Extreme State of Matter Physics at FAIR

Boris Sharkov

FAIR Scientific Director,
Chairman of the management board

31. 10. 2011 the NA, Washington
Facility for Antiproton and Ions Research - the light tower of the ESFRI Roadmap

New accelerator systems to be constructed in Darmstadt

- High-Energy Storage Ring (HESR)
- Collector Ring (CR)
- Recycled Exp. Storage Ring (RESR)
- Superconducting large-acceptance Fragment Separator (Super-FRS)
- Antiproton Production Target
- Rare Isotope Production Target
- New Experimental Storage Ring (NESR)
- 300m
- Synchrotrons (SIS100, SIS300)
- p-LINAC
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: Compressed 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
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)
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 all four scientific communities of FAIR
Science with the Modularized Start Version
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
- **PANDA**: Hadron Structure & Dynamics

In total: 2500 – 3000 Users
Highest Intensity Precision Beams of Energetic Ions and Antiprotons

Fundamental Research into the microscopic structure of matter

Creation of matter nucleosynthesis and the evolution of the Universe

Matter in extreme states and material studies & applications

Structure and fundamental properties of anti-matter
Nuclear STructure, Astrophysics and Reactions

> 800 members from 37 countries and 146 institutions

Annual NUSTAR Collaboration Meeting
Central Topics for NuSTAR at FAIR

- 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 \( \sim 10^{12} \) 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

B. Sharkov
### 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><strong>Masses</strong></td>
<td></td>
<td>bare ions, mapping study</td>
<td></td>
<td></td>
<td></td>
<td>Q-values, isomers</td>
<td></td>
<td></td>
<td>dressed ions, highest precision</td>
</tr>
<tr>
<td><strong>Half-lives</strong></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></td>
<td></td>
<td>nuclear periphery</td>
</tr>
<tr>
<td><strong>Matter radii</strong></td>
<td>interaction x-sect</td>
<td>matter radii</td>
<td>matter density distributions</td>
<td>matter radii from absorption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Charge radii</strong></td>
<td></td>
<td></td>
<td></td>
<td>charge density distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mean square radii</td>
</tr>
<tr>
<td><strong>Single-particle structure</strong></td>
<td>high resolution, angular momentum</td>
<td>complete kinematics, neutron detection</td>
<td>low momentum transfers</td>
<td></td>
<td></td>
<td>high-resolution spectroscopy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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

B. Sharkov
Technical Challenges: contributions by partner countries

Remote Handling

Target & Beam Catcher

Cryogenics

SC Multiplets

SC Dipoles

Radiation Resistant Magnets

Driver Accelerator

B. Sharkov
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

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

**Magnetic moments**
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

Length 442 m
Rigidity 50 Tm

4π detector PANDA Detector
<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Croatia</td>
<td>RBI, Zagreb, Split Univ.</td>
</tr>
<tr>
<td>China</td>
<td>CCNU Wuhan, Tsinghua Univ., USTC Hefei</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>Cas, Rez, Techn. Univ. Prague</td>
</tr>
<tr>
<td>France</td>
<td>IPHC Strasbourg</td>
</tr>
<tr>
<td>Hungary</td>
<td>KFKI Budapest, Budapest Univ.</td>
</tr>
<tr>
<td>Norway</td>
<td>Univ. Bergen</td>
</tr>
<tr>
<td>India</td>
<td>Aligarh Muslim Univ., Panjab Univ., Rajasthan Univ., Univ. of Jammu</td>
</tr>
<tr>
<td></td>
<td>Univ. of Kashmir, Univ. of Calcutta, B.H. Univ. Varanasi, VECC Kolkata</td>
</tr>
<tr>
<td></td>
<td>SAHA Kolkata, IOP Bhubaneswar, IIT Kharagpur, Gauhati Univ.</td>
</tr>
<tr>
<td>Korea</td>
<td>Korea Univ. Seoul, Pusan Nat. Univ.</td>
</tr>
<tr>
<td>Germany</td>
<td>Univ. Heidelberg, P.I., Univ. Heidelberg, KIP, Univ. Heidelberg, ZITI</td>
</tr>
<tr>
<td></td>
<td>Univ. Frankfurt IKF, Univ. Frankfurt, FIAS, Univ. Münster, FZ Dresden, GSI Darmstadt, Univ. Wuppertal</td>
</tr>
<tr>
<td>Korea</td>
<td>Korea Univ. Seoul, Pusan Nat. Univ.</td>
</tr>
<tr>
<td>Portugal</td>
<td>LIP Coimbra</td>
</tr>
<tr>
<td>Romania</td>
<td>NIPNE Bucharest, Univ. Bucharest</td>
</tr>
<tr>
<td>Russia</td>
<td>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.</td>
</tr>
</tbody>
</table>

The CBM Collaboration: 55 institutions, 450 members
Studies of hadronic matter at high densities

Motivation for NN collisions at 2-40 AGeV

Relativistic Nuclear Physics

- Optimum production of baryons with strange quarks
- Maximum compression in heavy-ion collisions
- Threshold for strange quarks
- Threshold for antiprotons
- Threshold for charm quarks

SIS 100/300

SIS

AGS

CERN SPS

Nuclear matter density (blue curve)

Rel. production of strange quarks (red curve)

Ion energy [AGeV]
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**

Temperature and pressure address with heavy-ion collisions

B. Sharkov
The evolution of the fireball

$\pi, K, \Lambda, \ldots$

$\rho, \Lambda$

$\varphi, \Xi, \Omega$

$\rho \rightarrow e^+e^-, \mu^+\mu^-$

resonance decays

... using multistrange particles: equation of state at high baryon densities
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
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: \(T: \text{up to } 10\ \text{eV} \quad \rho: \sim \text{solid} \quad P: \text{up to } 1\ \text{Mbar}\)
Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of matter in reproducible experimental conditions.

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

\[ \frac{dE}{dx} \sim -\rho \frac{Z^2}{E_i} \ln \Lambda \]

Intense Heavy Ion Beams

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

**HI**: High entropy states of matter - without shocks!
Intense particle beams are a novel, very efficient tool to study HEDP and WDM:


Main Advantages of Ion Beams are:

- High repetition rate, high coupling efficiency
- Large sample size [mm³ cm³]
- 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)
SIS-100: One beam line with replaceable elements:

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

Transverse distributions of beam intensity at focal plane for LAPLAS

HIHEX experiments
beam shaping system

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

Motivation

- Jupiter
- Sun Surface
- Magnetic Fusion
- Laser Heating
- PHELIX
- Inertial Confinement Fusion
- SIS 18
- SIS 100
- Sun Core
- SIS
- Inertial Cofinment Fusion
- Strongly-coupled plasmas
- Ideal plasmas
- Solid state density
- Density [cm\(^{-3}\)]
- Temperature [eV]

B. Sharkov
### 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>SIS-18</th>
<th>SIS-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/ion</td>
<td>400MeV/u</td>
<td>0.4-27 GeV/u</td>
</tr>
<tr>
<td>Number of ions</td>
<td>4.10^9 ions</td>
<td>5.10^{11} ions X100</td>
</tr>
<tr>
<td>Full energy</td>
<td>0.06 kJ</td>
<td>6 kJ</td>
</tr>
<tr>
<td>Beam duration</td>
<td>130 ns</td>
<td>50 ns</td>
</tr>
<tr>
<td>Beam power</td>
<td>0.5 GW</td>
<td>0.1TW X200</td>
</tr>
</tbody>
</table>

**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**

<table>
<thead>
<tr>
<th><strong>HIHEX</strong></th>
<th><strong>LAPLAS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Heavy Ion Heating and Expansion</em></td>
<td><em>Laboratory Planetary Sciences</em></td>
</tr>
</tbody>
</table>

- 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

Vladimir Fortov