CURRENT STATUS OF THE FAIR PROJECT[#]

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Abstract

The idea of an Facility for Antiproton and Ion Research (FAIR) has been developed during the past years to provide the international community a world-leading infrastructure for nuclear and hadron research [1]. It is planned to realize the project within an international cooperation of 14 partner states: Austria, China, Finland, France, Germany, Great Britan, Greece, India, Italy, Poland, Romania, Russia, Spain and Sweden. Decision has been taken to start the project by end of 2007.

The scientific case for FAIR is grouped around fascinating fields of research:

- Nuclear structure and nuclear astrophysics with beams of stable and in particular short-lived radioactive nuclei far from stability.
- Hadron structure, the theory of strong intraction primarily with beams of antiprotons.
- Investigation of nuclear matter phase diagram and quark-gluon plasma with heavy ion beams at high energies.
- Physics of dense plasmas in combination with petawatt LASER fields.
- Atomic physics, quantum electro-dynamics and ultra-high electromagnetic fields with beams of highly-charged heavy ions, and low energy antiprotons.
- Applied research with ion beams for materials science and biology.

To cope with this rich experimental program a unique concept for the FAIR accelerators was developed at GSI together with the international science community. This concept builds on and substancially expands developments made at GSI and other accelerator laboratories worldwide in the acceleration, accumulation, storage and phase space cooling of high-energy proton and heavy-ion beams.

This paper describes the current state of preparation of the FAIR project, focussing on the R&D work performed on lattice layout and key components, i.e. pulsed super-conducting magnets, beam cooling devices etc.

INTRODUCTION

Planned on the site of the existing GSI laboratory, the Facility for Antiproton and Ion Research will provide high intensity, phase space cooled beams ranging from antiprotons to uranium-ions to the experiments. The present layout of the facility is depicted in Figure 1. Two superconducting rapid cycling synchotrons with a circumference of 1100 m, with magnetic rigidities of 100 and 300 Tm, respectively, are the heart of the the FAIR accelerator complex. The 100 Tm synchrotron SIS 100 is the working horse. It will accelerate ions and protons at a repetition rate of about 1 Hz and send them either to the converter-targets for radioactive ion beams (RIB), for antiproton beam production, to fixed target areas, or to the SIS 300 for further acceleration to even higher energies.

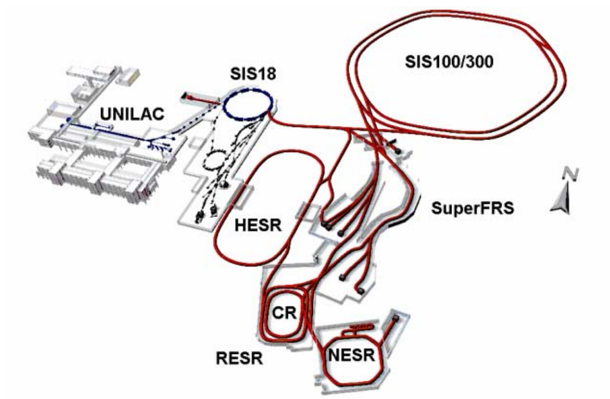

Figure 1: Schematic view of the FAIR facility. For further details see text.

Two dedicated storage rings, the New Experimental Storage Ring (NESR) and the High Energy Storage Ring (HESR) are versatile machines for in-ring experiments. Both storage rings will be filled with pre-cooled beams from a combination of a cooler and an accumulation ring, (CR and RESR).

The existing GSI linear accelerator UNILAC and the SIS18 synchrotron will serve as injectors for FAIR. A dedicated upgrade program has been started to achieve the required beam intensities. The program follows the lines:

i) increase the repetition frequency of SIS18 from 0.3 Hz up to 4 Hz,

ii) operate at the space charge limit at increased number of particles, i.e. accelerate ions at low charge state.

Beam losses caused by charge changing processes bear the risk of dynamic vacuum instabilities thus requiring a dedicated collimator system that "catches" those particles that undergo charge exchange. In addition vacuum chambers will be NEG-coated to increase the pumping speed. Using U^{28+} as reference ion rather than U^{73+} allows accelerating considerable higher intensities when operating at the space charge limit of the machine. However, the vacuum pressure has to stay well below 10^{-9} mbar at any time during the acceleration ramp. Furthermore the existing RF voltage has to be increased to 50 kV by exchanging the present system by a 2-gap MA loaded structure. Other measures to reduce losses such as an optimized injection system and improved diagnostics are in preparation or already installed. Table 1 compares the intensities for the reference beam as routinely achieved

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presently and planned for the injector. More details on the upgrade program are given in ref. [2, 3, and 4].

Table 1: Present and expected intensities after the upgrade of the SIS18 synchrotron

	SIS 18 today	SIS18 Upgrade	SIS18 for FAIR
Reference Ion	U^{73+}	U^{73+}	U^{28+}
Max. energy (GeV/u)	1	1	0.2
Max. intensity (particle/s)	$3 \cdot 10^9$	$2 \cdot 10^{10}$	$2 \cdot 10^{11}$
Repetition Frequency (Hz)	0.3	1	up to 4

THE FAIR SYNCHROTRONS

The FAIR accelerator complex consits of two dedicated rapid cycling superconducting synchrotrons [5] with maximum magnetic rigidity of 100 Tm (SIS100) and 300 Tm (SIS300), respectively. Both machines have identical circumference sharing a common tunnel.

SIS100 is designed for fast acceleration of up to $5 \cdot 10^{11}$ uranium ions to energies of 0.4 to 2.7 GeV/u, generating short single bunches of 50 to 100 ns duration, acceleration of $4 \cdot 10^{13}$ protons per pulse to an energy of 29 GeV for the antiproton production program. The SIS100 also serves as booster for the SIS300.

The SIS300 will either operate as a stretcher providing slow extracted beams at energies of 1.5 to 2.7 GeV/u or will accelerate fully stripped uranium ions up to 34 GeV/u in its high energy operating mode and extract the beam with spill durations of up to 100 s.

SIS100 lattice

Figure 2 depicts the layout of the SIS100 synchrotron. The six-fold symmetrical lattice makes use of a doublet structure in the arcs. The basic layout of a full sector or sextant comprises 14 unit cells of 12.9 m in length. The arc comprises eight full unit cells with a DF quadrupole doublet in front of the bending magnet terminated on both sides with a half-length dipole unit cell. Main lattice parameters are listed in Table 2.

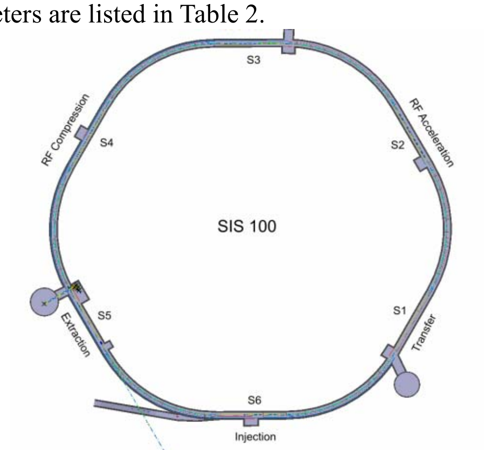

Figure 2: View to the SIS100 synchrotron.

In the straight sections dispersion is set to 0.2 to 0.4 m, depending on the tune setting. Three different working points have been choosen, according to the modes of operation: slow and fast extraction of heavy ions and acceleration of protons. Acceleration of proton beams to an energy of 29 GeV would require crossing of transition energy at γ_t = 18.6, thus a dynamic shift of transition energy will be introduced by adjustment of the dispersion function.

Table 2: Main lattice parameters of SIS100

Lattice Structure		doublet
Number of super-periods		6
Machine circumference	M	1083.6
Magnetic rigidity Bρ	Tm	100
Number of dipole magnets		108
Dipole bending angle α	Deg	3⅓
Maximum dipole field B	T	1.9
Bending radius R	M	52.6315
Dipole magnets per sextant		8 x 2 + 2 x 1
No. of quadrupole magnets		168
Maximum field gradient	T/m	27
Number of lattice cells N_F		6 x 14
Length of lattice cell L_F	M	12.9
Straight sections length	M	4 x L_F

Superconducting SIS100 magnets

The magnetic elements of the SIS100 follow the design principles of the NUCLOTRON, commissioned at LHE, Dubna in 1993 as described in ref. [6]. Equipped with iron-dominated magnets with superconducting coils, the superferric design is compatible to the required dipole ramp rate of 4 T/s and 1 Hz repetition rate.

A special superconducting cable is used: 31 strands are wrapped around a Cu-Ni tube and indirectly cooled by two-phase helium.

Figure 3 shows a photo of the NUCLETRON dipole magnet.

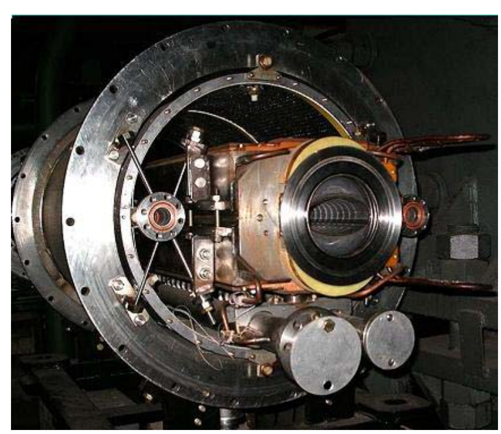

Figure 3: Photo of the original NUCLOTRON dipole.

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R&D activities towards a SIS100 magnet concentrated on the reduction of the heat load at the 4 K level in iron, coil and beam pipe.

The dynamic heat load of SIS100 dipole magnets is dominated by AC-losses (up t 80%). Furthermore, due to different operation modes, the heat load on average varies between 100% and 25% within minutes.

SIS300 lattice

The lattice of SIS300 has been re-optimized and simplified. For the six arcs a missing dipole FODO scheme with a half-length dipole matches the straight sections. Thus the geometries of the two synchrotrons are nearly identical, resolving earlier problems since SIS100 and SIS300 are mounted in the same tunnel on top of each other. Table 3 lists the main parameters of the lattice structure.

Table 3: Main parameters of the SIS300 lattice

Lattice Structure		FODO
Number of super-periods		6
Machine circumference	m	1083.6
Magnetic rigidity Bρ	Tm	300
No. of dipole magnets		48 + 12
Dipole bending angle α	deg	6⅓ + 3⅓
Maximum dipole field B	T	4.5
Bending radius R	m	66.6666
Dipoles per sextant		8 + 2 x 1
No. of quadrupole magnets		84
Maximum field gradient	T/m	45
Number of lattice cells N_F		6 x 14
Length of lattice cell L_F	m	12.9
Straight sections length	m	4 x L_F

SIS300 magnet system

The magnet structure of the SIS300 will use bend dipoles (bending radius 66.6 m) of 4.5 T maximum field. A ramp rate of 1 T/s has to be achieved. The Italian National Institute of Nuclear Physics (INFN) started a development program on this magnet. A half-length magnet is under construction and will be ready for testing in early 2009. Table 4 lists the main parameters of the SIS300 dipole magnet.

Table 4: Main parameters of the 4.5 T curved dipole magnet

central field	T	4.5
effective length	m	7.757
Coil inner Diameter	mm	100
Bending radius	m	66.6666
Peak field/Central field		1.09
Excitation current	A	8924
Collar thickness	mm	30
AC losses in the windings for a closed cycle 1.5T-4.5 T at 1T/s	J/m	20.7

More details on the superconducting magnets for the synchrotrons are given in ref. [7].

THE SUPER-FRAGMENT SEPARATOR

The superconducting fragment separator (Super-FRS) is a large-acceptance in-flight separator for exotic nuclei up to relativistic energies based on the experience of GSIs fragment separator [8]. Three branches are planned for reaction studies at complete kinematics and precision experiments with energy-bunched beams in a gas cell. Furthermore unique precision studies with brilliant electron-cooled exotic beams, including reaction studies with atoms from an internal target, will be performed in the ring branch, namely in the storage rings NESR and CR.

The layout of the Super-FRS is designed for a maximum beam rigidity of 20 Tm, for a momentum acceptance of ±2.5 %, and an angular acceptance of ϕ_y = ±40 % and ϕ_x = ±20 %, respectively, at a momentum resolution of 1500 for a beam emittance of 40 π·mm·mrad.

Figure 4 depicts the layout of the separator. Starting with a sequence of normal conducting radiation resistant magnets close to the production target, the Super-FRS magnet system consist of the pre-separator, followed by the main-separator, each equipped with an energy degrader stage. Both stages are achromatic, resulting in an image size at the final focal plane independent of momentum spread of the fragments.

Main system parameters of the Super-FRS are listed in Table 4.

Table 4: Main system parameters of the super-conducting fragment separator (Super-FRS)

Configuration		2-stage (2 + 4 dipole stages)		
Acceptance				
horizontal	mrad	±40		
vertical	mrad	±20		
Momentum	%	±2.5		
Target beam spot size				
horizontal σ_x	mm	1.0		
vertical σ_y	mm	2.0		
Momentum resolution				
first stage		750 (ε_x = 40 π mm mrad)		
second stage		1500 (ε_x = 40 π mm mrad)		
Branch		HEB	LEB	RB
path length	m	176	201	202
magnetic rigidity	Tm	20	7	13
Operation mode (beam/pulse length)				
slow extraction	s	1 - 20		-
fast extraction	ns	-		50

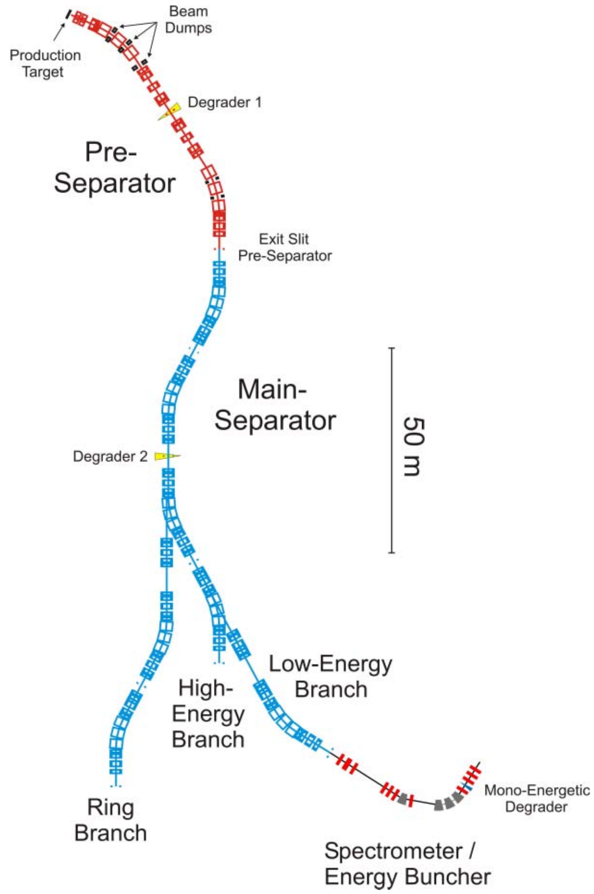

Figure 4: Layout of the Super-FRS for the production, separation and investigation of exotic nuclei. Separated rare isotope beams are delivered to three branches.

THE CR/RESR COMPLEX

Collector Ring and Accumulator Ring

The large acceptance Collector Ring (CR) and the Accumulator Ring (RESR), ref. [1], have been designed for fast stochastic pre-cooling and accumulation of antiproton beams emerging the production target at an energy of 3 GeV. The momentum acceptance of CR will be $\Delta p/p = \pm 3$ %, the geometrical acceptance 240 x 240 mm mrad. The ring is equipped with three stochastic cooling systems to achieve a phase space compression factor of 16.000 within an overall cooling time of 10 s. Batches of up to 10^8 antiprotons will be transferred to the RESR. Further cooled, a final stack of up to 10^{11} antiprotons is send from RESR to the HESR or transferred to the NESR storage ring. Figure 5 depicts the double ring complex.

In addition CR has to serve as pre-cooler ring for rare isotope beams from the Super-fragment separator up to 10^9 ions at kinetic energies of 740 MeV/u are stochastically cooled and then transferred to the NESR for in-ring experiments.

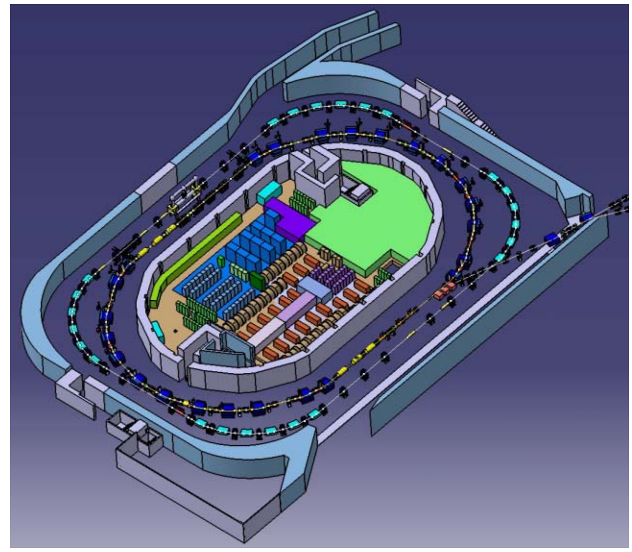

Figure: 5 View of the CR/RESR complex.

THE FAIR STORAGE RINGS

The New Experimental Storage Ring

Conceived as a versatile storage ring, the NESR [9] is employed in the experimental program with stored ion beams (stable and radioactive) and the preparation of antiprotons.

Designed in fourfold symmetry, the 18 m long straight sections allow ample space for the installation of an electron cooler, a gas-jet-, and an electron target. The fourth straight is intended to be employed in the investigation of electron scattering on radioactive nuclei. Thus a separate electron storage ring shares a common straight section with NESR.

The magnetic bending power of NESR will be 13 Tm, matched to the CR and RESR rings which are preparing the beams for NESR. Experiments with decelerated ions or antiprotons require ramping of all ring elements in two polarities. The operation with short-lived rare isotope beams defines the necessity for fast ramping at a rate of 1 T/s. This also applies to the magnetic field of the electron cooler system.

The basic lattice layout comprises two mirror-symmetrical unit cells with two quadrupole doublets and a 45 degree bending magnet in between at each of the four arcs. Transverse acceptance of 160 mm·mrad horizontally and 50 mm·mrad vertically at a momentum acceptance of ± 1.5 % have been achieved in the simulations. Tolerance studies have been performed taking into account multipole errors in the main dipole and quadrupole magnets. Simulation of random magnet errors and alignment tolerances are in progress.

Main parameters of the NESR are given in Table5.

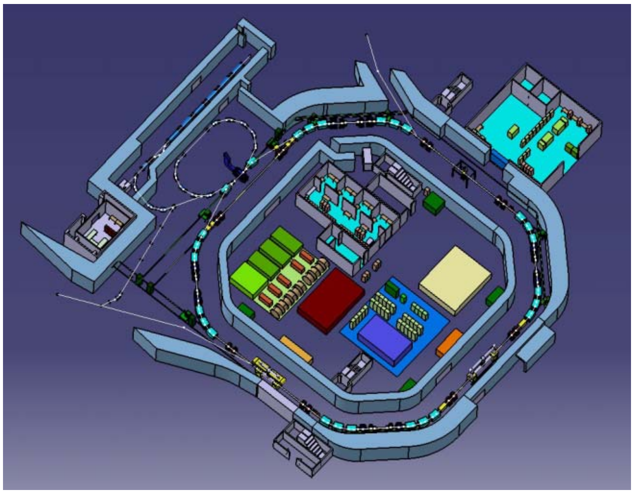

Figure 6: View to the NESR storage ring with the attached electron ring ER.

Table 5: Main parameters of the NESR storage ring

Circumference	m	222.11
Length of straight sections	m	18
Max./Min. magnetic rigidity	Tm	13 / 0.52
Max./Min. dipole field	T	1.6 / 0.064
Max. ramp rate	T/s	1
Max. A/Q		2.7
Horiz./vert. acceptance ($\Delta p/p=0$)	mm mrad	460 / 55
Horiz./vert. acceptance ($\Delta p/p=\pm 1.5\%$)	mm mrad	160 / 50
Momentum acceptance ($\varepsilon_H=0$)		± 2.1%
Horiz./vert. betatron tune		3.4 / 3.2
Transition energy γ_t		5.74
Maximum dispersion	m	7.24
Beam cooling systems	electron cooling	
Vacuum pressure	mbar	$\leq 10^{-11}$

The High Energy Storage Ring

The HESR [10] is designed as a race-track storage ring for antiproton beam rigidities up to 50 Tm. An internal H_2 gas-jet and/or (frozen H_2) pellet target and a large detector complex for secondary hadron and lepton detection (the PANDA detector) will be installed in one of the long straight sections.

A high energy electron cooler, delivering 1 A electron beam at energies up to 4.5 MV is planned. Together with a stochastic cooling system it will be possible to cover the so-called high luminosity mode, e.g. reaching peak luminosity of $2{\cdot}10^{32}$ cm^{-2} s^{-1} in the detector, and to achieve a momentum resolution down to $\Delta p/p \sim 10^{-5}$, at reduced intensity, in the high-resolution mode.

In Table 6 main design parameters of the HESR are listed.

Table 6: Main parameters of the HESR ring

Circumference	m	573.11
Phase advance/cell	2π	3
$\beta_{x,y,\ target}$	m	1 … 15
$\beta_{x,y,\ electron\ cooler}$	m	25 … 200
$\beta_{x,y,\ max,\ straight}$	m	590 … 130
$\beta_{x,y,\ max,\ arc}$	m	30
$D_{x,y,\ max,\ arc}$	m	12
Nat. chromaticity		-28 …- 16
γ_{tr}		6.0i variable
Dipole field	T	3.6
Quad gradient	T/m	34

CONCLUSIONS

The layout of the FAIR facility has been frozen. Detailed designs are currently being carried out at GSI and many partner laboratories. R&D on key-components has been demonstrated successfully, especially for rapidly-cycling magnets their feasibility for operation in the FAIR synchrotrons has been demonstrated. FAIR is expected to start in November 2007 as an international cooperation with contributing laboratories from the 14 FAIR member states.

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