radiography system which a core FAIR installation will be designed, constructed and commissioned in full-scale dynamic experiments with 4.5 GeV proton beam prior to FAIR using the same 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

Spatial resolution scalings with proton energy:

- object scattering $$\sigma_o \propto \frac{\ell_t^{\frac{3}{2}}}{p}$$
- chromatic aberrations $$\sigma_c \propto \frac{\ell_t^{\frac{1}{2}}}{p^{\frac{3}{2}}}$$
- detector blur $$\sigma_d \propto \frac{\ell_s \ell_t^{\frac{1}{2}}}{p}$$

PRIOR technical specifications (for FAIR experiments):

- proton energy: 4.5 GeV
- spatial resolution: ≤10 µm
- temporal resolution: 10 ns
- multi-framing capability: 1 – 4 frames within 1 µs
- target characteristics: up to 20 g/cm^2
- areal density reconstruction: sub-percent level field of view: 10 – 15 mm
- stand-off distance: 1 – 1.5 mproton illumination spot size: 3 – 15 mm
- total length after object plane: less than 15 m
- using permanent magnets and existing electromagnets

Accelerator centers for IFE related HED research with intense HIB

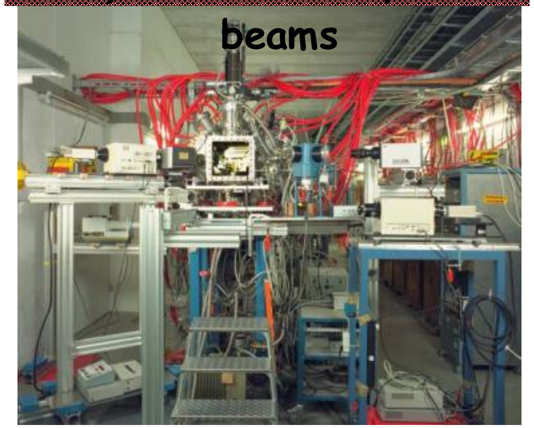
Present Plasma Physics experimental areas at GSI- Darmstad, Germany

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

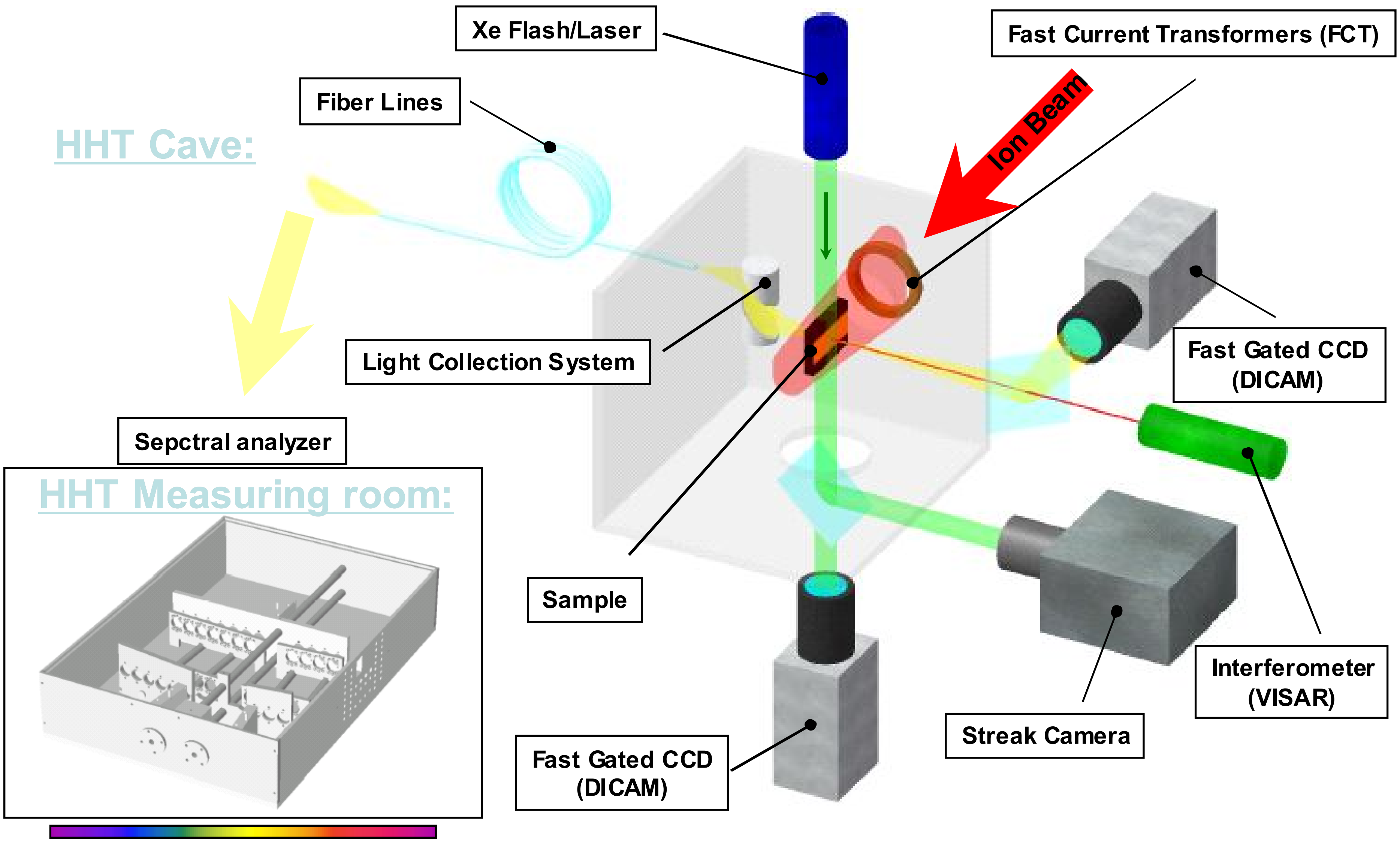
Z6 heavy ion beam [redacted]

laser beam [redacted]

HHT heavy ion beam [redacted]

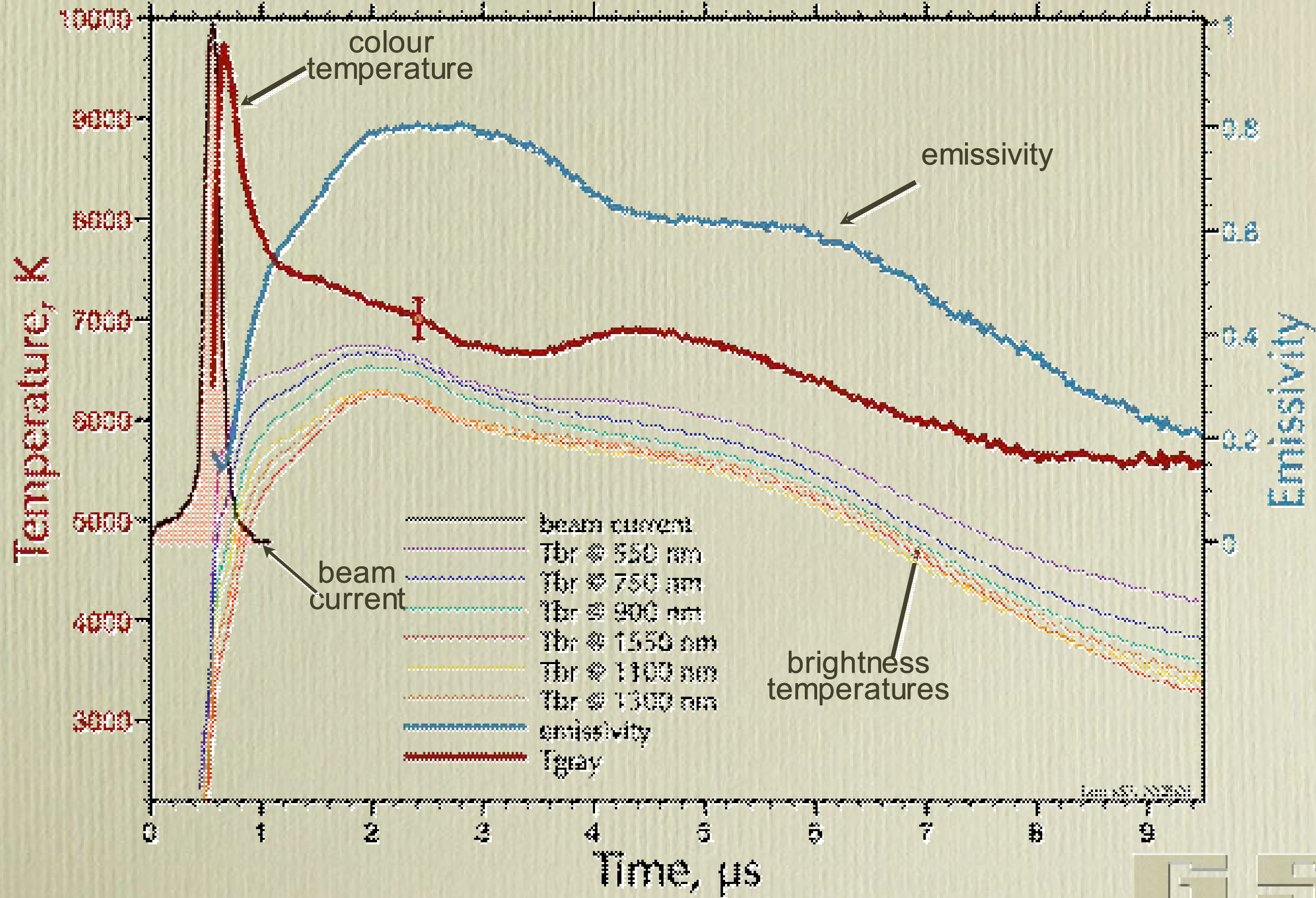
laser beam [redacted]

HHT Experimental Setup



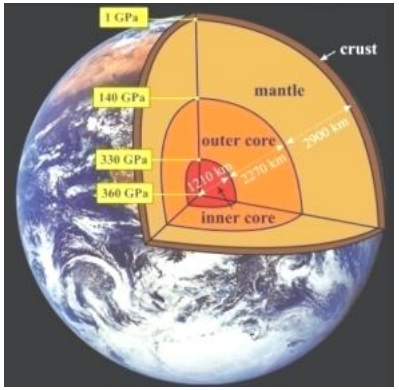
Temperature measurements in WDM experiments: tungsten foil heated up to 10,000 K and expanding

Beam: ^{238}U, 350 MeV/u, 120 ns, $2 \cdot 10^9$ Target: 100 μm W foil



BIOMAT Full Program at SIS 100 - Module 1

Materials research

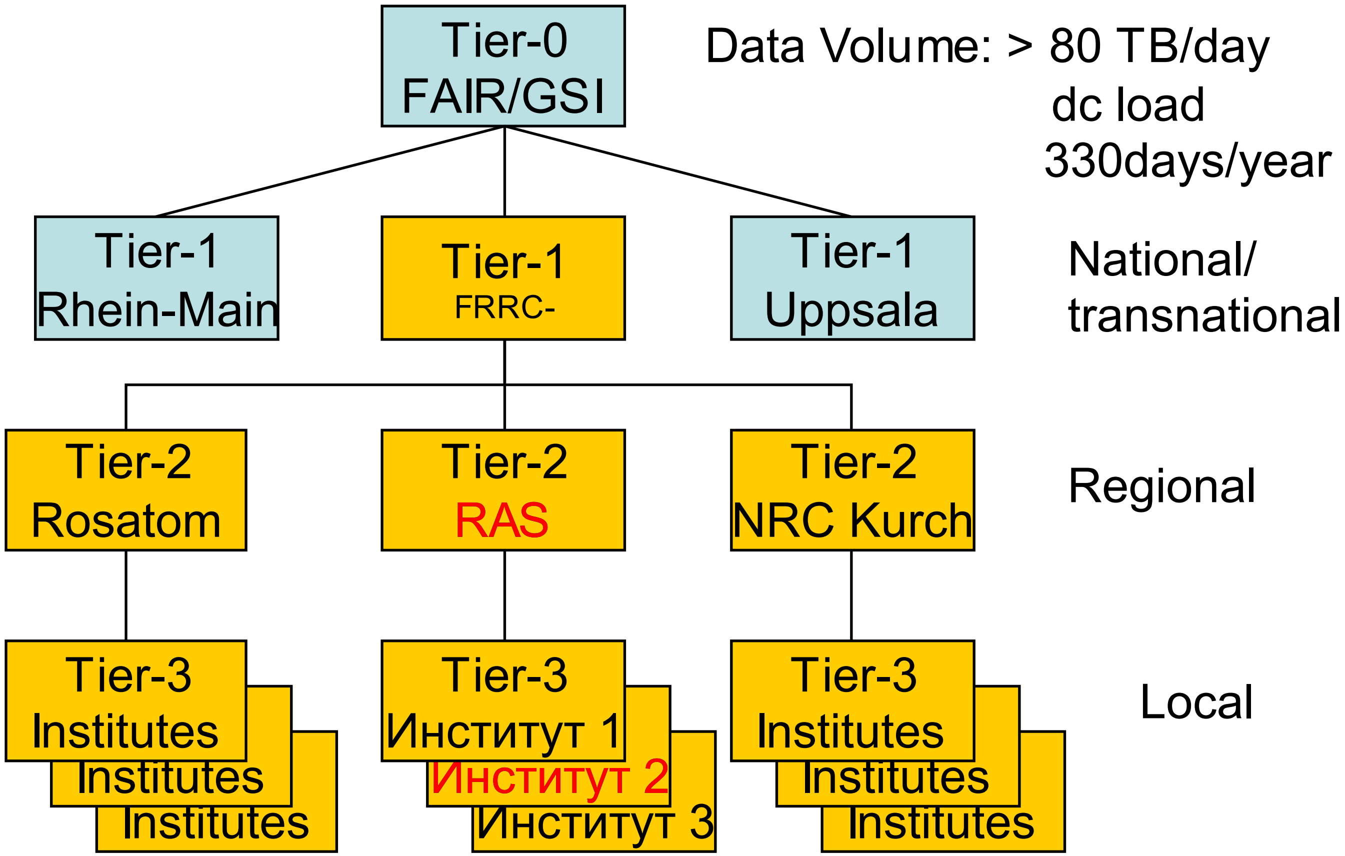


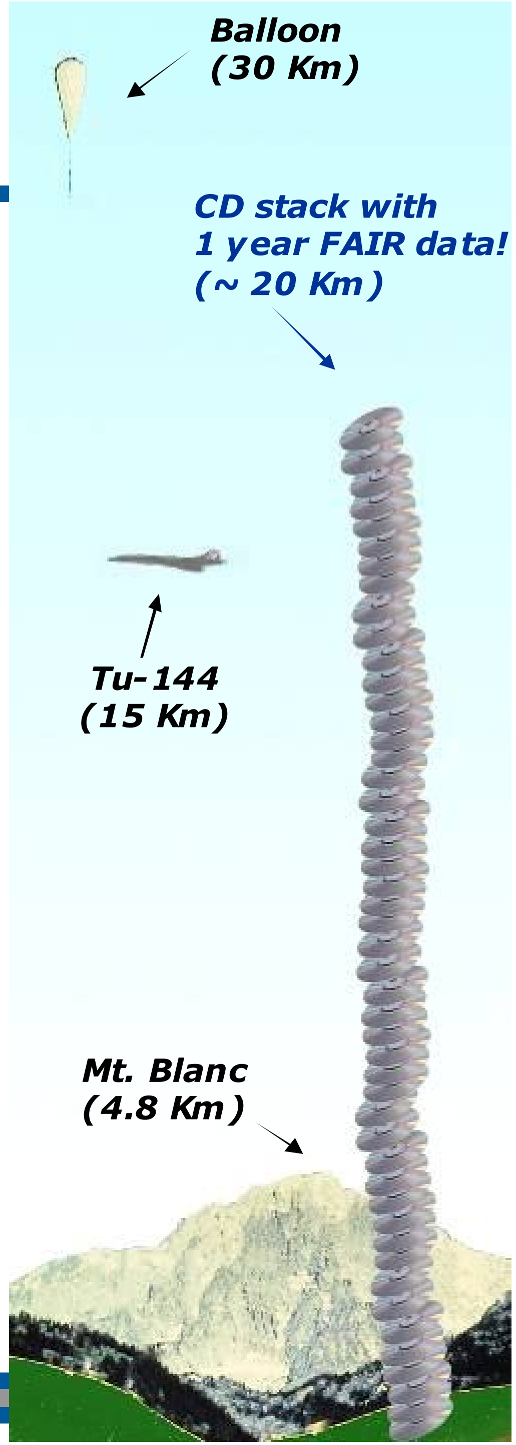
- **Exposure of matter to relativistic ions and high pressure:** phase transitions in mineralogy and geophysics
- **Ion-matter interaction at FAIR Energies:** energy-deposition and short-time processes at relativistic projectile velocities
- **Radiation hardness of materials:** requirements for accelerator and spacecraft-components

Biophysics

- **Cosmic radiation:** the main hindrance toward manned space exploration
- **Widely unknown biological effects of heavy ions**
- **A large experimental campaign in space radiation biophysic was started**

FAIR Computing





Tier-1 & Tier-2 совместно с БАК (LHC GRID)

Summary

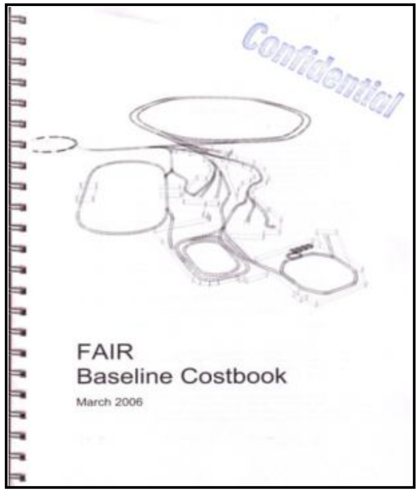
Construction Period, Cost, Users

- Construction until 2018
- Total cost 1.027 B€ (2005 prices)
- Scientific users: 2500 - 3000 per year

Financing

- up to   65 % Federal Government of Germany
- 10 % State of Hessen
- 25 % Partner Countries

FAIR GmbH
with
International Shareholders

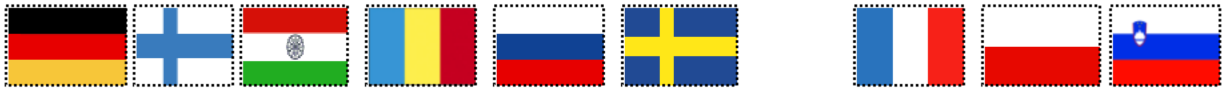


Operation cost will be negotiated in 3 years after FAIR GmbH will be established

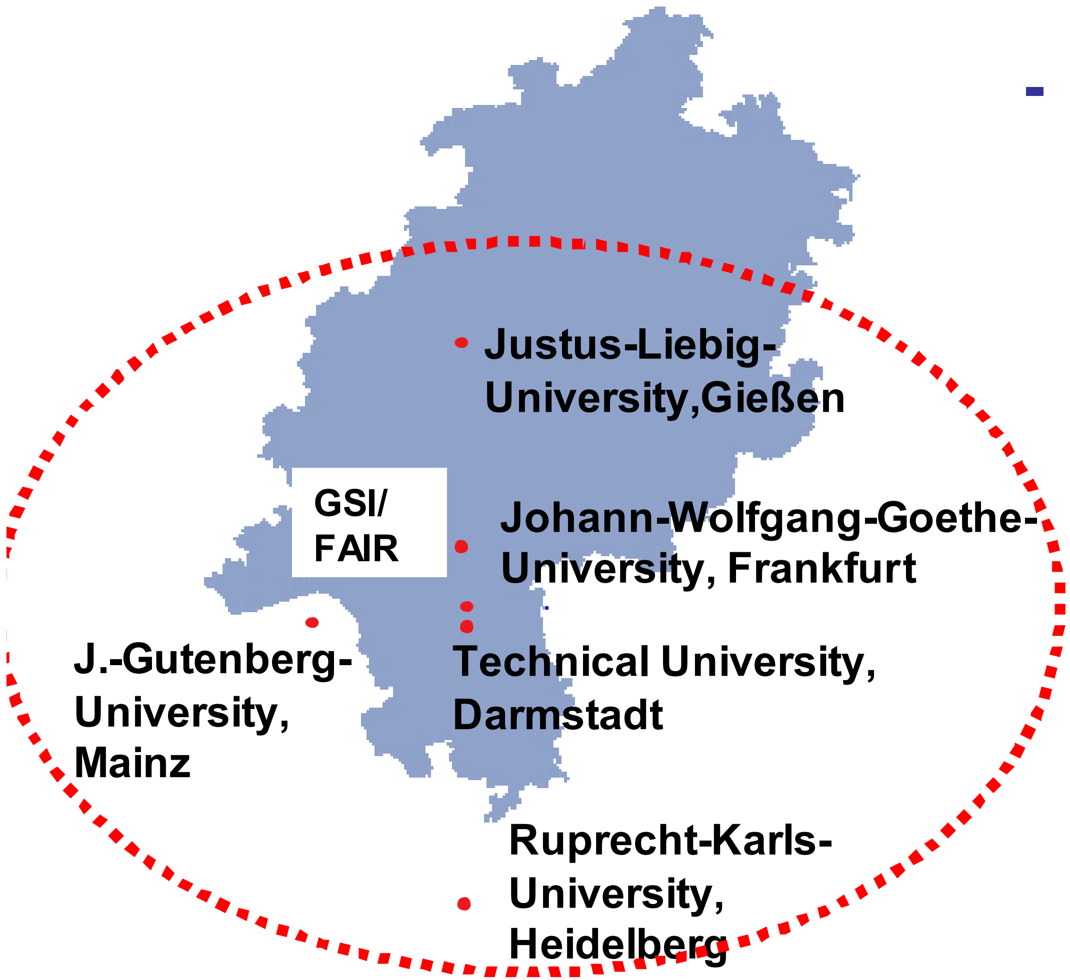
General MoU with CERN

signed on 18 November 2010

Rolf Heuer *Boris Sharkov*



Concept of GSI / FAIR – Associated Universities



- **with 'founding univ.' DA, F, GI, HD, and Mz ...**

- Joint research & development projects related to GSI / FAIR
- Joint initiatives for graduate education at the universities

Expansion of this concept to further universities envisaged!

HIC4FAIR, HGS FAIR, EMMI ….

FAIR – Russia Research Center @ ITEP-Moscow

Strategic goal:

- Technical support of the Russian FAIR research activities and work packages
- Communication and cross-fertilization between the different Russian FAIR research communities
- Support for FAIR- related projects of masters, PhD students and post-docs in various fields of FAIR related fundamental and applied sciences

Seminar of FRRC Fellows 2009

Main results:

- **15 workshops, technical meetings and seminars on FAIR related issues**
- **23 in 2009 and 30 Fellows in 2010 representing 10 Russian Institutes and Universities and all FAIR collaborations**
- **2 regular lecture curses**
- **Basic analysis for White paper of Russian participation in FAIR project**

Cost Estimate Modules 0-3 (Price Basis 2005)

Total accelerator and personnel Modules 0 - 3	**502**
Total civil construction Modules 0 - 3	**400**
Experiment funding	**78**
FAIR GmbH personnel and running costs	**47**
Grand Total Modules 0 - 3	**1027**

all values in M€

Firm Commitments for the FAIR Project

Contracting Party	Contribution [M€]
Finland	5.00
French Republic	27.00
Federal Republic of Germany	705.00
Republic of India	36.00
Republic of Poland	23.74
Romania	11.87
Russian Federation	178.05
Republic of Slovenia	12.00
Kingdom of Sweden	10.00
Total	**1.008,66**

Spain expected to join soon (11.87 M€)

China and UK want to contribute to experiments (6.6 M€)

Project costs (1027 M€)

Shareholders of FAIR GmbH

Shareholder	
GSI	
ROSATOM	
VETENSKAPSRÅDET	
BOSE Institute	
Romanian National Authority for Scientific Research	

on October 4th, 2010 (still valid today)

Expected future shareholders:

Raising New Funds

- New international Partners
  - Saudi Arabia
  - Brasilia
  - Turkey
  - Hungary
  - Norway . . .
- Increasing contributions to FAIR
  - China
  - Spain
  - India
  - Italy . . .
- EU Programme + National funding organizations…
- Costs optimisation, raising efficiency
  - Accelerator , CC , Experiments
    → implementation of MAC recommendations

Co-operation FAIR - GSI

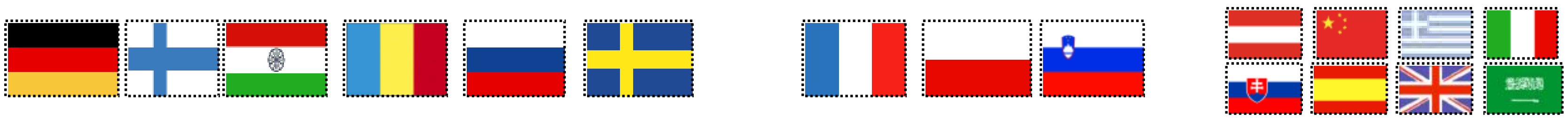
Project owner FAIR:

- Project Lead
- Project Administration
- Civil Construction (Bauherr)
- Project follow up for Accelerator and Experiments

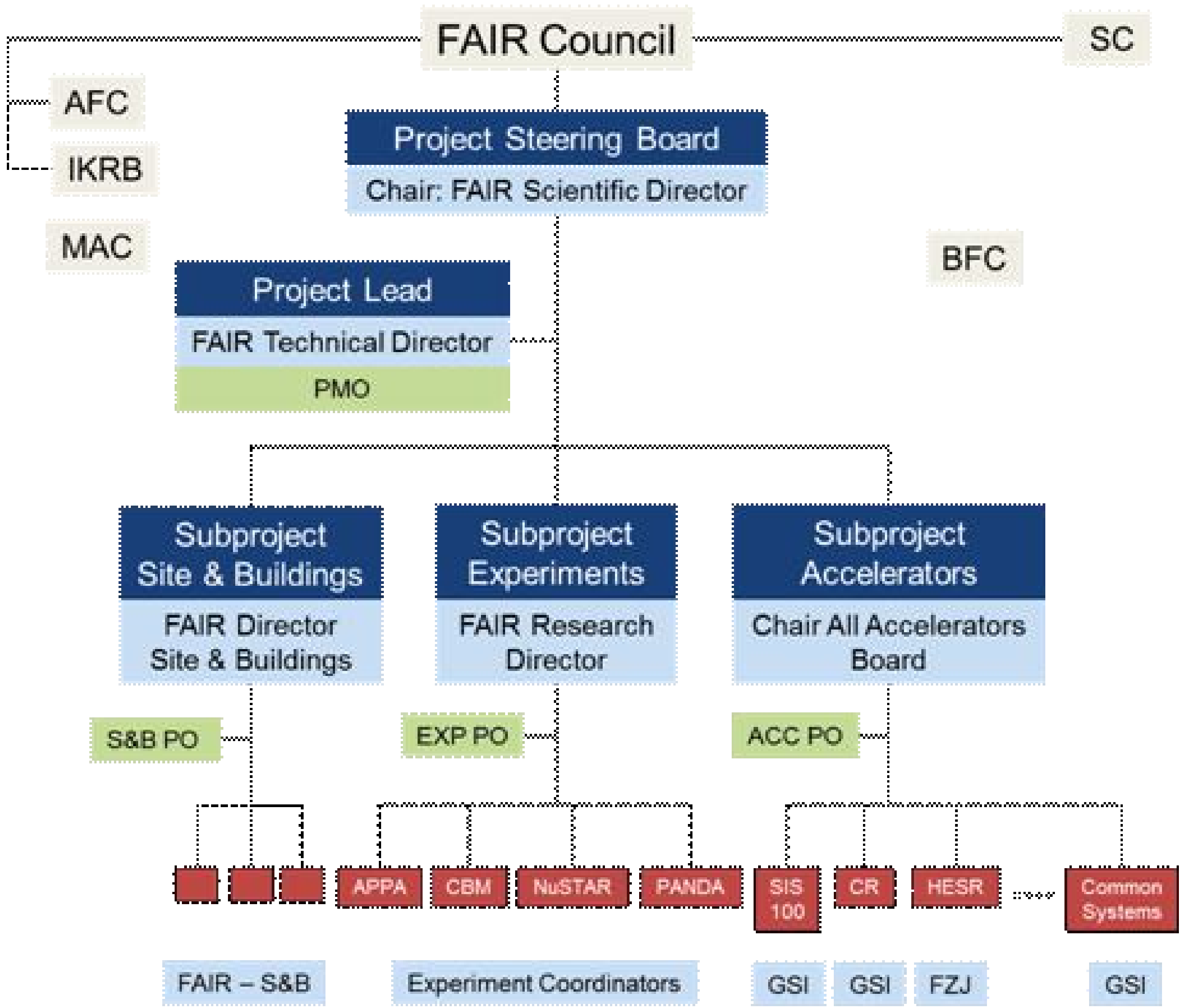
BMC

GSI :

- Shareholder for DE
- Funktional respons. for Accelerator
- Injector
- Participation in FAIR Collaborations
- Administrative support



Project Organisation



Ongoing activities

Administration:

• Transfer of all S&B contracts from GSI to FAIR GmbH
• stuffing in good progress, secondment of GSI personnel to FAIR negotiated successfully
• transition period in administration and changes in Trade Register went smoothly

ACC: start of tendering phase in 2012, in close co-operation with the partner countries (AAB, MAC, IKRB)

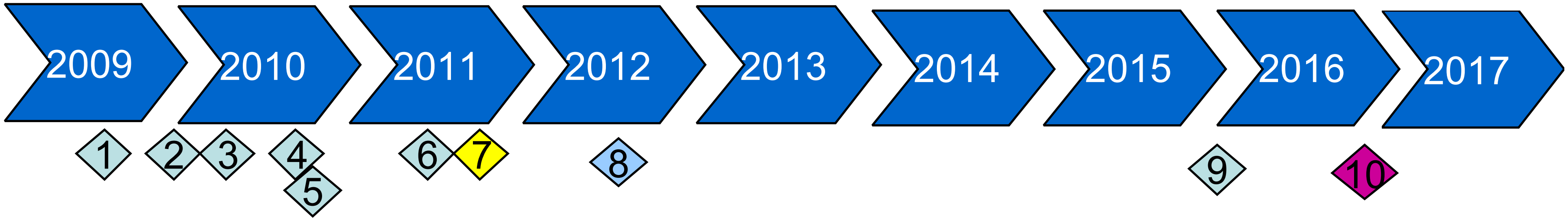
S&B:

- Application for the Building Permits in August 2011
- Obtaining of building permits from the Darmstadt civil construction authority (Bauaufsicht) beginning of 2012
- Begin of CC activities on site in winter 2011/2012 (05.12.2011)

EXP : build-up of the Subproject, TDRs for experiments, construction MoUs.

FAIR Project Organization has been implemented, PSB is operational.
Ongoing Public Relations efforts

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 (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

Summary

1. An intense heavy ion beam is a very efficient tool to induce HED states in matter; large sample size, week gradients, long life times.

2. Construction of the FAIR facility at Darmstadt will enable to carry out novel and unique experiments in the filed of HED.

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

5. FAIR is open for wide international collaborations

   FAIR @ Darmstadt – a crossroad of international activities.

   (associated partnership possible).

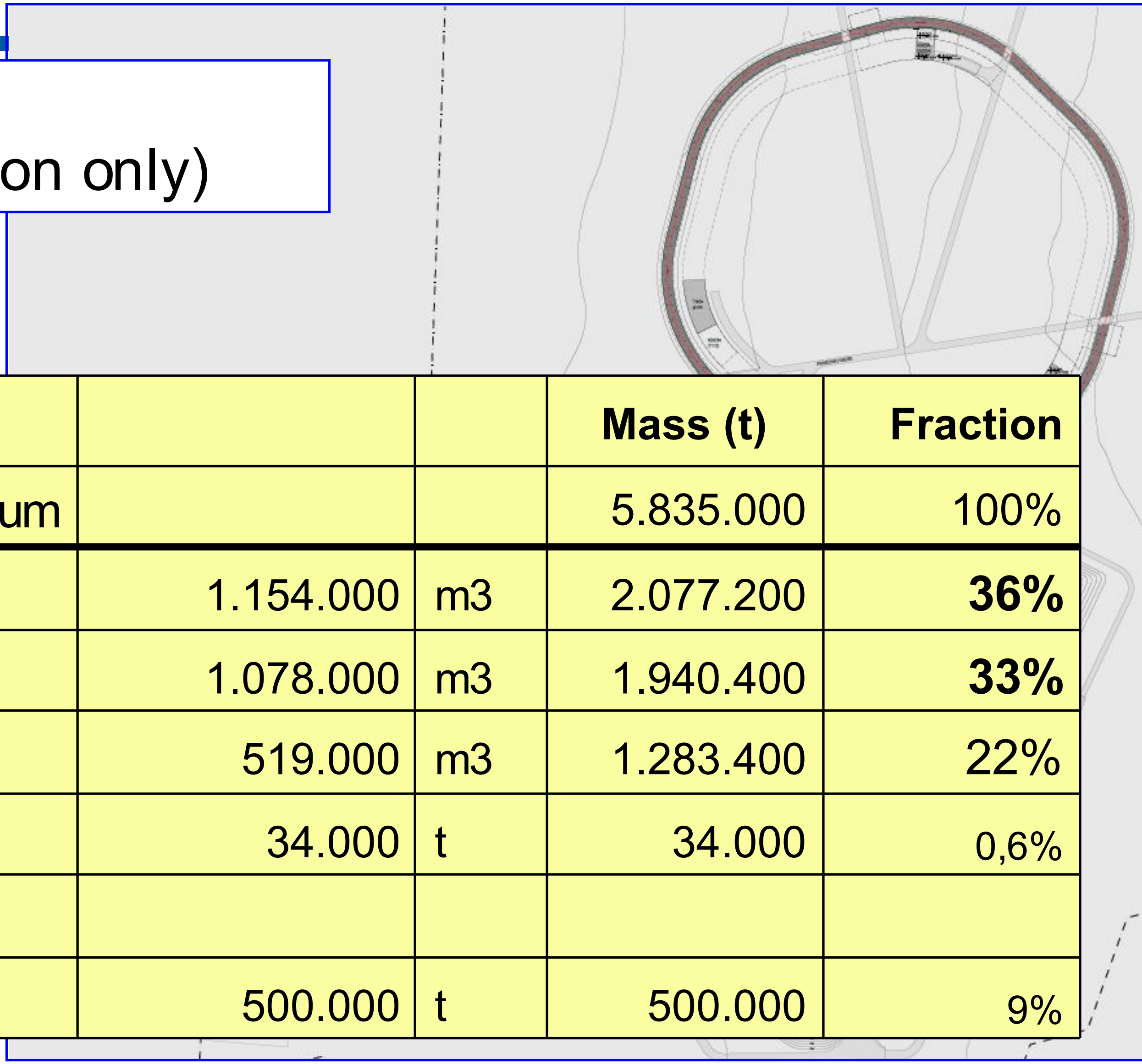
V.Fortov, I.Lomonosov, D.H.H.Hoffmann, M.Roth, A.Golubev, N.Alexeev, A.Shutov M.Basko, M.Churazov, G.Dolgoleva, A.Fertman, A.Golubev, O.Rosmej, A.R.Piriz, D.Varentsov, V.Imshennik, D.Koshkarev, M.Kulish, M.Maslennikov, S.A. Medin, V.Mintsev, Yu.Orlov, V.Suslin, V.Turtikov, E.Zabrodina,V.Zhukov, N.Tahir, V.Vatulin, V Vinokurov …

ITEP - Moscow, Russia
IHED RAS, Russia
Keldysh IAM, RAS, Russia
HZ GSI, Germany
TU-Damstadt, Germany
VNIIEF –Sarov, Russia

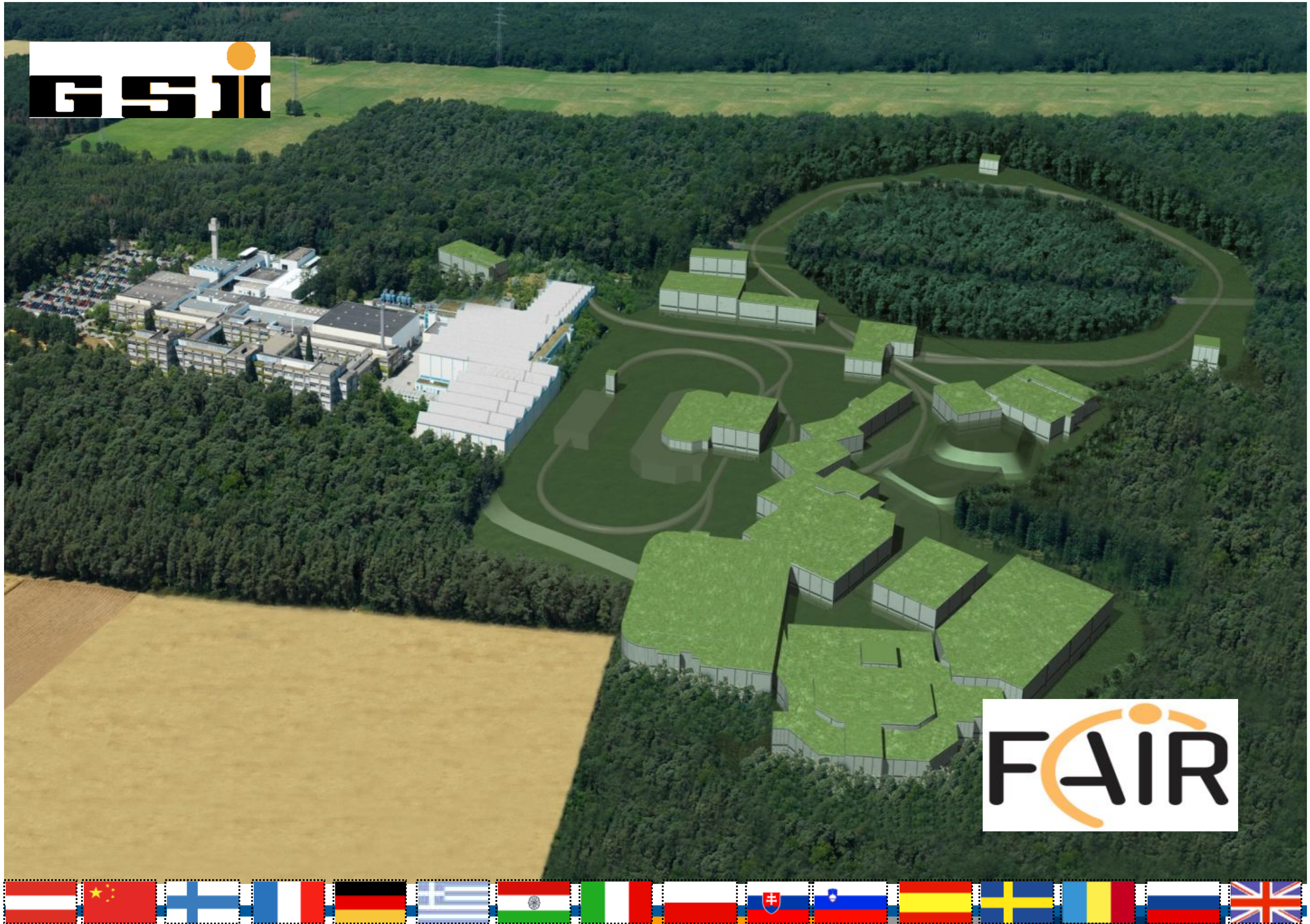
The realisation of FAIR has started!!!

Construction site, January 2012

Relevant Items
(Civil Construction only)



Type			**Mass (t)**	**Fraction**
Sum			5.835.000	100%
Soil out	1.154.000	m3	2.077.200	**36%**
Soil in	1.078.000	m3	1.940.400	**33%**
Concrete	519.000	m3	1.283.400	22%
Steel for concrete	34.000	t	34.000	0,6%
Other	500.000	t	500.000	9%



Austria China Finnland France Germany Greece India Italy Poland Slovakia Slovenia Spain Sweden Romania Russia UK

Facility for Antiproton and Ions Research

– the light tower of the ESFRI Roadmap

Austria China Finland France Germany Greece India Italy Poland Romania Russia Slovakia Slovenia Spain Sweden U K Saudi Arabia

Become FAIR enthusiasts –

join FAIR !

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