FAIR – Facility for Antiproton and Ion Research

Thomas Nilsson
FAIR-NUSTAR BR chair/spokesperson
Board of FAIR Collaborations

16th Lomonosov Conference on Elementary Particle Physics –
Moscow State University 2013-08-23
Oct 4th 2010 – a FAIR (GmbH) is born

Signing of the **FAIR Convention** by representatives of the founding countries **Finland, France, Germany, India, Poland, Romania, Russia, Slovenia, Sweden** in Wiesbaden

[Image of FAIR convention signing]
Facility for Antiproton & Ion Research

Nuclear Structure & Astrophysics (Rare-isotope beams)

Hadron Physics (Stored and cooled 14 GeV/c anti-protons)

QCD-Phase Diagram (HI beams 2 to 45 GeV/u)

Fundamental Symmetries & Ultra-High EM Fields (Antiprotons & highly stripped ions)

Dense Bulk Plasmas (Ion-beam bunch compression & petawatt-laser)

Materials Science & Radiation Biology (Ion & antiproton beams)

Accelerator Physics

16th Lomonosov Conference - MSU
## Accelerator Challenges

<table>
<thead>
<tr>
<th>Compact &amp; cost effective accelerators</th>
<th>Fast acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast cycling superconducting magnets dB/dt ~ 4T/s</td>
<td>High gradient, variable frequency Ferrite &amp; MA loaded cavities</td>
</tr>
</tbody>
</table>

**XHV @ high beam intensities**
Extremely high vacuum ~$10^{-12}$ mbar

**Precision beams**
Electron & stochastic cooling

**Major contributions by Russian laboratories (JINR, BINP, …)**
Experiments
Anti-Proton Annihilation @ DA

Two body thresholds
Molecules
Gluonic Excitations
Hybrids
Hybrids + Recoil
Glueballs
Glueballs + Recoil
$q\bar{q}$ Mesons

$q\bar{q}$

$\Lambda, \Sigma, \Xi, \Omega, D, D_s, D_s, \Lambda_c, \Sigma_c, \Xi_c, \Omega_c, \Omega_c$ etc.

$\tilde{q} \bar{q}$ Momentum [GeV/c]

0 2 4 6 8 10 12 15

Mass [GeV/c^2]

1 2 3 4 5 6

$\Lambda\Lambda, \Sigma\Sigma, \Xi\Xi, \Omega\Omega$ etc.

Hybrid (q\bar{g})

Glueball (gg)

PANDA

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QCD well understood at high $Q^2$
Emergence of eff. DoF at low $Q^2$
Study of the *strong interaction* in the transition region
Phenomena appear that are hard to predict from QCD: e.g. confinement, nature of hadrons, hadronic masses…

*Courtesy J. Ritman*
Exotics production in pp collisions

Production: all $J^{PC}$ accessible

Exotic $J^{PC}$ would be clear signal

Hybrids

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>1$^{++}$</th>
<th>1$^{+-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{1}S_{0}$, 0$^{-+}$</td>
<td>1$^{++}$</td>
<td>1$^{-}$</td>
</tr>
<tr>
<td>$^{3}S_{1}$, 1$^{-}$</td>
<td>0$^{+}$</td>
<td>0$^{-}$</td>
</tr>
</tbody>
</table>

Exotic $J^{PC}$ would be clear signal

G.Bali, EPJA 1 (2004) 1 (PS)
Charmonium Spectroscopy
QCD Exotics
Hypernuclear physics
Charm in nuclear matter
The PANDA Collaboration

517 Members from
67 Institutes
18 Countries
Australia, Austria, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, The Netherlands, USA, UK
Experiments

CBM

APPA

PANDA

Super-FRS

NUSTAR
What is the structure of compact stars?

**Quark Star**
- Quark Matter Core

**Neutron Star**
- **Surface:** Hydrogen/Helium plasma, Iron nuclei
- **Outer Crust:** Ions, Electron gas
- **Inner Crust:** Heavy ions, Relativistic electron gas, Superfluid neutrons
- **Outer Core:** Neutrons, protons, Electrons, muons
- **Inner Core:** Neutrons, Superconducting protons, Electrons, muons, Hyperons (Σ, Λ, Ξ), Deltas (Δ), Boson (π, K) condensates, Deconfined (u,d,s) quarks / color-superconducting quark matter
What is the structure of compact stars?

What is the origin of the mass of the hadrons which determine the visible mass of the universe?
What is the structure of compact stars?

What is the origin of the mass of the hadrons which determine the visible mass of the universe?

Why do we not observe individual quarks, the elementary building blocks of matter?
Fundamental Questions of (QCD-) Physics

- What is the structure of compact stars?
- Why do we not observe individual quarks, the elementary building blocks of matter?
- What is the origin of the mass of the hadrons which determine the visible mass of the universe?
- What are the properties and the degrees-of-freedom of nuclear matter under extreme conditions (high temperature and/or high density)?

Courtesy P. Senger
Exploring the QCD phase diagram

Probing the QCD diagram at very high $T$ and $\rho_B \sim 0$ (early universe):
ALICE, ATLAS, CMS at LHC
STAR, PHENIX at top RHIC energies

Probing the QCD diagram at moderate $T$ and very high $\rho_B$:
Beam energy scan at RHIC, NA61 at CERN SPS, CBM at FAIR, MPD at NICA
Exploring the QCD phase diagram

Baryon density in central Au+Au collisions

SIS100

Courtesy P. Senger
The Compressed Baryonic Matter Experiment

- Dipole magnet
- Ring Imaging Cherenkov Detector
- Transition Radiation Detectors
- Resistive Plate Chambers (TOF)
- Electro-magnetic Calorimeter
- Silicon Tracking Stations
- Micro-Vertex Detector
- Dipole magnet
- Projectile Spectator Detector (Calorimeter)
- Resistive Plate Chambers (TOF)
The CBM Collaboration: 58 institutions, 500 members

Croatia:
RBI Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
Münster Univ.
Tübingen Univ.
Wuppertal Univ.

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
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.

Romania:
NI PNE Bucharest
Univ. Bucharest

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

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

20th CBM International Collaboration Meeting
24 - 28th September 2012
Variable Energy Cyclotron Centre
Kolkata, India
Experiments

CBM

APPA

PANDA

Super-FRS

NUSTAR
Which are the nuclei relevant for astrophysical processes and what are their properties?

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

**r-process:**
- masses, half-lives
- \(\beta\)-delayed neutron emission
- \((\gamma,n), (n,\gamma)\) rates
- shell structure

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

Combine accurate nuclear physics with precision astronomy to **constrain astrophysical scenarios**
Open questions

• What are the limits for existence of nuclei?
  • Where are the proton and neutron drip lines situated?
  • Where does the nuclear chart end?
• How are complex nuclei built from their basic constituents?
  • What is the effective nucleon-nucleon interaction?
  • How does QCD constrain its parameters?
How does the nuclear force depend on varying proton-to-neutron ratios?

Shell quenching and reordering:
Transition from SO gaps (50,82,126) to HO gaps (40,70,112)

Softening of the nuclear potential:
High-l pushed upward and Spin-Orbit splitting reduced

A. Ozawa et al. PRL 84 (2000) 5493
T. Otsuka et al., PRL 87(2001)082502
How to explain collective phenomena from individual motion?

- **stable**
  - $r_p = r_n$, $\rho_0 = 0.17 fm^{-3}$
  - $d_p = d_n = \text{const} \approx 1 fm$

- **halo**
  - $r_p \neq r_n$
  - $d_p \neq d_n$

- **skin**
  - $r_p \neq r_n$
  - $d_p = d_n$

- **132Sn**
  - Soft mode discovered at GSI
  - 9.8 MeV

- **Halos**
- **Neutron Skins**
- **Pygmy Resonance**
- **Neutron stars**
- **EOS**

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### The Collaboration

- **Scientists**: > 800
- **Institutes**: 146
- **Countries**: 38

### The Approach

Complementary measurements leading to consistent answers

### The Investment

- **Super-FRS**: 82 M€
- **Experiments**: 73 M€

### The Project

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-FRS</td>
<td>RIB production, identification and high-resolution spectroscopy</td>
</tr>
<tr>
<td>DESPEC</td>
<td>$\gamma$, $\beta$, $\alpha$, p-, n-decay spectroscopy</td>
</tr>
<tr>
<td>HISPEC</td>
<td>in-beam spectroscopy at low and intermediate energy</td>
</tr>
<tr>
<td>ILIMA</td>
<td>masses and lifetimes of nuclei in ground and isomeric states</td>
</tr>
<tr>
<td>LASPEC</td>
<td>Laser spectroscopy</td>
</tr>
<tr>
<td>MATS</td>
<td>in-trap mass measurements and decay studies</td>
</tr>
<tr>
<td>R$^3$B</td>
<td>kinematically complete reactions at high beam energy</td>
</tr>
<tr>
<td>ELISE</td>
<td>elastic, inelastic, and quasi-free $e^-A$ scattering</td>
</tr>
<tr>
<td>EXL</td>
<td>light-ion scattering reactions in inverse kinematics</td>
</tr>
</tbody>
</table>
SUPERconducting FRAGMENT Separator

Transmission

Focusing System

Projectile Fission

Spectrometer / Energy Buncher

Main-Separator

Low-Energy Branch

High-Energy Branch

Ring Branch

Pre-Separator

Degrader 1

Degrader 2

Exit Slit Pre-Separator

Beam Dumps

Production Target

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NUSTAR - The Facility

Beam intensity improvement
FRS - Super-FRS: $10^2$ to $10^5$!

Low Energy Branch:
HISPEC, DESPEC, MATS, LASPEC

High Energy Branch: R$^3$B

Ring Branch: EXL, ILIMA, ELISE
PreSPEC-AGATA Set-up = Early Implementation of HISPEC

relativistic radioactive heavy-ions from the GSI Fragment Separator
Up to 1GeV/A $^{238}$U, 50% v/c

Advanced Gamma-ray Tracking Array (AGATA)
up to $5 \times 2 + 10 \times 3 = 40$
segmented HP Ge-crystals
$d \sim 20 \text{ cm}$
$\varepsilon_p \approx 17\%$
$\Delta E \approx 0.4\%$

Lund-Cologne-York Calorimeter (LYCCA)
A and Z particle-ID after secondary target by means of
-x,y tracking
- $\Delta E - E$ (Si-CsI)
- $\Delta t$ (plastic)

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The (early) 2012 Set-up in Reality

LYCCA  AGATA  HECTOR
Reactions with Relativistic Radioactive Beams

Superconducting Dipole:
Ready for installation in 2013
Construction by CEA Saclay

R3B Start version 2016

R3B

R3B-Si-TRACKER

R3B GLAD
Superconducting Dipole:
Ready for installation in 2013
Construction by CEA Saclay

NeuLAND

CALIFA

R3B from Super-FRS

Heavy fragments

Protons
CR perspective view

debuncher cavities
Schottky pickup
TOF Detectors
stochastic cooling

injection/extraction kickers

from F. Nolden
Potential for new masses with ILIMA

masses measured at the FRS-ESR

r-process path

nuclides with known masses

stable nuclei

will be measured with Super-FRS-CR

more beam (x1000)
more efficiency (x10)
more sensitivity: upgraded ToF and Schottky detectors

from Yu.A. Litvinov
NUSTAR Week Kolkata Oct 2012

> 800 scientists
146 institutes
38 countries
Experiments

CBM

APPA

PANDA

Super-FRS

NUSTAR
Atomic Physics, Plasma Physics, Bio Physics and Materials Research

Research Focus

Matter under Extreme Conditions & Extreme States of Matter

- Highest Charge States
- Relativistic Energies
- High Intensities
- High Charge at Low Velocity
- Low-Energy Anti-Protons

Extreme Static Fields
Extreme Dynamical Fields and Ultrashort Pulses
Very High Energy Densities and Pressures
Large Energy Deposition
Antimatter Research
Atomic Physics, Plasma Physics, Bio Physics and Materials Research

**SPARC**
- SP: R. Schuch
- 302 scientists
- 83 institutions
- 26 countries

**BIOMAT**
- SP: M. Durante C. Trautmann
- 136 scientists
- 70 institutions
- 20 countries

**HEDgeHOB**
- SP: D. Varentsov
- 175 scientists
- 43 institutions
- 14 countries

**APP**
- > 500 scientists
- > 90 institutions
- > 30 countries

**FLAIR**
- SP: K. Blaum
- 144 scientists
- 49 institutions
- 15 countries

**WDM**
- SP: F. Rosmej
- 71 scientists
- 24 institutions
- 8 countries

> 500 scientists
> 90 institutions
> 30 countries
> 90 institutions
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> 30 countries
> 90 institutions
> 30 countries
> 90 institutions
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> 500 scientists
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MSV for APPA (Status 2012): The Facilities

CRYRING: Cold Low-Energy Heavy Ions and Anti-Protons

HESR: Cold Relativistic Heavy Ions

Unique physics opportunities !!! ☺
QED in the non-perturbative regime
Correlated multi-body dynamics for atoms and ions
Precision determination of fundamental constants
Influence of atomic structure on nuclear decay properties
Fundamental physics and antimatter

Intense Laser

Positive Continuum
Transfer
Excitation
Ionization
Free Pair Production

Negative Energy Continuum

© Courtesy Th. Stöhlker
Plasma Physics at FAIR

Interaction of ions and photons with plasmas
Equation of state, phase transitions, transport phenomena
Matter under high pressure
Coupling of intense light with matter

Warm Dense Matter
- $T \sim 0.2 - 10$ eV
- $\rho \sim$ solid density
- $P \sim$ kbar, Mbar

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

Courtesy Th. Stöhlker
Plasma Physics with Intense Ion Beams

Relevant for astrophysics, planetary science, inertial confinement fusion research, research on materials under extreme conditions. Measurements are required for guidance of theoretical models.

Temperature [eV]

Degeneracy

\[ E_{\text{kin}} = kT = E_{\text{Fermi}} \]

Strongly coupled plasmas, \( \Gamma = \frac{E_C}{E_{\text{kin}}} > 1 \)

Courtesy Th. Stöhlker
## Staging

### Start Version Phase A (SIS100)

<table>
<thead>
<tr>
<th>Module 0</th>
<th>Module 1</th>
<th>Module 2</th>
<th>Module 3</th>
<th>Module 4</th>
<th>Module 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS100</td>
<td>Exp. halls</td>
<td>Super-FRS</td>
<td>Antiproton Facility</td>
<td>LEB, NESR, FLAIR</td>
<td>RESR</td>
</tr>
<tr>
<td></td>
<td>CBM &amp; APPA</td>
<td>NuSTAR</td>
<td>NuSTAR &amp; options NuSTAR</td>
<td>NuSTAR &amp; APPA</td>
<td>PANDA, NuSTAR &amp; APPA</td>
</tr>
</tbody>
</table>

### Phase B (SIS300)

2018

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## Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerators and personnel (including Super-FRS)</td>
<td>502 M€</td>
</tr>
<tr>
<td>Civil construction (excluding site related costs)</td>
<td>400 M€</td>
</tr>
<tr>
<td>FAIR contribution to experimental end stations *</td>
<td>78 M€</td>
</tr>
<tr>
<td>FAIR GmbH personnel &amp; running until 2018 (&gt;8 years)</td>
<td>47 M€</td>
</tr>
<tr>
<td><strong>Grand Total MSV, Modules 0 - 3</strong></td>
<td>1027 M€</td>
</tr>
</tbody>
</table>


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(inflation escalation until 2018: ca. +50%)
## FAIR Member States

<table>
<thead>
<tr>
<th>Contracting Party</th>
<th>Contribution (in 2005 €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finland</td>
<td>5.00</td>
</tr>
<tr>
<td>France</td>
<td>27.00</td>
</tr>
<tr>
<td>Germany</td>
<td>705.00</td>
</tr>
<tr>
<td>India</td>
<td>36.00</td>
</tr>
<tr>
<td>Poland</td>
<td>23.74</td>
</tr>
<tr>
<td>Romania</td>
<td>11.87</td>
</tr>
<tr>
<td>Russia</td>
<td>178.05</td>
</tr>
<tr>
<td>Slovenia</td>
<td>12.00</td>
</tr>
<tr>
<td>Sweden</td>
<td>10.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,008,66</strong></td>
</tr>
</tbody>
</table>

- **All numbers in 2005 €** (escalation until 2018 ca. +50%)
- **UK Associate Member** since 3/5/13
- **Spain expected to join soon as a full member**
- **Talks with China on Associate FAIR Member status**
- **Talks with Italy**
- **Additional contributions to experiments by many countries**
Civil Construction

Synchrotrons: 1.1 km
HESR: 0.6 km
With beamlines: 3.2 km

Total area > 200 000 m²
Area buildings ~ 98 000 m²
Usable area ~ 135 000 m²
Volume of buildings ~ 1 049 000 m³
Substructure: ~ 1500 pillars, up to 65 m deep

Existing SIS 18

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Bird’s View

Courtesy G. Rosner

16th Lomonosov Conference - MSU
...closing in

Courtesy G. Rosner

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Timeline

- 2011: Submission of building permits
- 2012: Site preparation
- 2013: Civil construction contracts
- 2014: Building of accelerator & detector components
- 2015: Completion of civil construction work
- 2016: Installation & commissioning of accelerators and detectors
- 2017: Start data taking

Courtesy G. Rosner
Conclusions

- The FAIR facility is that will offer world-wide unique research opportunities
  - plasma, atomic, nuclear and subnuclear physics
  - a truly international infrastructure
- Construction of the start version has commenced
  - Excellent potential for going to the full version and beyond