FAIR AT GSI

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Abstract

Based on the experience of the existing GSI facility and with the aim to apply new technical concepts in phase space cooling and fast ramping of superconducting magnets, an international **F**acility for **A**ntiproton and **I**on **R**esearch **FAIR** has been proposed in 2001. The basic ideas and unprecedented possibilities offered by FAIR have been described in the Conceptual Design Report (CDR) [1]. In March 2006 a Baseline Technical Report FBTR [2] has been produced to describe the concepts and the technical design of the different accelerator sections for the final layout of the FAIR facility. The properties of the described facility and the structure of the FBTR correspond to a detailed cost book.

INTRODUCTION

Within the last four years intensive studies were carried out in order

- to optimise the FAIR facility with respect to the technical layout and spatial arrangement on the available GSI site (see Figure 1),
- to define and fix the beam parameters for ion and antiproton beams, and
- to evaluate the costs.

This work and refined demands on the accelerators, caused modifications with respect to the original proposals in the CDR.

To achieve a most solid cost basis for the project a ‘bottom-up’ cost estimate was made which accounts for detailed component costs. The project investment costs were several times reviewed by the Technical Advisory Committee (TAC) and the CORE-A (accelerators) and CORE-E (experiments) committees. Furthermore cost-driving issues like room-temperature and superconducting magnets, power converters, cryogenics and the proton-linac were evaluated in addition in dedicated reviews.

LAYOUT AND KEY PROPERTIES

The final concept and layout of the facility (Figure 1) has evolved from the scientific requirements. 100-fold higher intensities compared to the present system, will be generated in fast ramped s.c. synchrotrons and, for uranium ions, lower charge states (U^{28+}) will be used to increase the space charge limit up to 10^{12}. However, heavy ion operation with reduced charge-states, at the desired energy of 1.5 GeV/u for the production of radioactive beams, requires a sufficient bending power. These aspects are considered in the design of the two-stage synchrotron SIS100/300. Beside heavy ion beams, SIS100 will also produce intense proton beams with $5 \cdot 10^{13}$ particles per spill at an energy of up to 30 GeV, allowing an efficient antiproton production.

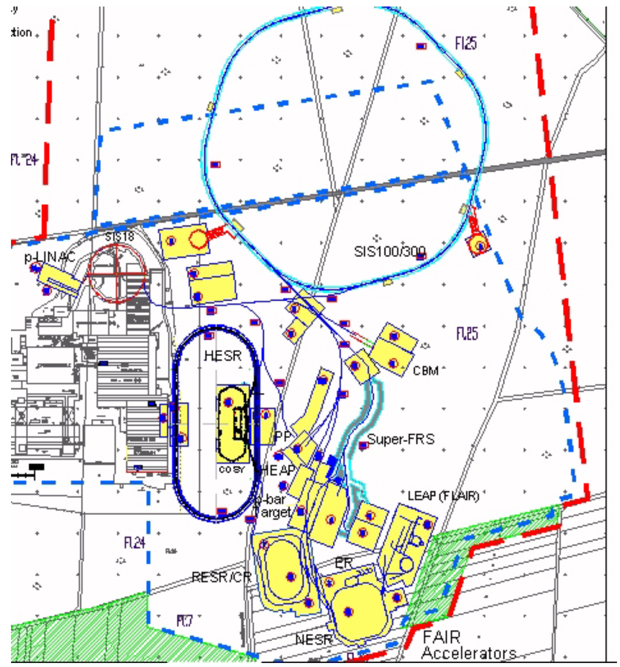

Figure 1: Layout of the existing (SIS18 in red left) and the planned facilities: the superconducting synchrotrons SIS100 and SIS300, the collector ring CR, the accumulator ring RESR, the new experimental storage ring NESR, the super fragment separator Super-FRS, the proton linac, and the high energy storage ring HESR. Also shown are the buildings for plasma physics, nuclear collisions, radioactive ion beams and atomic physics experiments, and for the low energy antiproton and atomic physics experiments in FLAIR.

By using high charge states (e.g. U^{92+}), heavy ion beams of high energy, i.e. 35-45 GeV/u, are generated in the fast ramped s.c. SIS300 synchrotron. The maximum intensity of $2\text{x}10^{10}$ per cycle for these beams allows a long spill of up to 100 s, while keeping a sufficient average intensity. Furthermore, SIS300 can be operated as a stretcher and provides a linac like beam of heavy ions with only short interruptions. Both, primary and secondary (radioactive and pbar) beams can be injected, cooled and stored in a system of storage rings with internal targets and in-ring experiments. Based on the developments and the expertise with beam cooling techniques at the present GSI facility, the future program will broadly take advantage of beams with highest quality. Summarizing, the FAIR accelerator facility will provide beams with the following characteristics:

a) <u>Full range of ion species:</u> The facility will accelerate all ions from protons up to the heaviest element, uranium. This will provide the necessary broad basis for the multi-disciplinary research program proposed for FAIR.

b) Highest beam intensities: Intensities of primary heavy-ion beams will increase by a factor of 100, secondary radioactive beams by a factor of up to 10,000 over the present GSI facility. This will push the sensitivity of experiments involving primary beams, but more important, will enable the production of high-intensity secondary beams, i.e. beams of short-lived nuclei and antiproton beams, which are the subject of many new research frontiers of FAIR.

c) Substantial increase in beam energy: An increase by a factor of 20 in energy is foreseen for beams of heavy ions like uranium. In this energy regime, nucleus-nucleus collisions are expected to generate hadronic matter at highest densities, a key research field of FAIR. Moreover, this enables unique studies of charm production in highly compressed matter.

d) Generation of 'Precision beams': Beams of highest quality will be achieved by sophisticated beam manipulation methods, such as stochastic and electron cooling, in particular also applied to the secondary radioactive and antiproton beams. Together with the statistical precision and high sensitivity resulting from the high beam intensities and interaction rates, the precision beams will allow entering into totally new areas of research in all of the FAIR science fields.

e) Synchrotrons and storage rings as accelerators of choice: For hadron beams, ranging from protons to uranium, synchrotrons provide the most economical solution to generate high beam energies. Even more important for the FAIR research program, storage rings are unique in their capability to store, cool, bunch, and stretch beams and thus fulfil the stringent phase-space requirements from internal target experiments. The choice of ring systems for the new facility matches perfectly to the existing accelerators, which thus can be used as injector and booster.

f) Technical innovations and challenges: The requirements set by the scientific goals of FAIR can only be met with new technical solutions. The most important are: The development of fast ramped superconducting magnets for the synchrotrons; electron- and stochastic beam cooler systems for a broad energy range, in particular also for high energetic antiproton beams; Rf bunch compression systems for the compression of intense heavy ion beams to the Gigawatt power regime (see Figure 2); techniques for the generation of ultra-high vacuum and for stable conditions at low charge state heavy ion operation and development of a superconducting large acceptance fragment separator for efficient collection and separation of secondary radioactive beams.

STORAGE RING COMPLEX

The synchrotron facility is complemented by a system of cooler-storage rings:

The **collector ring (CR)** for stochastic cooling of radioactive ion and antiproton beams coming from the

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

Ring	Circum-ference [m]	Beam rigidity [Tm]	Beam Energy [GeV/u]	Specific Features
Synchrotron SIS100	1084	100	2.7 for U^{28+} 29 for p	Fast pulsed superferric magnets with B_{max}= 2 T and dB/dt=4 T/s, Rf bunch compression to τ~50 ns, fast and slow extraction of $6x10^{12}$ U and $5x10^{13}$ p per cycle , $5\cdot10^{-12}$ mbar operating vacuum
Synchrotron SIS300	1084	300	34 for U^{92+}	Superconducting cosθ-magnets with B_{max}= 6 T and dB/dt=1 T/s, slow extraction of ~ $3\cdot10^{11}$ U-ions /s with high duty cycle or $2x10^{9}$ U-ions /s at high energy, $5\cdot10^{-12}$ mbar operating vacuum
Collector Ring CR	212	13	0.740 for A/q=2.7, 3 for pbar	Acceptance for antiprotons: 240 x 240 mm mrad, $\Delta p/p=\pm3x10^{-2}$, fast stochastic cooling of radioactive ions and antiprotons, isochronous mass spectrometer for short-lived nuclei
Accumulator Ring RESR	245	13	0.740 for A/q=2.7, 3 for pbar	Accumulation of antiprotons after pre-cooling in the CR, fast deceleration of short-lived nuclei with a ramp rate 1 T/s
New Experi-mental Storage Ring NESR	222	13	0.740 for A/q=2.7, 3 for pbar	Electron cooling of radioactive ions and antiprotons with up to 450 keV electron-beam energy, precise mass spectrometry, internal target experiments with atoms and electrons, electron-nucleus scattering, deceleration of ions and antiprotons with 1 T/s
High-Energy Storage Ring HESR	574	50	14	Superconducting cosθ-magnets with B_{max}= 4 T, stochastic cooling of antiprotons up to 14 GeV, electron cooling of antiprotons up to 9 GeV; internal gas jet or pellet target

production targets. The CR ring is equipped with a strong debuncher system and offers the possibility for mass measurements of short-lived ions in an isochronous mode.

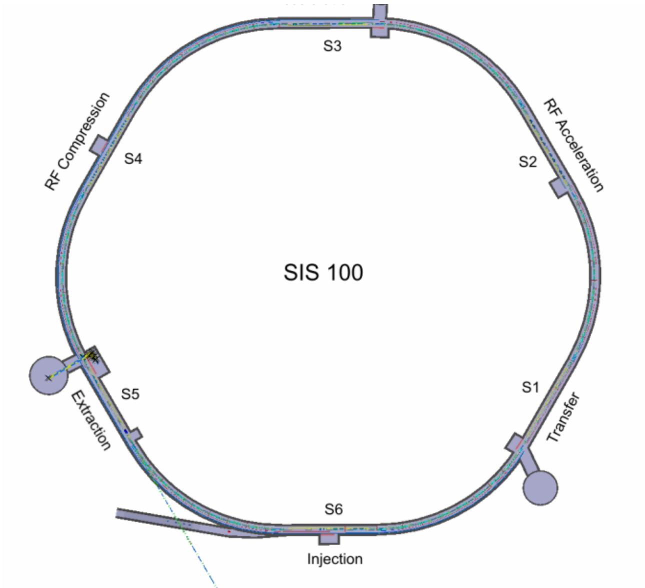

Figure 2: Distribution of the injection-, extraction- and transfer systems and the RF systems for acceleration and bunch compression in the six straight sections of SIS100

The **accumulator ring (RESR)** (see Figure 3) for accumulation of antiprotons and for fast deceleration of radioactive ion beams. The pbar accumulation process is supported by a fast stochastic cooling system.

A **new experimental storage ring (NESR)** for experiments with ions and antiprotons. Equipped with stochastic and electron cooling devices it will house a variety of experimental devices, including a precision mass spectrometer, internal target experiments and an electron-nucleus scattering facility. The NESR will be capable to further decelerate ions and antiprotons and to provide them to the FLAIR facility.

The **high-energy storage ring (HESR)** is optimized for internal experiments with antiproton beams at energies of up to 14 GeV. This ring is equipped with an internal pellet target and associated detectors. A high-energy electron cooler (up to 4.5 MeV electron energy) and a stochastic cooling system are foreseen to compensate the beam degradation due to target interaction and intra-beam scattering.

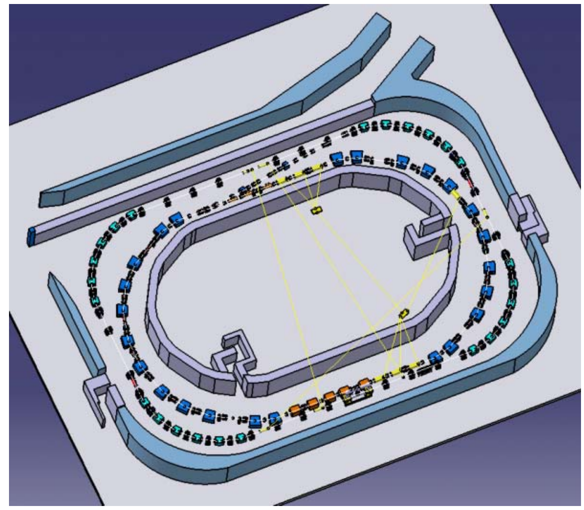

Figure 3: Top view of the CR/RESR area.

DESIGN CHALLENGES

The desired operation of the FAIR synchrotrons and storage rings can only be realized by the application of new technical concepts and solutions accompanied by sophisticated beam dynamics studies. Each technical design or layout of a component must be checked with respect to the coupling, interaction and feed back to the beam. Therefore in parallel to the FAIR technical developments, a number of beam dynamics study groups verify the beam stability and quality. Examples for such design challenges are:

a) **Control of the dynamic vacuum pressure.** Beam loss induced desorption of heavy molecules during operation with low charge state heavy ions, requires advanced pumping concepts (e.g. NEG coating) providing high pumping speed in combination with novel collimation concepts [3] which are presently under development for SIS18. For the simulation of the dynamic vacuum effects a new code (STRAHLSIM) [4] has been developed.

b) **Operation with high brightness, high current**

Table 2: Primary beam parameters from the SIS100/300 facility for different research fields

Research Field	Energy	Peak Intensity	Average Intensity	Time Structure
Structure and dynamics of nuclei (RIB)	U^{28+}: 1.5 GeV/u	~$6\cdot10^{11}$ ppp (storage ring experiments)	~$3\cdot10^{11}$ pps (fixed target experiments)	Single bunch ≈ 60 ns (for storage ring experiments) or c.w.
Hadron structure and quark-gluon dynamics	p : 29 GeV	$5\cdot10^{13}$ ppp	$5x10^{12}$ pps at 10 s cooling time in RESR	Single bunch ≈ 25 ns
Nuclear Matter and quark-gluon plasma	U^{92+}: 34 GeV/u	$2x10^{10}$ pps	$2\cdot10^{9}$ pps	< 100 s spill --
Dense plasma and bulk matter	U^{28+}: 0.4 -1 GeV/u	~10^{12} ppp	Single shot experiments	Single bunch 50 – 100 ns (depending on energy)
Ultra high electromagnetic fields	U^{73+}: 0.1 - 10 GeV/u	--	10^{9} pps	Slow or fast extraction

beams. The synchrotrons will operate close to the space charge limits with tolerable beam losses of the order of a few percent. The control of collective instabilities and the reduction of the ring impedances is a subject for the R&D phase. Furthermore, resonance trapping effects must be considered during the rather long stacking times and are studied by GSI groups together with external partners.

c) **Cooled secondary beams.** Fast electron and stochastic cooling at medium and at high energies will be essential for experiments with exotic ions and with antiprotons. In order to achieve the required luminosities in the antiproton storage ring HESR, magnetized electron cooling at high energies (4.5 MeV) is necessary. Simulations with the goal to determine the beam equilibrium are conducted by an international design study group in the frame of the EU FP6 program.

d) **High Rf voltage gradients.** Fast acceleration and strong compression of intense heavy ion beams requires compact Rf systems. Complex Rf manipulations with minimum phase space dilution (e.g. barrier bucket stacking and pre-compression) and the compensation of beam loading effects in Rf systems are important R&D issues. In parallel, in order to define the maximum cavity impedance, and to determine the requirements on feed back systems, 3D beam dynamics studies are performed on a parallel cluster of processors at GSI.

e) **Fast cycling superconducting magnets.** For both synchrotrons, s.c. magnets with high ramp rates are under development. The minimization of AC losses, the optimization of the field quality and the long term mechanical stability are key issues. For SIS300, curved alternatives to the short straight 6 T dipoles are being studied. The resulting magnet properties are checked by dynamic aperture and beam loss simulations.

Parallel Operation and Synergy

An important aspect in the design of the facility is a high degree of truly parallel operation of the different research programs. Simple beam splitting and switching to different target locations is of course generally possible at any accelerator with relatively small effort. But this in general does affect the integrated luminosity of a single experiment. Truly parallel operation, with the constraints of accelerator cycles, is considerably more difficult. It provides maximum integrated beam time or integrated luminosity for each of the different programs operating in parallel. This implies that the facility operates for the different programs more or less like a dedicated facility.The proposed facility concept is therefore cost-effective. A modest addition in facility structure, say an additional storage ring, provides essentially a full scale new program without the need of a central facility, since that already exists for the other programs. The proposed scheme of accelerator and storage rings has the characteristics to optimize such a parallel and highly synergetic scheme. The proposed scheme will work very well due to the considerable development and experience gained at the present GSI-facility: at the existing system, parallel operation of different beams from the three UNILAC injectors and sources, acceleration of these beams to different energies with different intensities, and serving different experiments at the UNILAC, at SIS (including ion beam tumour therapy), and at the ESR, is being routinely demonstrated.

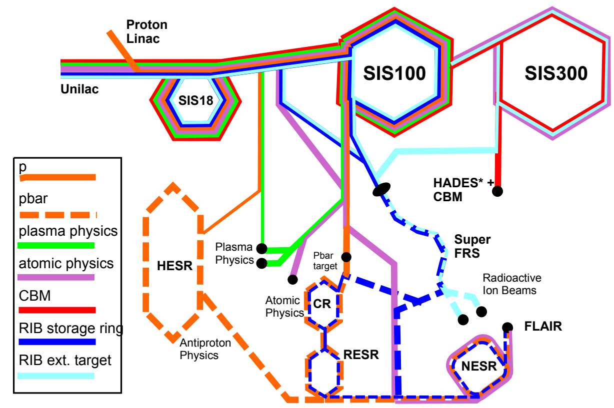

Figure 4: Schematics of the highly efficient parallel operation of the new facility. Up to four different scientific programs can be served in parallel: A proton beam (orange), accelerated in SIS100, produces antiprotons (orange dashed), which are then collected, accumulated and cooled in the CR/RESR storage-ring combination, and transferred either to the HESR or to the NESR for experiments. In parallel, i.e. during the fraction of the SIS100 super-cycle not needed for proton beam production, a primary heavy ion beam (blue) is accelerated in SIS100 and slowly extracted to the Super-FRS to produce radioactive secondary beams (blue dashed) for fixed target experiments. (Alternatively the radioactive beams could be sent to the CR and NESR instead of the antiprotons). In addition, every 10-100 seconds a high-energy heavy-ion beam (red) is accelerated in SIS100/300 and slowly extracted for nuclear collision experiments. Moreover, intense beam pulses (green) are provided every few minutes for plasma physics experiments which require very low repetition rates. Alternatively, atomic physics experiments (violet) may be served by SIS100 in the pauses of the antiproton production.

Figure 4 illustrates how parallel operation performs with a cooled and accumulated antiproton beam, in parallel to a fixed target experiment with radioactive beams and/or relativistic heavy-ion beams slowly extracted from the second synchrotron ring SIS300, and an additional beam for plasma physics.

UPGRADE OF THE EXISTING GSI ACCLERATOR FACILITY

The existing accelerators (UNILAC and SIS18) serve as injector for the new synchrotron SIS100 and especially in phase 1 partly also for the storage rings and the Super-

FRS. In order to match the requirements of the FAIR facility, upgrade programs for UNILAC and SIS18 are presently being performed. In the last three years GSI could increase the Uranium intensities for injection into SIS18 significantly. Clearly defined upgrade measures for the UNILAC will further raise the U^{28+} beam current from the present 2.5 emA to the required 15 emA. With this intensity, $2.7 \cdot 10^{11}$ U^{28+}-particles will be injected within 82 μs into SIS18.

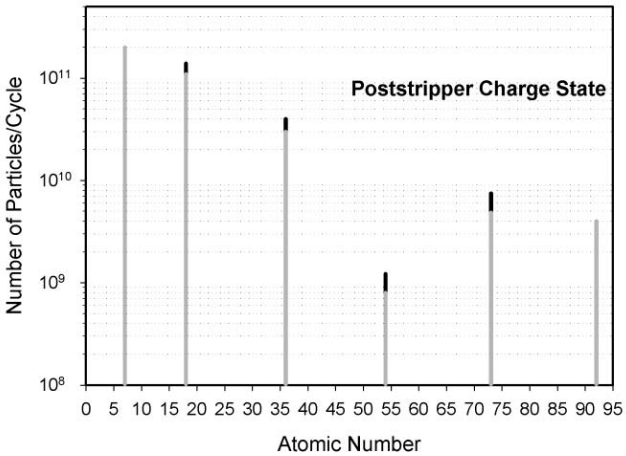

Figure 5: Present status of maximum number of particles of ions with different atomic numbers and intermediate charge states accelerated in SIS18.

The existing heavy ion synchrotron SIS18 will be used in two different operation modes within the FAIR project. In FAIR stage 1, SIS18 will serve as high energy accelerator, providing e.g. U^{73+}-ions at energies up to 1 GeV/u for the radioactive beam program involving the Super-FRS and the connected storage rings CR and NESR. In FAIR stage 2 and 3, SIS18 will be used in a fast repetition mode as booster for the new synchrotron SIS100.

a) SIS18 operation in phase 1 as driver for the radioactive beam program requires:

- Operation with one cycle per second (1 Hz) and
- High intensity operation with highly charged heavy ion beams, especially acceleration of $2 \cdot 10^{10}$ U^{73+} ions per machine cycle,

b) SIS18 operation as booster synchrotron for SIS100 requires:

- Operation with 4 Hz for protons or 2.7 Hz for heavy ions and
- High intensity operation with intermediate charge state heavy ion beams, especially acceleration of
  - $2 \cdot 10^{11}$ U^{28+} -ions per machine cycle or
  - $5 \cdot 10^{12}$ protons per machine cycle,
- Pulse-to-pulse switching between different ion species.

In the booster mode, SIS18 will be operated with a dipole ramp rate of 10 T/s up to a maximum dipole field of 1.8 T, which corresponds to a maximum magnetic rigidity of 18 Tm. At acceleration at harmonic number h=2 in SIS18, two bunches of ions will be prepared and transferred with each booster cycle to SIS100. Eight of ten buckets will be filled with four booster cycles. An extended upgrade program has been launched to achieve the described operation parameters. Nearly all main technical subsystems are involved. The most important upgrade tasks and the scheduled year of installation (in brackets) are:

- Task 1: RF System - New h=2 acceleration cavity and bunch compression system for FAIR stage 0, 1 (2009 and 2006/2007)
- Task 2: UHV System - New, NEG coated dipol- and quadrupole chambers (2008/2009)
- Task 3: Insertions - Set-up of a „desorption“ scraper system (2008/2009)
- Task 4: Injection/extraction systems - New injection septum, HV power supply and large acceptance extraction channel (2006)
- Task 5: Beam diagnostics system - Fast residual gas profile monitor and high current transformer (2007)
- Task 6: Injector - Set-up of a new transfer channel charge separator (2007)

The operation at a stable dynamic pressure of about $4 \cdot 10^{-10}$ mbar for injection and acceleration of $2.7 \cdot 10^{11}$ U^{28+}-ions requires an R&D phase for the development and testing of a new dedicated scraper system, including R&D in the field of gas desorption physics. However, even after the full UHV upgrade has been realized, a significant amount of ionization beam loss must be accepted (see Figure 6).

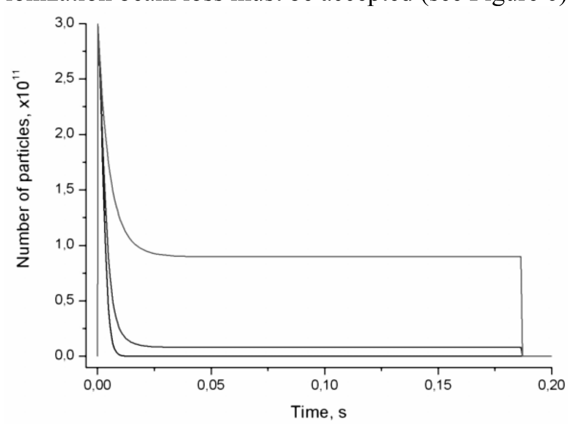

Figure 6: Expected U^{28+}-beam intensity evolution in SIS18 during a 4 Hz booster sequence, calculated with StrahlSim. It was assumed that only 8 % of the gases desorbed inside the “desorption” scrapers are able to interact with the revolving beam. The different curves indicate different steps of the UHV system upgrade.

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