An International Facility for Antiproton and Ion Research in Europe

Hans H. Gutbrod, GSI Darmstadt
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
Accelerated Heavy Ions

- .. make possible production of matter under extreme temperature and density similar to matter
  - in the Early Universe $10^{-3}$ s to $10^{-6}$ s after the Big Bang,
  - in supernovae and neutron stars
  - in the interior of planets or in the Sun

- .. are excellent tools for making rare isotopes far off stability by fragmentation to study nucleo-synthesis, nuclear structure and astrophysics

- .. are the only tool for making new chemical elements, i.e. superheavy elements

.. allow highest energy deposition in materials

.. or in tumors with millimeter precision

Ion Therapy
Heavy Ion **Intensity** Frontier

- **GSI:** 1995 → 2009 ?
- **RIKEN:** 2009 → 2012 ?
- **FAIR:** 2012 → 2012 ?

Heavy Ion **Energy** Frontier

- **CERN SPS:** 1985 → 2005
- **RHIC:** 1998 → 2010 ?
- **CERN LHC:** 2008 → 2020 ?

*Europe* x 1000

*Japan*
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 after slowing down to 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
Antiproton Facilities

Intensity Frontier

FNAL: 1983 ➔ 2009 ?

USA

Europe

CERN SPS: 1981 ➔ 2006

FAIR: 2013/4 ➔ 20??

Europe

Unique features:
- e⁻ cooling
- Storage
- In-ring experiments

Japan

J-PARC

2009 ➔ 20??
In 2015, 8 years and 1187 Million € later

GSI GmbH + FAIR GmbH

Observers

CN DE ES FI FR GB GR IN IT PL RO RU SE

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FAIR – Facility for Antiproton and Ion Research

GSI GmbH

FAIR GmbH
Accelerator Physics and Key Technologies for FAIR

- **High gradient, low frequency RF cavities**
  - CR compressor cavity

- **Novel lattice/collimation design**: Beam optics studies
  - Control of stripping losses

- **Superconducting, fast ramping synchrotron magnets**: 4T/s
  - SIS 100 dipole magnet

- **Fast stochastic and electron cooling**
  - HESR e-cooler

- **Ultra high vacuum for intense beams**
  - Desorption test-stand

- **SIS 300 dipole magnet**
SC magnets for SIS300: France, Italy and GSI

- INFN
- IN2P3
- BNL follow up of „GSI001“ 4 T, 1 T/s
- SC cable development
- Curved dipole prototype
- SIS300 Quadrupole Field calculations, Design, cryogenics
FAIR accelerator developments in Russia and Spain

**BINP Novosibirsk**

**IHEP Protvino**

**Rosatom**

**JINP Dubna**

**UNK dipole**

**IHEP Protvino Rosatom**

- Magnet,
- power converters,
- vacuum components on sc magnets for NESR/RESR

**SIS300**

**SIS100**

**Short NUCLOTRON-type prototyp at GSI**
FAIR accelerator developments in China and India

Institute of High Energy Physics, Chinese Academy of Sciences

Institute for Modern Physics, Lanzhou

Institute for Plasma Physics, Hefei

Superferric dipoles for Super-FRS and CR and high intensity beam stoppers

Variable Energy Cyclotron Center, Kolkata

Center of Advanced Technology, Indore

Saha Institute of Nuclear Physics, Kolkata
**HESR Consortium FZ Jülich, TSL Sweden and PANDA experiment collaboration**

Collaboration

>350 participants

10⁷ events/s

**TSL**

- 30 m cooling length
- Pelletron
- Electron energy 4 - 8 MeV

1.4 m

30 m cooling length

**PANDA**
FAIR – Planned Experimental Facilities

- UNILAC
- SIS 18
- SIS 100/300
- ESR
- RESR
- CR
- NESR
- Super FRS
- HESR
- Super FRS
- NESR
Research Communities at FAIR

Plasma Physics: \( \times 600 \)
higher target energy density 600kJ/g

Hadron Physics with antiprotons of 0 - 15 GeV

Nuclear Matter Physics with 35-45 GeV/u HI beams, \( \times 1000 \)

Hadron Physics with antiprotons of 0 - 15 GeV

Special Features:
- 50ns Bunched beams
- Electron cooling of secondary beams
- SC magnets fast ramping
- Parallel operation

Nuclear Structure & Astrophysics with rare isotope beams, \( \times 10,000 \) and excellent cooling

High EM Field (HI)
Fundamental Studies (HI & p)
Applications (HI)
Up to 4 fold Parallel Operation at FAIR!
EU support for FAIR related activities in FP6

**EU-6FP-CNI:**
⇒ FAIR injector SIS18 intensity upgrade, HADES upgrade + R3Bmagnet
EU-Support: 10,4 M€

**EU-6FP-Design Study:**
⇒ Secondary Beams (RIB and Antiprotons)
EU-Support: 9 M€

**EU-6FP-I3 programmes**
⇒ I3HadronPhysics: FAIR related
EU-Support: 10,8 M€
⇒ EURONS: FAIR related
EU-Support: 2 M€
Baseline Technical Report

Official FAIR project description

6 Volumes with more than 3500 pages, more than 2600 authors
and 17 experiment collaborations

For download of the report:

http://www.gsi.de/fair/reports/btr.html
UK in FAIR experiments (as of March 2005)

No graduate students, nearly no post docs
Present Committee Structure of the International Project FAIR

13 potential 'Member states'

ISC
International Steering Committee

STI Working Group
Scientific + Technical Issues

PAC QCD
PAC NUSTAR
PAC APPA
TAC
CORE
Cost Review Groups

Mini-TACs
- Cryogenics
- Warm magnets
- Cold magnets
- Power Supplies
- Beam Instrumentation
- p-Linac

AFI Working Group
Administrative + Funding Issues

LFI
Legal Framework Issues

FCI
Full Cost Issues

Observers:

CN DE ES FI FR GB GR IN IT PL RO RU SE
DRAFT: FAIR Joint Core Team

Council - Shareholders assembly

- Scientific Council
- Finance Committee
- Management team [2]
  (directors office)
  - Member-States relations [2]
  - Safety
  - Audit & Controlling
  - Public relations
  - EU projects [1]

Management (Team Leader) [1]

External Committees:
Scientific Advisory Committees
Accelerator Advisory Committee
Resource Review Boards

Research [4]
- Visitors science prog.
- NUSTAR
- Resource coordinator
- Technical coordinator
- PANDA
- CBM
- APPA

Accelerator [6]
- HESR
- NESR
- RESR/CR
- SES100
- SES300
- HEBT
- Super-FRS
- p-LINAC
- p-Bar
- TARGET
- Injector Upgrade

Integration [1]
- Mech. & Electr. Interfacing
- Accelerator Interfacing
- Experiment Interfacing
- Documentation and Quality management

Integration
- Project Coordination
- Planning
- Regulatory aspect & Permits

Integration

Research

Accelerator

Functions to be taken over by the Core Team are marked in orange. Numbers in brackets indicate FTE at startup. Where a one-to-one assignment between personnel and function is not yet reasonable or where one person is going to fill more than one function, only the leading box is indicated in orange (e.g. Accelerator).
The dashed line to the Administration indicates that the Administration branch is not intended to belong to the proper Core Team in the sense of line management (cf. text).
Proposed FAIR – Roadmap: Establishment of FAIR GmbH

**Contracting Parties**

- **ISC**
  - Negotiations (ongoing, 'till end of 2006)
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR GmbH structure and kick-off staffing

- **STI**
  - Monitoring of technical planning and project costs (ongoing process up to the formation of FAIR GmbH)

- **AFI**
  - Mandate for IKAB
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR structure

- **Joint Core-Team**
  - Technical project decisions (follow up design changes) / FAIR preparation tasks (ongoing process up to the formation of FAIR GmbH)

- **IKAB**
  - Technical evaluation of potential in-kind contributions (ongoing process up to the formation of FAIR GmbH)

**Shareholders**

- **ISC**
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR GmbH structure and kick-off staffing

- **STI**
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR structure

- **AFI**
  - Bylaws, draft FAIR structure
  - Convention, Final Act, AoA; Joint Core Team

- **Joint Core-Team**
  - Technical project decisions (follow up design changes) / FAIR preparation tasks (ongoing process up to the formation of FAIR GmbH)

**Bylaw Subgroup**

- **ISC**
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR structure

- **STI**
  - Convention, Final Act, AoA; Joint Core Team
  - Bylaws, draft FAIR structure

- **AFI**
  - Bylaws, draft FAIR structure
  - Convention, Final Act, AoA; Joint Core Team

- **Joint Core-Team**
  - Technical project decisions (follow up design changes) / FAIR preparation tasks (ongoing process up to the formation of FAIR GmbH)

**IKAB**

- Technical evaluation of potential in-kind contributions (ongoing process up to the formation of FAIR GmbH)
Status of technical discussions for identifying commitments for accelerator parts

No commitments exist on in-kind contributions, besides Sweden for Cryring, but some verbal expressions of interest:

• CN-China: Interest expressed verbally for design and construction of CR and Super-FRS dipoles
• DE-Germany: GSI: items to be specified, presently working on all frontiers
  FZ-Jülich: HESR design and construction together with Sweden
• ES-Spain: Dipoles NESR and RESR, power supplies, vacuum, *if superconducting!*
• FI-Finnland: items to be specified,
• FR-France: items to be specified (design of SIS300 quadrupoles), *techn. meetings postponed*
• GB-United Kingdom: items to be specified, *meeting foreseen October 12th.*
• GR- Greece: items to be specified, no contact so far
• IN-India: Energy Buncher (4x 80 t sc dipoles), beam stoppers, MoU, *next techn. meeting November 2-4*
• IT-Italy: Curved SIS300 dipoles proposed verbally, *R&D MoU*
• PL-Poland: items to be specified
• RO-Rumania: items to be specified
• RU-Russia: SIS100 magnets, SIS300 magnets, e^-RIB collider, prototyping of 2 SIS100 magnets
  *Rosatom minister Kirienkov requested to be contacted by German minister*
• SE-Sweden: Cryring, part of Electron Cooler for HESR, other items to be specified
## FAIR: major work packages

### FAIR WPs

<table>
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<tr>
<th>CostBook 3.0 (MD)</th>
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<td>WBS 2.3</td>
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<td>NESR</td>
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<tr>
<td>1.0 Experiments</td>
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</table>

### TS-2 Magnets

| Bend   | China  | 12.2 |
| Bend   | GSI    | 15   |
| Bend   | S & G  | 4    |
| Bend   | 0,22   | 7    |
| Bend   | 0,7    | 4    |
| Bend   | 4      |      |
| Bend   | 24     |      |
| Bend   | S & G  |      |

### TS-3 Power Converter

<table>
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<tbody>
<tr>
<td>TS-4 RF-System</td>
<td>TS-5 Inj/Extraction</td>
<td>TS-6 Diagnostics</td>
<td>TS-7 Vacuum</td>
<td>TS-8 Part. Sources</td>
<td>TS-9 ECOOL</td>
<td>TS-10 St. Cooling</td>
<td>TS-11 Special inst.</td>
<td>TS-12 Local Cryo</td>
<td>TS-14 Common System</td>
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<td>Vacuum</td>
<td>ECOOL</td>
<td>St. Cool</td>
<td>St. Cool</td>
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<td>Local Cryo</td>
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<td>Local Cryo</td>
<td>GSI</td>
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<td>1,3</td>
<td>0,7</td>
<td>49</td>
<td>0,8</td>
<td>6,3</td>
<td>3,1</td>
<td>12</td>
<td>GSI</td>
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</tbody>
</table>

### WP for discussion

- Magnet QC: 49 GSI
- Alignment: 5,5 GSI
- El. Power: 16 GSI

### Intention to take WI

- Controls/Interfaces: 24 GSI
- Quench Detection: 2,1
International FAIR Project: the Intensity Frontier

Key Technologies

- Beam cooling
- Rapidly cycling superconducting magnets
- Narrow bunching of beams

Primary Beams

- **All elements** up to Uranium
- Factor 100-1000 over present intensity
- **50ns bunching**

Secondary Beams

- **Rare isotope beams** up to a factor of 10 000 in intensity over present
- Low and high energy antiprotons

Storage and Cooler Rings

- Rare isotope beams
- **e−** Rare Isotope collider
- **10^{11}** stored and cooled antiprotons for Antimatter creation
Nuclear synthesis, structure and Astrophysics

• How are heavy nuclei produced?
• What is their half-life?
• What is their mass?
• Where is the limit of stability?
How are nuclei made?

Exotic Doubly Magic Nuclei

Neutron-rich nuclei from Fragmentation and In-Flight Fission

100 Sn
Discovered at GSI
7 atoms in 280 h
SIS 300  2/s

132 Sn
SIS 300  10^8/s

Ni

48 Ni
Discovered at GANIL
SIS 300  35/h

56 Ni
SIS 300  10^9/s

78 Ni
Discovered at GSI
3 atoms in 130 h
SIS 300  8/s

r-process
The In-Flight Rare-Isotope Beam Facility 0 - 1500 AMeV

- Superconducting FRagment Separator
- High-Energy Reaction Setup
- Multi-Storage Rings (CR, NESR, eA)
- Energy-Bunched Stopped Beams

Key characteristics:
- all elements, H to U
- intensity > $10^{12}$ ions/sec.
- high and low energies
- pulsed and CW beams
Plasma Physics

• Interior of massive planets like Jupiter
  ..do we understand the interior of planets?

• Warm and dense plasmas
  ...Equation of State, etc.,

• Energy production through Inertial Confinement Fusion:
  ..do we understand the basic physics problems?
ΔE Energy loss of heavy ions in hot plasma is larger than in cold matter

Expected Beam Parameters
SIS 100 (GSI)
\( N = 2 \times 10^{12} \) Uran
\( E_0 = 1 \) GeV/u
\( E_{\text{tot}} = 80 \) kJ
\( \tau = 50 \) ns
Range in solid Pb \( \approx 1.55 \) cm
beam radius \( \approx 0.05 \) cm
\( E_s = 600 \) kJ/g
\( P_s = 12 \) TW/g
Plasma Physics with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures

Motivation
Stage 1
(2007-2011)

Radioactive beam physics

- Nuclear structure and nuclear astrophysics
- Atomic physics studies with highly charged/radioactive ions & plasma physics
Stage 2
(2011-2013)

Proton-antiproton physics

• QCD studies with protons and antiprotons
• Precision studies with antiproton beams addressing fundamental symmetries and interactions
• 1-10AGeV relat. heavy ion beams for atomic and nuclear collision studies, e.g. with HADES
## FAIR Baseline Cost

### CORE Evaluation and TAC recommendation

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Amount (M€)</th>
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<tbody>
<tr>
<td>Accelerators</td>
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<tr>
<td>Baseline Experiments **</td>
<td>180</td>
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<tr>
<td>Buildings &amp; Supply Systems</td>
<td>289</td>
</tr>
<tr>
<td><strong>Total Investments</strong></td>
<td>1002</td>
</tr>
<tr>
<td>Manpower (2400 MY)</td>
<td>185</td>
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<tr>
<td><strong>Total Project Construction Cost</strong></td>
<td><strong>1187</strong></td>
</tr>
</tbody>
</table>

75% of construction cost from Germany, 25% from member states

Operation costs shared among member states

**additional funding expected from 30 non-member states already involved in FAIR experiments**
**Estimated annual incidences of expenditure for construction**

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<td>Total annual expenditures</td>
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<td>65,0</td>
<td>134,0</td>
<td>171,0</td>
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<td>179,0</td>
<td>158,5</td>
<td>125,9</td>
<td>96,9</td>
<td>22,2</td>
<td>8,3</td>
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</table>
Key technology: Fast Cycling Synchrotrons

SIS100 magnets: 50 K yoke with superconducting coil (Nuclotron JINR Dubna)

Developments:
Reduction of AC losses during ramp,
achievements: 40 W/m -> 13 W/m
$B_{\text{max}} = 2 \text{T}, \frac{dB}{dt} = 4 \text{T/s}, f = 1 \text{ Hz}$

SIS 300 magnets: $\cos \theta$ - magnet

Developments:
Reduction of AC losses during ramping by improved cable and coil design
Efficient conductor cooling
$B_{\text{max}} = 6 \text{T}, \frac{dB}{dt} = 1 \text{T/s}$
(HERA: 4 mT/s, RHIC: 70 mT/s, LHC: 8 mT/s)

„GSI001“ 4 T, 1 T/s by BNL
Study of the Phase diagramm of strongly interacting Matter via Di-Leptons

RHIC, LHC: high temperature, low baryon density

FAIR SIS300: moderate temperature, high baryon density
FAIR Baseline Technical Report

Official FAIR project description

6 Volumes with more than 3500 pages and more than 2600 authors

Volume 2  Accelerator and Scientific Infrastructure

Volume 3A  Experiment Proposals on QCD Physics
  3.1  CBM

Volume 3B  Experiment Proposals on QCD Physics
  3.2  PANDA
  3.3  PAX
  3.4  ASSIA

Volume 4  Experiment Proposals on Nuclear Structure & Astro Physics (NUSTAR)
  4.1  LEB-SuperFRS
  4.2  HISPEC/DESPEC
  4.3  MATS
  4.4  LASPEC
  4.5  R3B
  4.6  ILIMA
  4.7  AIC
  4.8  ELISa
  4.9  EXL

Volume 5  Experiment Proposals on Atomic, Plasma & Applied Physics (APPA)
  5.1  SPARC
  5.2  HEDgeHOB
  5.3  WDM
  5.4  FLAIR
  5.5  BIOMAT

Volume 6  Civil Construction and Safety
Discovery of 6 new elements at GSI

<table>
<thead>
<tr>
<th>Bohrium</th>
<th>Hassium</th>
<th>Meitnerium</th>
<th>Darmstadtium</th>
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<tbody>
<tr>
<td>Element 112</td>
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</table>
Interior of neutron stars?
CBM Collaboration
More than 350 participants

10⁷ collisions/s requires new fast detectors and new information technology solutions
10x LHC experiment
The Proton Mass $\quad 938 \text{ MeV}$

much larger than

sum of the three constituent quarks:

$\sim 18 \text{ MeV}$

What creates the MASS of nucleons and of other subatomic particles?