November 16, 2009

Technical Document 1

attached to the
Convention concerning the construction and operation of a
Facility for Antiproton and Ion Research in Europe (FAIR)

Description of the FAIR facility to be constructed and the stages of construction (Part A)

and

The Modularized Start Version – A stepwise approach to the realization of the Facility for Antiproton and Ion Research in Europe (FAIR) (Part B)

PART A

Description of the FAIR facility to be constructed and the stages of construction

1. Overview

This document provides the technical and scientific description of the Facility for Antiproton and Ion Research (FAIR), an international accelerator facility for research in Europe, to be constructed at the site of the GSI Laboratory at Darmstadt, Germany. It represents a summary overview extracted from the Baseline Technical Report (BTR) for FAIR, prepared by the international research community and the FAIR project team and published in 2006.

The present document includes: i) an outline of the accelerator systems and their performance characteristics; ii) a brief description of the research programs and the associated experimental facilities; iii) a summary of the technical support systems and civil construction; and iv) a brief outline of the stages of construction. The associated information on schedule, cost and manpower needed to realize the facility and to bring it into operation are given in Technical Document 2 .

2. Accelerator Facility

2.1 Overview

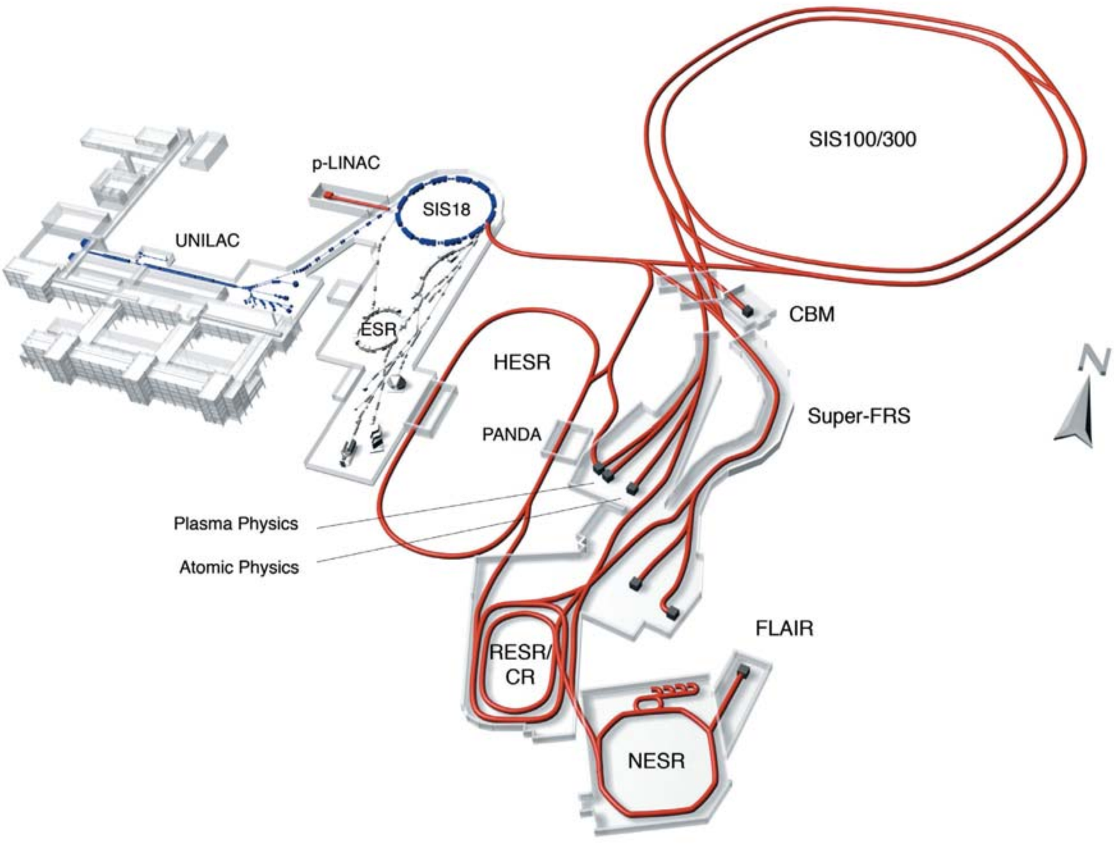

Figure 1: Layout of the FAIR facility: The existing accelerators at GSI (on the left in blue) act as injector for the new accelerator systems to be constructed (on the right in red).

The concept of the FAIR Accelerator Facility has been developed by the international science community and the GSI Laboratory. Its goal is to provide unprecedented, intense, high-quality beams of stable and unstable nuclei as well as of antiprotons in a wide range of intensities and energies for a multifaceted forefront science program. The present layout is shown in Fig. 1.

The concept builds and substantially expands on seminal developments made over the last 15 years at GSI and at other accelerator laboratories worldwide in the acceleration, accumulation, storage and phase-space cooling of high-energy proton and heavy-ion beams. Based on that experience and adopting new developments, e.g. fast cycling superconducting magnets, stochastic and high-energy electron cooling of ion beams, ultra-high vacuum technology, in-ring experiments with stored, cooled beams, the facility concept in Figure 1 was developed.

2.2 FAIR Performance Requirements and Basic Facility Concept

The concept and design specifications of the FAIR accelerator facility were derived from the requirements set by the scientific programs:

Beams of all ion species and of antiprotons: FAIR is to provide beams of all ion species, from hydrogen to uranium, as well as antiprotons over a large energy range (from particles at rest up to several tens of GeV per nucleon energy in the laboratory frame).

Highest beam intensities: For primary beams, the intensity increase over present aims at a factor of up to several hundred for the heaviest ion species. For the production of radioactive secondary beams and for high-power pulses for plasma physics research, the high-intensity beams circulating in the SIS100-synchrotron are to be compressed to short bunches of 50 - 100 ns duration. The increase in primary beam intensity translates into gain factors from 1,000 to 10,000, for secondary radioactive ion beam intensities, due to the higher acceptances of the subsequent separators and storage rings.

Table 1: Key parameters and features of the FAIR synchrotrons and cooler/storage rings

Ring	Circum-ference	Beam rigidity	Beam Energy [GeV/u]	Specific Features
Synchrotron SIS100	1083.6 m	100 Tm	2.7 for U^{28+} ions 29 for protons	Fast pulsed superferric magnets up to 2 T, 4 T/s, bunch compression to ~60 ns of $5 \cdot 10^{11}$ U ions, fast and slow extraction, $5 \cdot 10^{-12}$ mbar operating vacuum
Synchrotron SIS300	1083.6 m	300 Tm	34 for U^{92+}ions	Pulsed superconducting cosθ-magnets up to 6 T, 1 T/s, slow extraction of ~$3 \cdot 10^{11}$ U-ions per sec. with high duty cycle, $5 \cdot 10^{-12}$ mbar operating vacuum
Collector Ring CR	210.5 m	13 Tm	0.74 for A/q=2.7 3 for antiprotons	Acceptance for antiprotons: 240·240 mm mrad, $\Delta p/p=\pm 3 \cdot 10^{-2}$, fast stochastic cooling of radioactive ions and antiprotons, isochronous mass spectrometer for short-lived nuclei
Accumulator Ring RESR	245 m	13 Tm	0.74for A/q=2.7 3 for antiprotons	Accumulation of antiprotons after pre-cooling in the CR, fast deceleration of short-lived nuclei, ramp rate 1T/s
New Experimental Storage Ring NESR	222 m	13 Tm	0.74 for A/q=2.7 3 for antiprotons	Electron cooling of radioactive ions and antiprotons with up to 450°keV electron-beam energy, precision mass spectrometer, internal target experiments with atoms and electrons, electron-nucleus scattering facility, deceleration of ions and antiprotons, ramp rate 1 T/s
High-Energy Storage Ring HESR	574 m	50 Tm	14 for antiprotons	Stochastic cooling of antiprotons up to 14 GeV, electron cooling of antiprotons up to 9 GeV; internal gas jet or pellet target

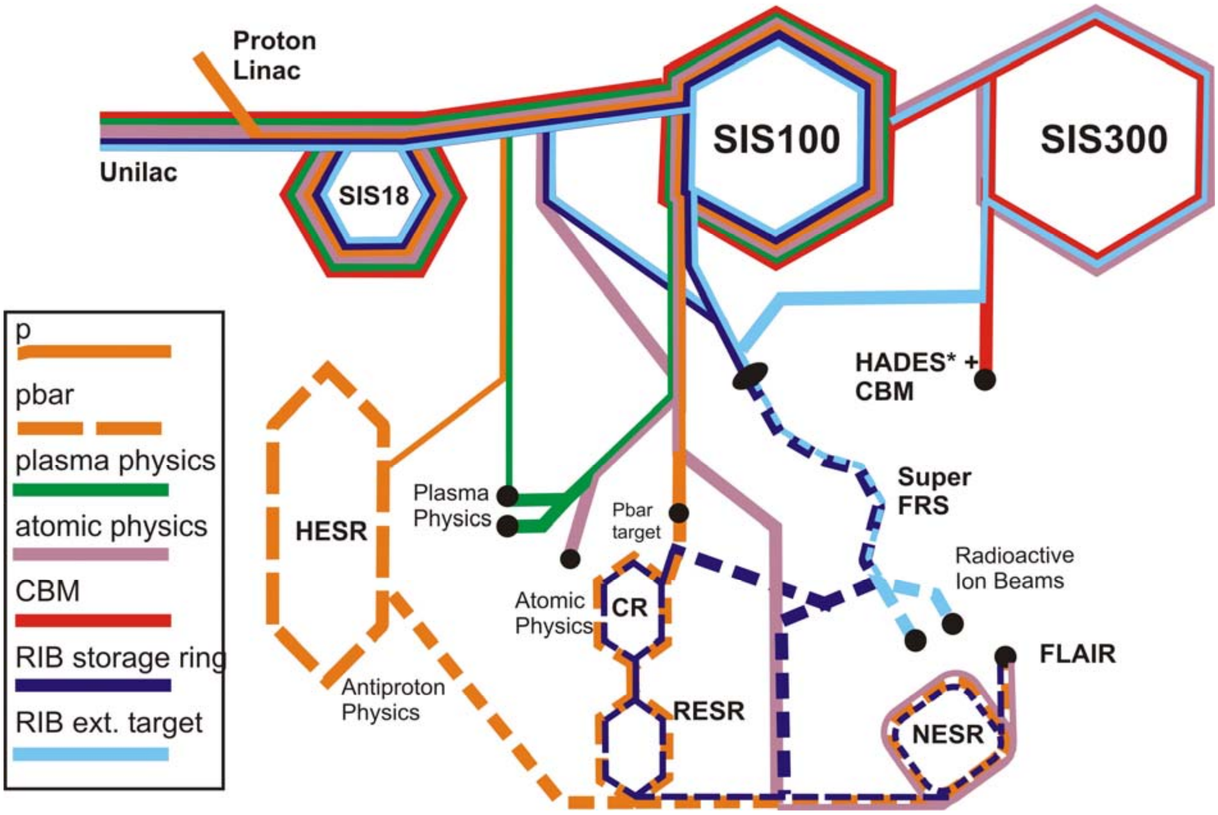

Figure 2: Schematic of parallel operation at the new facility with up to four different scientific programs: A proton beam (orange) produces antiprotons (orange dashed) in the antiproton target-station for experiments in the HESR or the NESR. In parallel, a primary ion beam (blue) produces radioactive secondary beams (blue dashed) at the Super-FRS for fixed target or NESR experiments. In addition, a high-energy heavy-ion beam (red) is accelerated in SIS100/300 and slowly extracted over 10-100 seconds for nuclear collision experiments. Moreover, intense highly compressed beam bunches (green) are provided every few minutes to plasma physics targets. Alternatively, atomic physics experiments (violet) are served by SIS100 in the pauses of the antiproton production.

Increase in beam energy: For antiproton production, intense proton beams are to be provided with energies near 30 GeV. To achieve highest baryon densities and enable charm production in high energy nucleus-nucleus collisions, the SIS300-synchrotron is designed for beam energies ranging from 35 AGeV for uranium to 45 AGeV for argon.

Highest phase-space density and high-quality beams: Through phase space cooling techniques, such as stochastic, electron, and also laser cooling, FAIR aims for high quality primary and secondary beams with momentum spreads and emittances reduced by several orders of magnitude compared to regular facilities with uncooled beams. Together with the statistical precision and high sensitivity that result from high beam intensities, these high-quality beams will allow novel precision experiments.

These experimental requirements lead to the following facility concept and layout for the accelerators:

Synchrotrons and storage rings as accelerator structures of choice: Synchrotrons are the simplest and most cost-effective way to accelerate ion beams to high energies, from protons to uranium ions. Even more important, in view of the planned research program with FAIR, the time structure of the primary beams given by the synchrotron acceleration, allows an ideal adaptation to the subsequent storage rings.

Rapidly-cycling superconducting synchrotrons and acceleration of medium charge states: The high primary beam intensities will be achieved by fast cycling superconducting synchrotrons plus, for heavier ions, by acceleration of low charge-state ions. The charge-state enters quadratically into the space charge limit. The reduced charge-state, at the desired energies of up to 1.5 AGeV for secondary radioactive ion beams, requires the larger bending power of SIS100.

High bending power for higher particle energies: The high bending power of SIS100 allows the acceleration of protons to about 30 GeV for an efficient antiproton production. For the research program on nucleus-nucleus collisions at energies up to 35 AGeV for fully stripped (92+ charge state) uranium, the second synchrotron ring SIS300 with a correspondingly higher bending power is needed. It is designed for long extraction periods and can also be used as a stretcher ring.

Table 1 summarizes technical parameters and performance characteristics of the various accelerator components of FAIR.

2.3 Parallel Operation and Synergy

An important consideration in the design of the facility was a high degree of a truly parallel operation of different research programs. The proposed scheme of synchrotrons and storage rings, with their intrinsic cycle times for beam acceleration, accumulation, storage and cooling, respectively, has the potential to optimize such a parallel and highly synergetic operation. The facility operates for the different programs more or less like a dedicated facility. Figure 2 illustrates this with an example.

3. Experimental Programs and Facilities

In general terms, the research goals and scientific objectives of the science at FAIR can be grouped into 3 major areas:

i) a deeper understanding of the structure and properties of matter; this includes a reduction of the structure of matter to the basic building blocks and fundamental laws, forces and symmetries; and an understanding how complexity arises from these fundamental constituents, a complexity which does not come from a simple linear superposition but involves non-linear processes, correlations and coherences;

ii) contributions to our knowledge about the evolution of the Universe; the hierarchical structure of matter, from the microscopic to the macroscopic, is directly related to the sequence of steps in the evolution and generation of the visible world;

iii) use of ion beams in technology and applied research

These general research goals can be grouped into the following specific fields of research at FAIR:

- Nuclear structure and nuclear astrophysics with beams of stable, but in particular also of short-lived (radioactive) nuclei far from stability;
- Hadron structure, the theory of the strong interaction quantum chromo-dynamics (QCD), and the QCD vacuum, primarily with beams of antiprotons;
- The nuclear matter phase diagram and the quark-gluon plasma with beams of high-energy heavy ions
- Physics of very dense plasmas with highly compressed heavy-ion beam bunches in unique combination with a petawatt laser currently under construction
- Atomic physics, quantum electro-dynamics (QED) and ultra-high electro-magnetic fields with beams of highly-charged heavy ions and antimatter
- Technical developments and applied research with ion beams for materials science and biology

The respective experiment proposals and collaborations are listed in Table 2. The table also indicates the major experimental apparatus involved in the respective research programs.

4. Civil Construction

4.1. Overview

The FAIR complex will be constructed to the east of the existing GSI facility. The ring tunnel will be built below ground. All other buildings will be constructed above ground. Construction of FAIR will require clearing approximately 14 hectares of forest that will be re-vegetated or be compensated for in another area.

The legal and regulatory procedures for the development plan (Bebauungsplanverfahren) have already been successfully completed; a corresponding statutory decision was taken by the Darmstadt City Council on February 14, 2006.

The project will use the existing accelerator as an injector. The ring tunnel will be built in a cut and cover method at a depth of approximately 17 meters. It will be overlaid with 10 m of earth to comply with the requirements of radiation safety. The removed earth will be recycled for shielding purposes and terrain modelling for the new facility. This includes the necessary earth shielding for radiation safety. The ring tunnel is connected to 3 buildings which are symmetrically located around the ring and accessible via a cross-over tunnel for each building and labyrinths as passageways and with niches. All of the other buildings will be arranged south of the large ring tunnel. Due to the large surface area involved, the above-ground solution is considered because it is more economical.

Table 2. Individual research programs approved for FAIR with science goals and the associated scientific instrumentation Some future options evaluated by the program committees but not part of the baseline facility are also listed.

Experiment	Scientific Area	Research Program	Technical Facility	Baseline Facility
R3B	NUSTAR[1]	Inverse kinematics reaction studies with relativistic radioactive ion beams	Large reaction set-up allowing complete kinematics reaction experiments	yes
HISPEC/ DESPEC	NUSTAR	High resolution, high efficiency particle and gamma spectroscopy of nuclei far off stability	γ detectors (AGATA) plus set-ups for charged particle and neutron detection	yes
LASPEC	NUSTAR	Laser spectroscopy of radioactive ion species	Multi-purpose laser spectroscopy station	yes
MATS	NUSTAR	High precision, high efficiency mass and life-time measurements on radioactive nuclei	Combined set-up of an electron beam ion trap (for charge breeding), ion traps (for beam preparation), and a precision Penning trap system.	yes
ILIMA	NUSTAR	Mass and lifetime of stored and cooled radioactive ion beams	Schottky mass and isochronous mass spectroscopy	yes
EXL	NUSTAR	Inverse-kinematics light ion reactions on radioactive nuclei	In-ring reaction set-up	yes
AIC	NUSTAR	Mass (rms) radii of nuclei far off stability	Antiproton (radioactive) ion collider	no
ELISe	NUSTAR	Elastic, inelastic and quasi-free electron scattering of nuclei far off stability	Electron-ion collision device incl. a high resolution electron spectrometer	yes
NCAP	NUSTAR	Production of specific radio-nuclides for (off-site) neutron capture studies	None	no
EXO-pbar	NUSTAR	p-n abundance at the nuclear surface of nuclei far off stability	Very low-energy radioactive ions with antiprotons stored in a Penning trap	no
PANDA	QCD[2]	QCD and hadron physics with cooled high energy antiproton beams	Large internal target detector system covering almost the full solid angle	yes
CBM	QCD	QCD phase diagram in high-energy nucleus-nucleus collisions	Large fixed target detector system covering almost the full solid angle	yes
PAX / ASSIA	QCD	QCD and hadron physics studies with polarized antiproton beams	Collider detector system covering a large solid angle	no
HEDgeHOB/ WDM	APPA[3]	Warm and dense bulk matter produced by intense ion and/or laser pulses	Experimental stations for plasma physics	yes
FLAIR	APPA	Precision studies with low energy or stopped antiproton ion beams	Ultra-low energy electrostatic storage ring, a Penning trap, low energy antiproton target stations	yes
SPARC	APPA	Atomic physics spectroscopy and collision studies with stored high energy ion beams	Fixed-target and in-ring experiments	yes
BIOMAT	APPA	Applications of ion and antiproton beams in biophysics, biology, materials research and other disciplines	Various multi-purpose target stations	yes

[1] Nuclear Structure, Astrophysics and Reactions
[2] QCD and Hadron Physics
[3] Atomic Physics, Plasma Physics and Applications

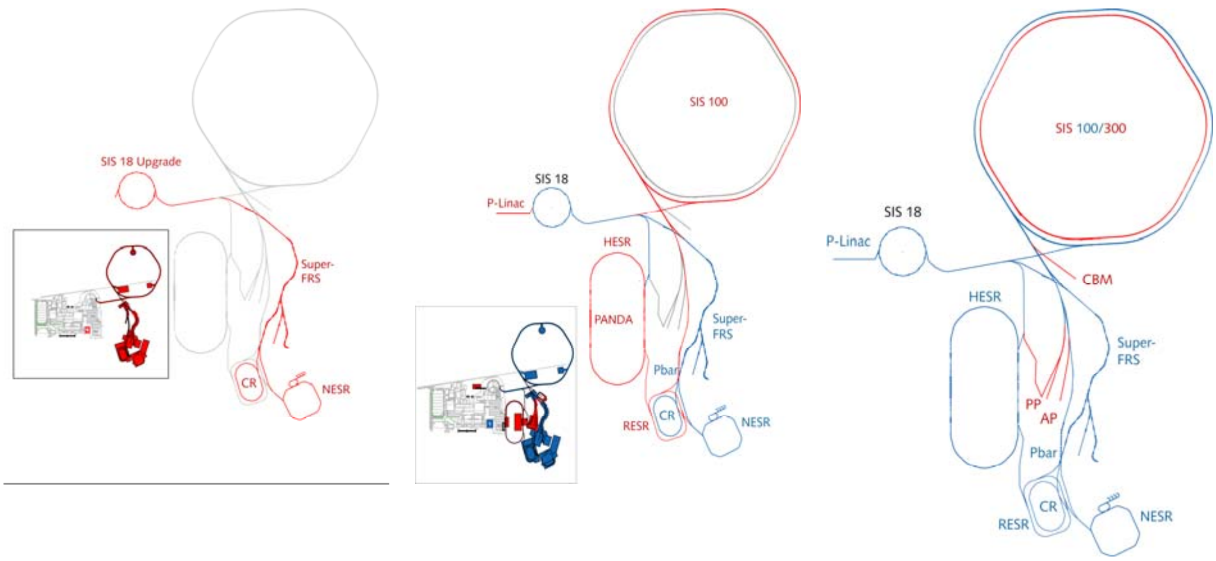

Figure 3: Stages of construction and operation of the FAIR facility. At stage 1 (left), only items marked in red will be constructed. The insert shows the civil construction taking place at stage 1. At stage 2 (middle), items drawn in red will be constructed whereas accelerator components in blue will already be operating. Buildings drawn in blue will exist already. At stage 3(right), no more civil construction will take place, and the accelerator components in red will be constructed.

4.2. Staging of Construction

Construction, commissioning and beginning of operation of FAIR will proceed in three stages. The total construction time for the FAIR facility will be 8 years.

Stage 1 — Radioactive beam physics: nuclear structure and nuclear astrophysics; atomic physics and plasma physics studies with highly charged and/or radioactive ions

Stage 2 — Proton-antiproton physics and relativistic heavy ions: QCD studies with protons and antiprotons; precision studies with antiproton beams addressing fundamental symmetries and interactions; dense baryonic matter physics using relativistic heavy ions at energies 1 – 10 GeV/u; atomic physics at relativistic energies.

Stage 3 — Full facility capability and all research programs: parallel operation of up to four research programs; full energy and luminosity for nuclear collisions program; precision QCD Studies at PANDA; plasma research; atomic reaction studies with fast beams.

The staging is reflected in the sequence of availability of buildings. The planning has been optimized with respect to minimizing constructions costs and construction time. Alternatives are possible, however might be realized at higher costs only. Thus the proposed schedule as was derived by BUNG Beratende Ingenieure was taken as the baseline for the present planning of FAIR. The stages of construction are displayed in Fig. 3.

5. Radiation Safety

The radiation shielding plan for FAIR is based on detailed calculations of the production, transport and attenuation of radiation. Two approaches were used:

i) the Moyer model (inverse square law and an exponential decrease of the dose in the shielding material);

ii) Monte Carlo techniques to simulate the generation of radiation and the transport through the shielding;

The FAIR Facilities will meet the conditions stipulated by the German radiation protection legislation:

(i) Radiation emerging directly from the facility must not exceed a level of 0.7 to 1 mSv per year (8760 h)

(ii) Radiation exposure by the emission of radio-nuclides must not exceed a level of 0.3 mSv per year.

(iii) The sum of (i) and (ii) must be below 1 mSv (§46 StrlSchV, the German radiation protection ordinance).

(iv) The radiation exposure (outside the radiation controlled areas) must not exceed a level of 6 mSv per year (2000 h) on the institute premises and of 1 mSv per year outside the premises.

Part B:

The Modularized Start Version –
A stepwise approach to the realization of the
Facility for Antiproton and Ion Research in Europe
(FAIR)

This Technical Document 1B is complimentary to the Technical Document 1A and should not be considered a stand-alone document.

Preface

In order to enable an expeditious start of the construction of FAIR, taking into account the recent cost estimates and funding commitments, while ensuring top scientific excellence and the outstanding discovery potential of the facility, a modular approach to construct FAIR is planned and has been approved.

This modular approach takes into account the following objectives:

- It allows for setting up single, relatively independent construction modules that serve the experiments of all the scientific communities of FAIR.
- It provides the flexibility to realize FAIR according to the available funding.

It leads to the definition of seven modules of which a subset of four modules form the Modularized Start Version, which will be constructed first. It allows for rapid achievement of major scientific goals for the four science communities[1] of FAIR:

APPA: Atomic and plasma physics, and applied sciences in the bio, medical, and material sciences;
CBM: Physics of hadrons and quarks in compressed nuclear matter, hypernuclear matter;
NuSTAR: Structure of nuclei, physics of nuclear reactions, nuclear astrophysics and radioactive ion beams (RIB);
PANDA: Hadron structure and spectroscopy, strange and charm physics, hypernuclear physics with anti-proton beams.

[1] in alphabetical order

Description of FAIR Modules

The inherent ab-initio approach for FAIR is that it consists of different target stations and storage rings all served by the double synchrotron SIS100/300. The modular approach maintains this approach. Table 1 gives a short overview on the modules, focusing on the experimental goals and technical challenges.

Table 1: *Overview of the modules with explanations and a brief description of the goals and challenges*

Module configurations	Explanations	Goals and challenges
Module 0 SIS100 with connection to existing GSI accelerators	Central accelerator unit, used by all science programmes	Novel accelerator technologies (e.g. fast-ramping superconducting magnets, compact broad band radio-frequency resonators, XHV, ...)
Module 1 Experimental areas	Buildings housing the CBM/HADES detectors and experiment set-ups for atomic physics, BIOMAT, and high-energy experiments (APPA)	Experiments on dense, strongly correlated nuclear matter with CBM/HADES; high-energy atomic physics, plasma, materials science, and bio (medical) science (ESA reference lab)
Module 2 Super-FRS (without CR)	Central NUSTAR instrument: RIB generation and isotope separator with one fixed-target branch and ring branch	Radioactive ion beams (RIB); nuclear structure and reactions, nuclear astrophysics
Module 3 High-energy antiprotons (p-linac, antiproton target, CR, HESR)	Generation and preparation of intense antiproton beams with the HESR for PANDA	Hadron physics and QCD with antiprotons with HESR/PANDA; cooled precision beams, hypermatter nuclei
Module 4 Low-energy RIBs and antiprotons	NESR ring with hall; FLAIR hall and second fixed-target area for NuSTAR	Experiment stations for decelerated highly-charged ions for APPA and low-energy antiproton programme (FLAIR), Electron cooled RIBs for NUSTAR
Module 5 RESR storage ring	Parallel operation of NuSTAR and APPA with PANDA, increased intensity of antiproton beam	Full parallel operation mode; maximum luminosity for PANDA
Module 6 SIS300 e-cooler for HESR ER@NESR	SIS300 providing for highest beam energies and central to all four science programmes providing for full parallel operation; electron cooled high-energy antiprotons; Electron Ring for NuSTAR	Full experimental programme for CBM; providing the high-luminosity mode for PANDA; Slow extraction for NuSTAR

Based on recent cost estimates and the firm funding commitments of the FAIR Member States the Modularized Start Version (see Fig. 1) comprises of Modules 0 – 1 – 2 – 3.

This Modularized Start Version provides for outstanding and world-leading research programmes in all four scientific areas of FAIR. Modules 4 to 6 are scientifically highly desirable and obvious upgrades of the Modularized Start Version further strengthening the long-term potential and scientific viability of FAIR.

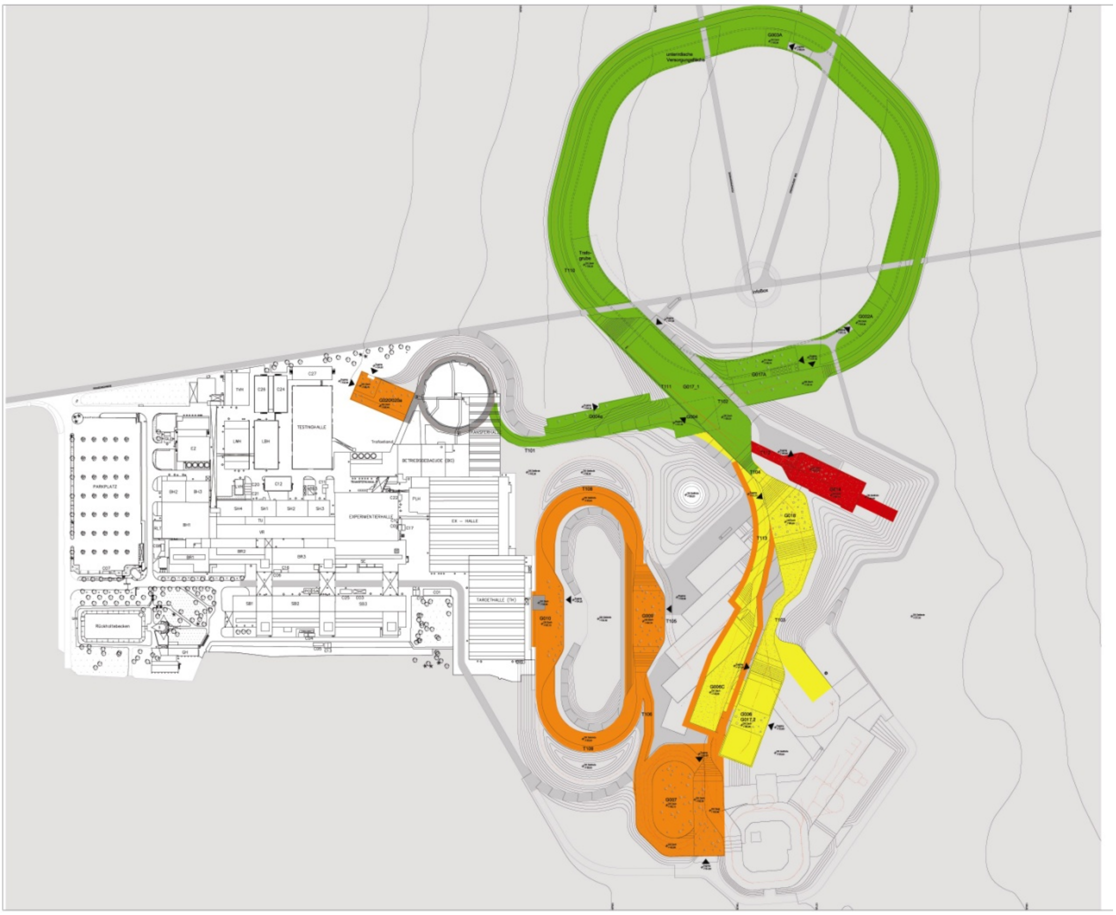

Figure 1: *The FAIR Modularized Start Version. Colouring of modules: 0 – green; 1 – red; 2 – yellow; 3 – orange. The Modules 4 to 6 are not marked in colour. Not shown is an additional experimental area above ground, which is part of Module 1. On the left hand side of the figure, the existing GSI facility is shown.*

Below, general considerations for the experimental programmes and the detailed compilation of the Accelerators and beam lines of the FAIR Modularized Start Version are given.

General considerations for experimental programmes

APPA

The APPA experimental hall built within Module 1 will allow novel and exciting experiments in the realm of bio and materials sciences as well as in atomic and plasma physics. For the FLAIR community and the experimental groups within the SPARC collaboration concentrating on storage rings and traps these physics programmes are shifted into Module 4. To compensate for those experiments not being part of the Modularized Start Version, experimental options will be provided at GSI/ESR and CERN/AD.

CBM

While SIS300 in Module 6 provides the long term prospective for CBM, the immediate roadmap is constituted by the unique experiments that are made possible by the combination of the upgraded HADES detector, an initial implementation of CBM and SIS100 beams. The upgrade of HADES with timing RPC detectors is already in progress.

NuSTAR

The central part of the NuSTAR programme at FAIR is the high-acceptance Super-FRS in Module 2 with its multi-stage separation that will provide high intensity mono-isotopic radioactive ion beams of bare and highly-ionized exotic nuclei at and close to the driplines. Module 2 foresees the construction of the Super-FRS together with the experimental area of the high-energy branch (HEB). Besides the focal planes of the Super-FRS, this would be the experimental area available to NuSTAR. Hereinafter it will be assumed that this experimental area can be shaped to the needs of different experiments, i.e., to accommodate all fixed target NuSTAR experiments (R3B, HISPEC/DESPEC, MATS, LASPEC) with a start version of their respective set-ups. The R3B experiment will reach its full scientific capability in this scenario. Module 3 contains among other items the construction of a storage ring, the CR. A world-wide unique feature of the NuSTAR programme at FAIR is the ability to perform experiments with stored radioactive ion beams.

PANDA

Cutting-edge measurements will be done by PANDA from the very beginning of the Modularized Start Version; however the programme will benefit significantly from Modules 5 and 6, which provide higher intensities and luminosities.

Realization of Accelerator Components in the Modularized Start Version

Accelerator Systems

- Heavy-Ion Synchrotron SIS 100 (with reduced accelerating rf cavities)
- Super-Fragment Separator (Super-FRS)
- Collector Ring (CR)
- Proton Linear Accelerator
- Antiproton Target and Separator
- High-Energy Experimental Storage Ring (HESR), without Electron Cooling facility

Beam Lines

- SIS 18 to FAIR accelerators (not to HESR and not to PP)
- SIS 100 to Super-FRS
- SIS 100 to Antiproton Target
- SIS 100 to CBM
- SIS 100 to high-energy APPA cave
- Super-FRS to CR
- Super-FRS to NUSTAR fixed target branch
- CR to HESR