Heavy Ion Inertial Fusion Experiments at FAIR

Boris Sharkov

FAIR scientific managing director,

IAEA Vienna  19. 03. 2015.
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
New accelerator systems entered the construction phase in Darmstadt

- High-Energy Storage Ring (HESR)
- Collector Ring (CR)
- Recycled Exp. Storage Ring (RESR)
- New Experimental Storage Ring (NESR)
- Superconducting large-acceptance Fragment Separator (Super-FRS)
- Rare Isotope Production Target
- Antiproton Production Target
- 300m

Synchrotrons (SIS100 SIS300)

p - LINAC
Acc Performance for FAIR Experiments

- **Beam Intensities:**
  - intensities of primary beams: x 100 – x 1000
  - intensities of secondary beams: x 10.000

- **Beam Energies:**
  - energies: x 30

- **Unprecedented Variety of Ions:**
  - antiprotons
  - protons to Uranium, radioactive beams

- **Beam Quality:**
  - cooled antiprotons
  - intense cooled RIBs

- **Pulse Structure:**
  - extremely short pulses (70 ns) to slow extraction (quasi CW)

- **Parallel Operation:**
  - (Finally) operation of up to four experiments simultaneously
• Steering company

• International Convention

• Partners

Wiesbaden, 2010
Module 4:
low energy RIB and low energy antiprotons
NESR

Module 5:
RESR storage ring
P+ beam line
HESR cooler
EC ring

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)
The 4 Scientific Pillars of FAIR

APPA: Atomic, Plasma Physics and Applications
CBM: Compressed Baryonic Matter
NUSTAR: Nuclear Structure, Astrophysics and Reactions
PANDA: Antiproton Annihilations at Darmstadt

MSV provides for outstanding and world-leading research programmes in all four scientific areas, Biomedicine and Materials Science for in total 2500 - 3000 users

Scientific program is competitive and world class
Science with the Modularized Start Version

- PANDA
- CBM/HADES
- APPA
- NuSTAR

Diagram showing various scientific instruments and facilities connected in a network.
Plasma Physics @ SIS100 FAIR

- Phase transitions shocked/compressed matter
- Opacity measurements of Warm Dense Matter
- Day-1 experiments
  - Proton microscopy of shocked/compressed materials
  - Opacity changes from Cold- to Warm Dense-Matter
Plasma Physics

- Interior of massive planets like Jupiter
  
  \( \text{..do we understand the interior of planets?} \)

- Warm and dense plasmas
  
  \( \text{...Equation of State, transport properties, etc.,} \)

- Energy production through Inertial Confinement Fusion:
  
  \( \text{..do we understand the basic physics problems?} \)
Physics of Generating High Energy Density in Matter with Ion Beams

\[ P_\rho = \frac{E_\rho}{\tau_b} = 1.602 \cdot 10^{-19} \left( \frac{dE}{dx} \right) \cdot \frac{N}{\pi \cdot r^2} \left( \frac{J}{g \cdot s} \right) \]

- \( E_\rho \): Specific Deposition Energy [J/g]
- \( \tau_b \): Beam bunch length [s]
- \( P_\rho \): Specific Deposition Power [W/g]
The uniqueness of heavy ion beams compared to other techniques (Laser, Z-pinch)

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

**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  $\rho$: ~ 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

<table>
<thead>
<tr>
<th>Ion beam</th>
<th>U^{28+}</th>
<th>SIS-18</th>
<th>SIS-100</th>
<th>only available at FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/ion</td>
<td>400MeV/u</td>
<td>0.4-27 GeV/u</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of ions</td>
<td>4.10^9 ions</td>
<td>5.10^{11} ions</td>
<td>X100</td>
<td></td>
</tr>
<tr>
<td>Full energy</td>
<td>0.06 kJ</td>
<td>6 kJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam duration</td>
<td>130 ns</td>
<td>50 ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam power</td>
<td>0.5 GW</td>
<td>0.1 TW</td>
<td>X200</td>
<td></td>
</tr>
</tbody>
</table>

**Lead Target**

<table>
<thead>
<tr>
<th></th>
<th>1 kJ/g</th>
<th>100 kJ/g</th>
<th>X100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy</td>
<td>5 GW/g</td>
<td>1 TW/g</td>
<td>X200</td>
</tr>
<tr>
<td>WDM temperature</td>
<td>~ 1 eV</td>
<td>10-20 eV</td>
<td></td>
</tr>
</tbody>
</table>
Basic motivations for HI IFE

- Intrinsic efficiency: $\eta_{G}>10$
- High repetition rate: $\sim 1 - 10$ 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.

"Russian" target
M. Basko, V. Vatulin 1997
8 (10) converters 1.7 mm each,
Energy deposition 4.5 MJ/6ns
Principal motivation for cylindrical targets

Near-relativistic heavy ions with energies $\geq 0.5$ 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 $\sim 7-18$ g/cm$^2$ in cold heavy metals. Such ranges can be naturally accommodated in cylindrical targets with axial beam propagation.

![Axial profile of the beam energy deposition rate](image)

$E_{\text{dep}} = 2/3 E_{\text{beam}}$

Direct drive may become a competitive target option when

- azimuthal symmetry is ensured by fast beam rotation ($> 1$ GHz) around the target axis,

  \[ M. \ M. \ Basko, \ T. \ Schlegel, \ J. \ Maruhn \ \textit{PHYSICS OF PLASMAS} \ V \ 11, \ 4, \ 2004, \ \text{R.Piriz, N.Tahir.} \]

- 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.

\[ \text{M.Basko et al., HIF 2002} \]
<table>
<thead>
<tr>
<th>CYLINDRICAL TARGET</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DT fuel mass</td>
<td>(g)</td>
</tr>
<tr>
<td>Total mass</td>
<td>(g)</td>
</tr>
<tr>
<td>Length</td>
<td>(mm)</td>
</tr>
<tr>
<td>ρR parameter</td>
<td>(g/cm²)</td>
</tr>
<tr>
<td>Burn fraction</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td></td>
</tr>
<tr>
<td>Fusion energy</td>
<td>(MJ)</td>
</tr>
</tbody>
</table>

**Energy release partition**

<table>
<thead>
<tr>
<th></th>
<th>(MJ)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Ion debris</td>
<td></td>
<td>153</td>
</tr>
<tr>
<td>Neutrons</td>
<td></td>
<td>580</td>
</tr>
</tbody>
</table>
Target irradiation by rotating ion beam

\[ \rho \geq 100 \text{ g/cm}^3, \]
\[ \rho R \geq 0.5 \text{ g/cm}^2 \]
\[ E = 6.3 \text{ MJ (instead 7.1 MJ)} \]
**Fast ignition with heavy ions: assembled configuration**

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

The 400 kJ 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

![Diagram of assembled configuration](image)

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

Ignition and burn propagation

![Diagram of ignition and burn propagation](image)

2-D hydro simulations (ITEP + VNIIIEF) 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

<table>
<thead>
<tr>
<th></th>
<th>Ion energy (GeV)</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compression beam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>7.1 (profiled)</td>
<td></td>
</tr>
<tr>
<td>Duration (ns)</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Maximum current (kA)</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Rotation frequency (GHz)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Rotation radius (mm)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Ignition beam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Duration (ns)</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Maximum current (kA)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Focal spot radius (µm)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Main linac length (km)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>2x4 (reactor)</td>
<td></td>
</tr>
<tr>
<td>Driver efficiency</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>
**REACTOR CHAMBER CHARACTERISTICS**

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

**REACTOR CHAMBER FOR HIF POWER PLANT:**

wetted first wall design

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 micro-explosion.

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.
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
This technique involves isochoric and uniform heating of bulk matter by an intense ion beam and the heated material is allowed to expand isentropically in 1D plane.

- Expanded Hot Liquid
- Two Phase Liquid-Gas Region
- Critical Parameters
- Strongly Coupled Plasma


Numerous high-entropy HED states:
- EOS and transport properties of e.g., non-ideal plasmas, WDM and critical point regions for various materials
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
Regions of the phase diagram accessible in experiments at FAIR

# 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

## LAPLAS
*Laboratory Planetary Sciences*
- 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
Experimental Scheme: Low entropy compression of a test material like H, D$_2$ or H$_2$O, in a multilayered cylindrical target

[Hydrogen Metallization, Planetary Interiors]


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

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

$\beta$ = 1.2 g/cc, P = 11 Mbar, T = 5 ev
Ion optical design of the **LAPLAS** beam line: focusing and RF beam deflector (wobbler), ITEP design.

**Transverse beam intensity distribution in the focal spot**
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
Dynamic confinement of targets heated quasi-isochorically with heavy ion beams

A. Kozyreva¹, M. Basko², F. Rosmej³, T. Schlegel¹, A. Tauschwitz³ and D.H.H. Hoffmann¹,³

Target: Solid (cryogenic) hydrogen
For isochoric heating in $\epsilon = 130 \text{ kJ/g} \rightarrow T = 0.64 \text{ eV}$ (Warm Dense Matter regime)
Present Plasma Physics experimental areas at GSI-Darmstadt, 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

**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, $4 	imes 10^9$ U ions in 125 ns pulse, ~ 1 kJ/g
- Laser beam - PHELIX: 0.5 kJ @ 0.5 ps (PW)
  - 1-5 kJ @ 10 ns
Ion Beam Facilities for HEDP

ИТЭФ, Москва
HIFS-VNL, Berkeley
IMP, Lanzhou
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 started.** It will enable to carry out novel and unique experiments in the field of HED and HIFE.

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

5. FAIR is open for wide international collaborations on HED and HI IFE – Darmstadt – a crossroad of international activities.
   
   (associated partnership possible).
The FAIR Project for HEDP

Finland France Germany India Poland Romania Russia Slovenia Sweden UK
Acknowledgements


ITEP - Moscow, Russia
IHED RAS, Russia
Keldysh IAM, RAS, Russia
HZ GSI, Germany
TU-Damstadt, Germany
VNIIEF – Sarov, Russia
Universidad de Castilla - La Mancha, Ciudad Real, Spain
Plasma Physics with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures

- Magnetic Fusion
- Inertial Confinement Fusion
- Laser Heating
- Ion Beam Heating
- Sun Core
- PHELIX
- SIS 100
- SIS 18
- Sun Surface
- Jupiter

Motivation
## Critical Parameters of Some Metals

I.V. Lomonosov and V.E. Fortov

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

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 $\rho l$ target conserved going from cold to plasma target. It is also very important to determine plasma parameters accurately.

X-rays generated by Phelix laser heat the main volume of the target.
Various design of Hohlraum targets

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

$T_{\text{rad}} = 30 \text{ eV}$

Type of Asterix target as x-ray source for Hohlraum target (GSI proposal)
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 constrain astrophysical scenarios
The Super-FRS

Central instrument for the NuSTAR program!!

Two-stage separation yields isotopic nuclear beams

- 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 facilities 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

<table>
<thead>
<tr>
<th>Super-FRS</th>
<th>R3B</th>
<th>ILIMA</th>
<th>EXL</th>
<th>ELISE</th>
<th>AIC</th>
<th>HISPEC/DESPEC</th>
<th>exo+pbar</th>
<th>MATS</th>
<th>LASPEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Q-values, isomers</td>
<td>dressed ions, highest precision</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Half-lives</td>
<td>ps...ns-range</td>
<td>bare ions, s...h</td>
<td></td>
<td></td>
<td></td>
<td>dressed ions, μs...s</td>
<td>nuclear periphery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matter radii</td>
<td>interaction x-sect</td>
<td>matter radii</td>
<td>matter density distributions</td>
<td>matter radii from absorption</td>
<td>nuclear</td>
<td></td>
<td>mean square radii</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge radii</td>
<td>high resolution, angular momentum</td>
<td>complete kinematics, neutron detection</td>
<td>low momentum transfers</td>
<td>high-resolution spectroscopy</td>
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</table>

- Highest intensity and transmission
- "High" energy (unambiguous identification)
- World-wide unique storage-ring complex
- Exotic nuclei and antiprotons
- New isotopes (r-nuclides)
- Neutron radioactivity, neutron dripline
- Modification of shell structure, new excitation modes
- Unexpected observations and phenomena

Complementary instruments, cutting-edge technology
Technical Challenges: contributions by partner countries

Remote Handling

Target & Beam Catcher

Cryogenics

SC Multiplets

Main-Separator

SC Dipoles

Remote Handling Diagram

Target & Beam Catcher Diagram

Cryogenics Diagram

Radiation Resistant Magnets

Focusing System

Driver Accelerator
The Collaboration

At present 410 physicists from 53 institutions in 16 countries

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*

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

**At FAIR: 100 times more abundant than at CERN**
Hypernuclear landscape with HypHI

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

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

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

Known hypernuclei
$10^4$ /week
$10^3$ /week

Phase 0 (2009) at GSI: Light hypernuclei

With hypernuclear separator
Magnetic moments
Exploring strange dimensions for the nuclear chart: Hyperon Clusters
HESR and PANDA

Length 442 m
Rigidity 50 Tm

4π detector PANDA Detector
The CBM Collaboration: 55 institutions, 450 members

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
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<tbody>
<tr>
<td>Croatia</td>
<td>RBI, Zagreb Split Univ.</td>
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<tr>
<td>China</td>
<td>CCNU Wuhan Tsinghua Univ.</td>
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<td>Czech Republic</td>
<td>CAS, Rez Techn. Univ. Prague</td>
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<td>France</td>
<td>IPHC Strasbourg</td>
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<td>Hungary</td>
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<td>Norway</td>
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<td>Germany</td>
<td>Univ. Heidelberg, P.I.</td>
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<td>LIP Coimbra</td>
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<tr>
<td>Ukraine</td>
<td>T. Shevchenko Univ. Kiev Kiev Inst. Nucl. Research</td>
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</tbody>
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CBM Collaboration Meeting in Dubna Oct. 2008

B. Sharkov

14th CBM Collaboration meeting 5-9 Oct. 2009, Split, Croatia
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

- 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 $r_B$?

CBM and HADES at SIS 100 and SIS 300

address with heavy-ion collisions

B. Sharkov
Looking into the fireball ...

... using penetrating probes: short-lived vector mesons decaying into electron-positron pairs
Atomic, Plasma Physics and Applied Physics (APPA)

BIOMAT
- 110 scientists
- 28 institutions
- 12 countries

SPARC
- 284 scientists
- 83 institutions
- 26 countries

FLAIR
- 144 scientists
- 49 institutions
- 15 countries

Plasma-physics
- 246 scientists
- 55 institutions
- 16 countries