Outline

1. Introduction
2. Major events and decisions
3. Civil construction – realization plan
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5. Progress achieved in the Accelerator Project
6. Progress of the Experiments
7. Research at GSI continues – beam time 2016 and recent research highlights
8. Intermediate research program FAIR Phase 0
9. Summary and outlook
FAIR Accelerator Complex
FAIR Accelerator Complex

**FAIR**

... accelerates particle beams from (anti)protons up to uranium ions with

- very high intensities
  - up to a factor of \(~100\) increase for primary Uranium beams (~ \(5 \times 10^{11}\) \(\text{U}^{28+}\) ions /s),
  - up to a factor of \(~10,000\) increase for secondary rare isotope beams
- high pulse power (up to \(~50\) kJ / 50 ns)
- suite of storage cooler rings equipped with stochastic and electron cooling for brilliant beam quality

... develops and exploits innovative particle separation and detection methods, as well as novel computing techniques

... to perform forefront experiments towards the production and investigation of

*New Extreme States of Matter.*
FAIR – the Universe in the Laboratory

CBM  
nuclear matter at high densities

APPA  
ions in extreme electro-magnetic fields

PANDA  
hadron physics with antiprotons

NUSTAR  
neutron-rich nuclei
FAIR – four research pillars

**APPA**
- Atomic Physics and Fundamental Symmetries,
- Plasma Physics,
- Materials Research,
- Radiation Biology,
- Cancer Therapy with Ion Beams / Space Res.

**CBM**
- Dense and Hot Nuclear Matter

**NUSTAR**
- Nuclear Structure far off stability,
  Physics of Explosive Nucleosynthesis (r process)

**PANDA**
- Hadron Structure & Dynamics with cooled antiproton beams
FAIR – four research pillars

- PANDA
- CBM
- NUSTAR
- Super-FRS

- APPA
- HESR
- SIS 100
- SIS100 EH
- Super-FRS

- FAIR – four research pillars
  - PANDA
  - CBM
  - NUSTAR
  - Super-FRS
International Participation in FAIR

- FAIR governed by international convention
  - 9 shareholders + 1 assoc. partner (orange)
- Scientists from all over the world are engaged
  - More than 200 institutions from 53 countries are involved with their scientists (orange + blue) → FAIR community growing
Major events and decisions ...

... Council decisions from September 2015

- Despite the cost increase in civil construction Council confirmed in June 2015 the goal to realise the FAIR facility as outlined in the Convention → Modularised Start Version (MSV)
- MSV to be completed by 2025
- In September 2015, the Shareholders committed to confirm the first tranche of additional funding in 2016; commitments for the second tranche are to be made by 2019
Major events and recent decisions in 2016

- Confirmation of most FAIR partners to cover their share in the additional cost for civil construction has been received; the remaining confirmations are expected soon.

13 September 2016: BMBF approved funding for the civil construction of FAIR northern site area

- 26 September and 22 November 2016: Inquiry and contracting of civil construction has started; first calls for tender for ground water lowering, trench sheeting, excavation and building shell for construction have been launched.

- 7 December 2016: Full integrated planning for the FAIR construction and commissioning presented in the Council. Solid resource loaded plan for completion of the project by 2025.
Civil construction – realization plan

FAIR CC animation
Integrated Project Time Schedule: FAIR Buildings, Accelerators & Experiments

- Planning scope is the FAIR MSV
- Completion by 2025
- Full integration in planning of Civil Construction, Machine & Experiments is achieved
- A staged approach is realized (“Along the Beamline” / North & South) to speed up the start of experiments
- Installation windows prior finalization of Civil construction starting in 2021 until 2024
- Components (Machine & Experiments) for this installation identified & respective dates set
- Continuous progress monitoring is defined and established
Integratetd Project Time Schedule – Level 1: FAIR Buildings, Accelerators & Experiments
## Integrated Project Time Schedule – Level 1: FAIR Buildings, Accelerators & Experiments

<table>
<thead>
<tr>
<th>Project</th>
<th>Start Date</th>
<th>End Date</th>
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</thead>
<tbody>
<tr>
<td>FAIR Buildings</td>
<td>08.06.2017</td>
<td>16.12.2022</td>
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<tr>
<td>GEOD Transfer Building/TIF0N Transfer SIS100/T112N Tran</td>
<td>29.11.2017</td>
<td>16.12.2022</td>
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<td>GD17 Cryo Compressor Building</td>
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<td>SG 100 procurement phase</td>
<td>17.10.2011</td>
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<td>SG100 installation into tunnel, commissioning without beam phase</td>
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<td>SG100 commissioning with beam</td>
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<td>qLInac installation after REO, commissioning with beam</td>
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<td>08.08.2008</td>
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**FAIR Buildings 7/2017 – 12/2022**

**FAIR Acc. & Exp. Install. and commiss. w/o beam 1/2021 – 8/2024**
Progress achieved in the FAIR Accelerator Project
Procurement of the FAIR Accelerators SIS100

- **S.c. dipol magnet**: Release of series production in July 2016 (Germany)
- **First SIS100 s.c quadrupole yoke and s.c. coil at JINR (Russia/Germany)**
- **First SIS100 bunch compressor cavity**: SAT (on-site acceptance test) successful (Germany)
- **First cryogenic bypass line delivered and under cold testing at GSI (Poland)**
- **FOS (first of series) sextupole magnet delivered. SAT successful, Series released (Denmark)**.
- **Parts for FOS acceleration cavity produced. Assembly started. FAT (factory acceptance test) in Dec. 2016 (Germany)**
Procurement of the FAIR Accelerators
Super-FRS

FOS s.c multiplett: PDR approved in July. Steel and wire ordered. Coil mock-up in production (Italy).

~70 ton

Collaboration agreement signed with CEA, including design and technical follow-up (France)

Radiation hard dipole. Prototype testing almost completed. Tendering on short term (Russia)

Target chamber with plug ins. Collaboration and R&D contracts with KVI-CART (NL)

The update of TDR (Annex) is ready and approved. Several spec. completed
The full 3D model of CR system is ready (DMU model)
MA debuncher cavity in SAT at GSI.
Prototype of Stochastic cooling Pick-up under development.

December 2016: Collaboration contract signed for the dipole magnets (production until 2021) and potentially for all other components with BINP, Novosibirsk (Russia)
Large amount of dipole and quadrupole delivered to FZJ (Sigma Phi France):

- 36 von 46 dipole
- 56 of 84 quadrupoles magnets at FZJ. Last quadrupole expected until Q2 2017
- First sextupole parts built in Romania until Dec. 2016
- Injection kicker FAT started (Sigma Phi France)

All dipole chambers delivered and shipped to GSI for NEG coating and send back to FZJ.

First stochastic cooling pick-up and kicker installed in COSY. Amplifier expected end of the year.

Final dipole PC produced according to schedule of buildings. All quadrupole PCs delivered to FZJ by Sigma Phi.
The Experiments

APPA,
CBM,
NUSTAR,
PANDA
NUSTAR - Origin of elements in the universe

"Nucleosynthesis sites" in the universe

"Nucleosynthesis sites" at FAIR

Type I Supernova
Type II Supernova
Neutron Star Merger
Nova
Sun

Proton number, Z

SIS 100
production target

SFRS

MATS & LaSpec
HISPEC/DESPEC
R³B

ILIMA, EXL at CR and at ESR, HESR, Cryring
NUSTAR - Origin of elements in the universe

„Nucleosynthesis sites“ in the universe

High SIS100 energies + SFRS: superior charge separation and beam quality

SIS 100 → production target

Proton number, Z

Kinetic Energy [MeV/u]

Threshold for \(\Lambda\)-production
Threshold for \(\Delta\)-excitation
Coulomb excitation up to \(E^* = 13\) MeV

NUSTAR - Origin of elements in the universe
Physics goals/ highlights of the NUSTAR program

• Understanding the 3rd r-process peak by means of comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and level structure along the N=126 isotones;

• Equation of State (EoS) of asymmetric matter by means of measuring the dipole polarizability and neutron-skin thicknesses of tin isotopes with N larger than 82 (in combination with the results of the first highlight);

• Exotic hypernuclei with very large N/Z asymmetry.
Progress in preparing the NUSTAR experiments:
SC $R^3B$ Dipole GLAD installed at GSI

GLAD magnet (French in-kind contribution)
Commissioning und first tests 2016/17

In 2018, start of physics program with GLAD
using beams from SIS18 and FRS at 1 GeV/u
**Novel detectors developed for NUSTAR**

- **O-TPC**: discovered $\beta$-delayed 3p-emission of $^{31}$Ar
- **Backward-angle neutron detector** for tensor-force experiments
- **Ion Catcher → LEB-MATS/LASPEC**

**GADAST prototype measurements at S2**

**Full integrated S2 fiber tracker**

**Simulations for a pion detector integrated at S2**
From the WG Draft Report on “Nuclear Structure and Reaction Dynamics”:

**FAIR** will be the European flagship facility for the coming decades. The unique accelerator and experimental facilities will allow for a large variety of unprecedented fore-front research in physics and applied science.

The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale, deepening our understanding of fundamental questions.

The urgent completion of FAIR, the Super-FRS and NUSTAR@FAIR, are of utmost importance for the community.

In the interim period it is vital that a high-level research programme and use of the new detectors for FAIR at GSI continues using the existing beams and facilities.
From the WG Draft Report on “Nuclear Astrophysics”:

... In the future, a major step will be made with the FAIR-NUSTAR facility, which is expected to give access, for the first time, to many of the r-process path nuclei at N=126 by means of fragmentation of high-intensity and high-energy 238U-beam.

Thus, a change of paradigm can be expected in the near future, providing first experimental data in a yet unknown region of the nuclear chart, and very stringent constraints for the r-process nucleosynthesis of the heaviest stable nuclei. ...
CBM: FAIR delay and competing experiments

FAIR delay
Main objectives of the CBM physics program at SIS100 not affected by the delay of the MSV due to unrivalled rate capability of the CBM setup

Competing experiments
- STAR at RHIC-BNL (BES)
- NA61 at CERN-SPS
- MPD at JINR-NICA
- BM@N at JINR

CBM: world wide unique high-precision measurements of rare diagnostic probes like multi-strange hyperons, hypernuclei, dileptons, charm, and multi-differential observables.
Consequences of the FAIR evaluation for CBM: Focus on SIS100 beam energies

Physics program: Exploring QCD matter at neutron star core densities (> 5 \( \rho_0 \))

- nuclear matter equation of state
- search for phase transition, phase coexistence, exotic phases
- onset of Chiral symmetry restoration
- hypernuclei, strange matter

Detector optimization:

- Compact detector configuration to increase acceptance
  - Reduction of detector layers for TRD and Muon system
    - Adoption to larger beam deflection at lower energies:
      - Horizontal displacement of forward hadron calorimeter
      - Horizontal adjustment of beam pipe
      - Larger acceptance of beam dump
CBM detector and DAQ tests at CERN SPS

- Successful operation of detectors and of the DAQ system
- Events successfully reconstructed from free-streaming data
- Data quality allows for investigation of detector performance
HADES Preparation for FAIR

Detector upgrades

- **ECAL** (PSP 1.1.2.3)
- **RICH-700** (synergy with CBM – UV detector)
- **MDC-FEE** (PSP 1.1.2.4, 1.1.2.5)
- **FW-Tracker** (synergy with PANDA – straws)
- **FW-RPC** (for excellent TOF and good charge resolution)
- **FW-Wall** (synergy with CBM – PSD)
- **START** (synergy with CBM – $t_0$ detector)

Up to 50 kHz interaction rate, improved electron-id, detection of photons, large acceptance for exclusive processes.
From the WG Draft Report on “Properties of Strongly Interacting Matter”:

CBM at FAIR will measure both hadronic and leptonic probes with a large acceptance in fixed-target mode. For this next-generation experiment, the emphasis is put on very high rate capability, with the ambitious design goal of 10 MHz peak rate.

Such high interaction rates will overcome the limitations in statistics suffered by current experiments and permit the measurement of extremely rare probes like e.g., yields and flow of identified anti-baryons, in particular multi-strange hyperons, intermediate-mass lepton pairs, and particles containing charm quarks.

The combination of high-intensity beams with a dedicated high-rate detector system provides worldwide unique conditions for a comprehensive study of QCD matter at the highest net-baryon densities achievable in the laboratory.
PANDA physics program now focused onto:

- **Strangeness:** High statistics sample of unexplored territory hyperon ($\Lambda^*$, $\Sigma^*$, $\Xi^*$, $\Omega^*$) spectroscopy
- **Charm(-like):**
  X,Y,Z-factory, high statistics allow new approach to lineshapes, transitions, nature of the states
  Heavy-light mesons unexplored high spin states, lineshape
- **Nucleon Structure:**
  *highest rates at lower* $q^2$ *for* $G_E$, $G_M$, TDA, WACS, TMD
- **Hypernuclei and nuclear targets:**
  Hyperon-potential in nuclei, excited states of $\Lambda\Lambda$-hypernuclei
Strategy of PANDA

- After intense discussion with the scientific community, there is
  – a focusing of the **first key experiments**
  – a definition of the **start setup**
  – a proposal for **intermediate experiments/activities**

- And in addition:
  - Development of dedicated analysis methods at ELSA, MAMI, BESIII, Jlab, COMPASS to ensure a quick start of PANDA.
  - Application of modern PANDA technologies at present and future facilities, e.g. Trackers, Cherenkov (DIRC), EMC, Photon readout, Readout electronics
Joint Data Acquisition Developments for CBM/HADES and PANDA

DiRICH MAPMT/MCP readout chain
common development for HADES, CBM and PANDA

DiRICH 3x2 PMT readout module

- Perfect synergy between FAIR experiments
- Based on TRB3 project (GSI development)
- Development funded by BMBF

- Prototypes of all modules available and under evaluation (06 / 2016)
- Very promising first results
From the WG Draft Report on “Hadron physics”:

... FAIR is expected to provide ... a unique research environment for all aspects of hadron physics coming from experiments with antiprotons.

The strategic importance of PANDA for hadron physics cannot be overestimated. It provides a unique opportunity for a comprehensive research programme in hadron spectroscopy, hadron structure and hadronic interactions.

The combination of PANDA’s discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world.

... PANDA continues to be viewed as a major flagship experiment, which attracts a large international community.
From fundamental to applied research –
Atomic physics, Plasma Physics, Application

APPA
Interplay between Relativity, Correlation, and QED in the Non-Perturbative Regime

\[ \alpha Z \approx 1 \]

- Radiative corrections 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
Stored and Cooled

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei
From Rest to Relativistic Energies (up to 4.9 GeV/u)

Cooling: The Key for Precision

From Single Ions to Highest Intensities
Dense plasmas
- Temperatures $10^3...10^6$K
- Densities 0.1...1000x solid
- Pressures kbar...Gbar

A great challenge for theory:
- Strong coupling: $E_{\text{pot}} \geq k_B T$
- Quantum effects: $E_F \sim k_B T$
- Collisions (conductivity, heat transport): $\Lambda_c < 0$
- Partial ionization
- Continuum lowering
- ...

Exotic states, complex properties:
- Equation of state, melting + phase transitions, transport properties, metallization,...
- Transport properties (heat, radiation), equilibration,...., non-equilibrium states
- Interaction of ions and photons with plasma
- Atomic & nuclear physics in dense plasmas

Dense plasmas are strongly correlated many particle quantum systems
FAIR will offer exciting new possibilities for research in High-Energy Density Science

Unique properties of heavy-ion driven plasmas
- large volumes (mm³)
- uniform conditions
- thermal equilibrium
- any target material
- rep. rate, reproducibility

Protons as dense matter probe
- Long range (~m) of relativistic protons
- High-resolution imaging of small angle deflection → accurate density meas.
- Ultra-intense proton pulses allow for short (~10ns) time exposure

• FAIR will produce the worlds largest volumes of uniform HED matter (x100 increase in specific energy deposition over GSI)
• FAIR will host the worlds highest resolution proton microscope
Biophysics

- Space radiation biophysics
- Biological effects of very high energetic ions
- Shielding measures: new materials
- Particle therapy: “theranostics” (use of high energetic proton beams for simultaneous diagnostics and therapy)

Materials Research

- Ion-matter interaction at highest energies and highest charge states
- Materials behavior under extreme conditions (high flux irradiations)
- Irradiations under multiple extremes (high pressure, temperature, dose)
- Radiation hardness of accelerator and spacecraft components
Progress in preparing the APPA experiments:
Sophisticated & Versatile Instrumentation

**Observables:** Photons, electrons, positrons, ions

- **Targets**
- Position-sensitive solid-state detectors
- High-resolution spectrometers
- Particle detectors
- Particle spectrometers
- High pressure cell
- Traps
- X-ray optics, channel-cut crystals
- Laser systems
Beam Time 2016
- 3 months during the first half year
- Global machine availability about 75% for parallel operation
- Very efficient parallel operation at SIS/ESR: on average beam delivery to three experiments in pulse-to-pulse operation
- Instrumental highlight: start of commissioning of the Cryring
- Physics highlight: pioneering measurements of proton-capture reactions at the internal target of ESR → demonstrating the feasibility of precision studies of astrophysical reactions at storage rings.
Highlights from 2016 Beam Time at GSI

- Successful start of commissioning of the Cryring@ESR (first turn achieved)
- Successful proof-of-concept of nuclear astrophysics studies in storage rings using the $^{124}$Xe ($p,\gamma$) nucleosynthesis reaction
- Successful test of novel APPA / SPARC instrumentation
- Tests of CVD diamond detector
  - In vacuum operation without cooling
  - Rate capability up to $10^7$ MIPs/s/mm$^2$
  - Timing resolution (sigma) 90ps
  - Radiation hard material CVD diamond
Further research highlights

**Laser Spectroscopy of Nobelium (Z=102)**

- doi:10.1038/nature19345, 9/16

**Virtual photon radiation from Au+Au collisions**

- Inclusive excess mass spectrum
- all known sources subtracted
- fully corrected for acceptance
- Almost exponential spectrum up to vector meson region.
- Fit to $dN / dM \propto M^{3/2} \times e^{-M/T}$
- $T_{\text{emitting source}} = 95 \pm 5$ MeV

**Theory r-process in neutron star mergers**

- Sensitive to properties of exotic nuclei and fission

G. Martinez-P., PRC 92, 055805 (2015)
GSI continues to play a leading role in the ALICE Collaboration:

- Participation in the ongoing analysis
- Operation of the Tier 2 Center/Analysis Center
- Contribution to high intensity upgrade for LHC Run 3
Intermediate Research Program FAIR Phase 0

- Goals
  - Forefront research by employing and testing new FAIR detectors
  - Exploiting upgraded GSI accelerator facilities
    - ongoing upgrade of SIS18 completed by mid 2018
  - Education of young scientists
  - Maintain and extend skills and expertise
  - Serve national and international user community

- Plan
  - Establish an international Program Advisory Committee
  - 1st call for proposals for beam time slot 2018/19 in spring 2017
FAIR Phase 0 Program

- Benefit from UNILAC and SIS18 upgrade
- Make use of Cryring, R3B magnet and other novel FAIR instrumentation
# FAIR Phase 0 – scientific opportunities for the four research pillars of FAIR

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<th>Facility</th>
<th>Research Activity</th>
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<td>SPARC</td>
<td>ESR-HITRAP-</td>
<td>Strong field QED, atomic collisions, fundamental symmetries, border to nuclear physics</td>
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<tr>
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<td>CRYRING</td>
<td>Biophysics, heavy ion therapy, Material Science</td>
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<td>Di-lepton production in pion-induced and HI reactions</td>
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<tr>
<td>miniCBM</td>
<td>miniCBM@SIS18</td>
<td>Test of subsystem plus data acquisition of CBM</td>
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<tr>
<td>CBM</td>
<td>External</td>
<td>Beam energy scan at STAR/RHIC (tests/ physics at NICA)</td>
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<thead>
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<td>FRS</td>
<td>Separator-/spectrometer expt.’s with exotic nuclei</td>
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<tr>
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<td>FRS-ESR</td>
<td>Nuclear physics with exotic beams in storage rings</td>
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<tr>
<td>NUSTAR</td>
<td>HISPEC/DESPEC</td>
<td>In-beam and stopped-beam spectroscopy experiments</td>
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<td>NUSTAR</td>
<td>R3B@SIS18</td>
<td>Reactions with relativistic radioactive beams</td>
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<td>SHIP, TASCA</td>
<td>Physics and chemistry of SHE</td>
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<th>PANDA</th>
<th>Facility</th>
<th>Research Activity</th>
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<td>PANDA</td>
<td>HADES</td>
<td>Hyperon Dalitz decays with HADES (use of PANDA F-TRK)</td>
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<td>PANDA</td>
<td>External</td>
<td>Search for exotic states, charmonium and time-like form factors at BESIII/Beijing/IHEP. Magnetic moment of $\Delta(1232)$, e-m universality, multi pi0 prod. at MAMI</td>
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FAIR is in good shape for full completion by 2025.
Installation incl. commissioning of the experiments is planned during 2021-2024

GSI/FAIR Research Strategy towards 2025:
• R&D for and construction of the FAIR experiments
• FAIR phase 0 – intermediate research program bridging the construction phase from 2018 until commissioning of the FAIR accelerators and experiments.