CHALLENGES AND PROGRESS IN THE FAIR ACCELERATOR PROJECT

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Abstract

The proposed project FAIR (Facility for Antiproton and Ion Research) is an international accelerator facility of the next generation. It builds on the experience and technological developments already made at the existing GSI facility and other laboratories, and incorporates new technological concepts. Its heart is a double ring synchrotron facility SIS100/300 with five times the circumference of the existing SIS18. A system of cooler-storage rings CR, RESR, NESR and HESR for effective beam cooling at high energies and various experimental halls will be connected to the facility. The existing GSI accelerators UNILAC and SIS18 serve as injector for the new facility.

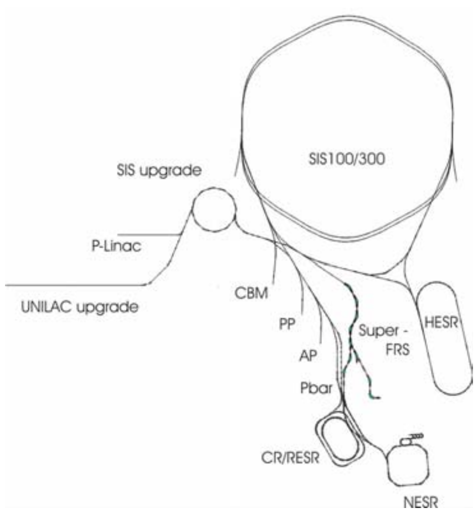

Figure 1: The planned FAIR accelerator facility.

The double-ring synchrotron will provide ion beams of unprecedented heavy ion and proton beam intensities as well as of considerably increased energy. Thereby intense secondary beams of unstable nuclei or antiprotons can be produced. The system of storage-cooler rings allows the quality of these secondary beams - their energy spread and emittance - to be drastically improved. Moreover, in connection with the double ring synchrotron, an efficient parallel operation of up to four scientific programs can be realized at a time. Reaching the main goals of the new FAIR facility, highest beam intensities, brilliant beam quality, higher beam energies, highest beam power and parallel operation requires many technological and beam physical innovations.

UNILAC

A major effort was made in the last three years to increase the delivered uranium intensities for injection into SIS18. The enhancement of heavy ion beam intensities results from an improved ion source performance, an upgrade of the HSI-RF structures, an increased stripper gas density, the optimization of the Alvarez-matching, the reduction of the number of single gap resonators, the sweeper mode for foil stripper operation, and the use of various new developed beam diagnostics devices. For the FAIR injector operation, UNILAC has to provide $2.7 \cdot 10^{11}$ U^{28+} -particles within 82 µs, which means a current of 18emA of $^{238}U^{4+}$ beam from the High Current Injector (HSI). The UNILAC-upgrade program will be continued with the design of a new front-end for U^{4+} acceleration, with stronger power supplies for the quadrupoles in the ALVAREZ section (for higher phase advance), a charge state separator system for the foil stripper in the transfer channel, and versatile (partly non-destructive) beam diagnostics devices suitable for the operation with megawatt (1450 MW) heavy ion beams [1].

PROTON LINAC

Besides the research program with radioactive ion beams, a major part of the FAIR experimental program is dedicated to antiproton physics. Taking into account the pbar production & cooling rate, $2 \cdot 10^{16}$ primary protons/h have to be provided. Therefore a new 70 MeV proton linac is planned to generate proton beams with an intensity of 70mA for injection into SIS18. The protons will be generated in an Electron Cyclotron Resonance (ECR) proton source. The extraction energy of 95 keV as well as the conceptual layout of the subsequent LEBT is equal to the layout of the front-end system of IPHI at CEA/Saclay [2]. Bunching and acceleration to 3 MeV will be done in an RFQ of either a 4-vane or a 4-rod type. The first type is state-of-the-art at the chosen RF-frequency, while the second type might be of considerable lower costs. For the time being, both designs are followed and a decision will be made within 2005. The main linac comprises 11 Crossed-bar H-cavities (CH) accelerating the beam to its final energy. CH-cavities represent the extension of well established IH-cavities to higher particle velocities [3]. In connection with the applied KONUS beam dynamics they provide high effective shunt impedances which in turn allow for a compact and cost efficient linac.

SIS18

An extended upgrade program has been launched to achieve the proposed operation parameters in the SIS18 mode for FAIR stage 1 and the booster mode in stage 2 and 3. Six main technical subsystems are involved in the upgrade program. Most of the corresponding work packages are technically well defined and will be realized during the next three years. For operation at a stable dynamic pressure of maximum $4 \cdot 10^{-10}$ mbar after injection and the acceleration of $2.7 \cdot 10^{11}$ U^{28+}-ions we still require an R&D phase which is dedicated to the development and testing of a well designed collimation system, including R&D in the field of gas desorption physics. The upgrade program, which will be partly supported by a EU construction program, involves the following technical issues :

- Installation of a 110 kV connection to the power grid for fast ramping with 10 T/s (4 Hz booster operation) exclusively used by GSI
- Design and installation of a new acceleration cavity for operation at h=2 and the generation of a two harmonic bucket together with the existing RF system
- Installation of two MA loaded bunch compression cavities
- Upgrade of the UHV system with new NEG coated dipole and quadrupole chambers
- Installation of a dedicated collimation system for the confinement and control of desorption gases
- Upgrade of the injection and extraction systems to minimize losses during multi-turn injection and extraction at low beam energies
- Operation at the space charge limit

SIS100

SIS100 is the main accelerator of the FAIR project. It is a new large synchrotron (C=1083m) designed for a magnetic rigidity Bρ=100 Tm, i.e. comparable in size to the large proton synchrotrons PS (CERN) and AGS (BNL). SIS100 is designed for the acceleration of high intensity and high energy proton and heavy ion beams. The proposed FAIR research programs define the following key parameters:

- For the radioactive beam program about $1\cdot10^{12}$ U^{28+} -ions per second at energies from 0.4 to 1.5 GeV/u in a single short bunch with lengths from 50 to 90 ns.
- For the antiproton facility $2.5\cdot10^{13}$ protons at 29 GeV every 5 s in a single bunch with a length of 25 ns.
- For plasma physics research at least $1\cdot10^{12}$ U^{28+} -ions at energies from 0.4 to 2.7 GeV/u in a single short bunch (30 to 90 ns), and
- For the research program on high energy nuclear collisions, $2\cdot10^{9}$ U^{92+} -ions as booster for SIS300.

Since the space charge limit for synchrotron acceleration scales with the factor A/q^2, intermediate charge state heavy ions (U^{28+}) will be used. Thereby the maximum beam intensity per synchrotron pulse is increased by the factor 6.8 for the charge state 28 compared to 73, which is the charge state used for the present SIS18 operation. In addition, a short synchrotron cycle time of T~1 s is required to achieve an average beam intensity of about $1\cdot10^{12}$ uranium ions per second. Therefore, new technical features will be developed for SIS100: (1) operation at a very low base pressure of p= $1\cdot10^{-12}$ mbar, i.e. in the XHV range, (2) careful control of beam losses due to charge exchange q=28→29 with residual gas molecules, by implementing a new, well-designed collimator systems, (3) s.c. synchrotron magnet operation at a high ramp rate with 4 T/s, (4) bunch compression for high intensity proton and uranium ion beams to provide single short bunches with pulse lengths of about 50 ns for the production and storage of secondary beams, and installation of two synchrotrons, i.e. SIS100 and SIS300 in one common tunnel. These technical features define new challenges for the synchrotron design, which reach far beyond the conventional design of existing proton synchrotrons. Especially the operation with intermediate charge state heavy ions requires new design concepts for the control of ionization losses and the generated desorption gases [4].

SIS300

SIS300 will be operated in two different modes. First in a so-called stretcher mode and second in a high energy mode. In the stretcher mode SIS300 will provide continuous slowly extracted beams of high intensity in the energy range of SIS100. To achieve the highest possible number of particles, SIS300 must be operated with intermediate charge state, heavy ions too. E.g. it is planned to provide slowly extracted U^{28+} beams with an intensity of 10^{12} ions/s at energies between 0.4-1.5 GeV/u for fixed targets experiments at the Super-FRS. In the second operation mode, SIS300 will be supplied with fully stripped heavy ion beams from SIS100 (e.g. U^{92+}). Fully stripped heavy ions will be generated by means of a stripper in the transfer line from SIS18 to SIS100. In this mode, the fully stripped heavy ions will be accelerated up to the maximum magnetic rigidity of 300 Tm. E.g. U^{92+} beams will be accelerated up to an energy of 34 GeV/u and slowly extracted with spill durations of up to 100 s.

HEBT

The beam transport system for the FAIR project will provide loss-free, emittance conserving transport of ion-, proton- and antiproton-beams:

- to and from the synchrotrons and storage rings,
- to and from the antiproton production target,
- to and from the SUPER-FRS, and
- to the experimental areas.

The required interconnections are shown in figure X. The topology of the FAIR facility is to a large extent determined by the diversity of beam line systems and the corresponding ion optical requirements. Individual beam line sections will be shared by different types of beams for different experiments. Sharing beam line sections simplifies the overall beam line layout. However, multiple use of individual beam line sections requires fast magnet ramping from cycle to cycle. The system is designed such that every single experiment can be served with a static setting of all beam line magnets. There is only one exception: The 50Tm proton beam line from SIS100 to the HESR reuses a part of the injection beam line. SIS300 delivers beam either to the CBM cave at a maximum rigidity of 300Tm or to the SUPER-FRS at a maximum rigidity of 100Tm. A separate beam line from SIS300 to the SUPER-FRS allows completely independent

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operation of the SIS100 and its beam line system during slow extraction from SIS300 (parallel operation). All beam line bends are compensated with respect to dispersion in first order. In many cases this determines the required amount of quadrupoles.

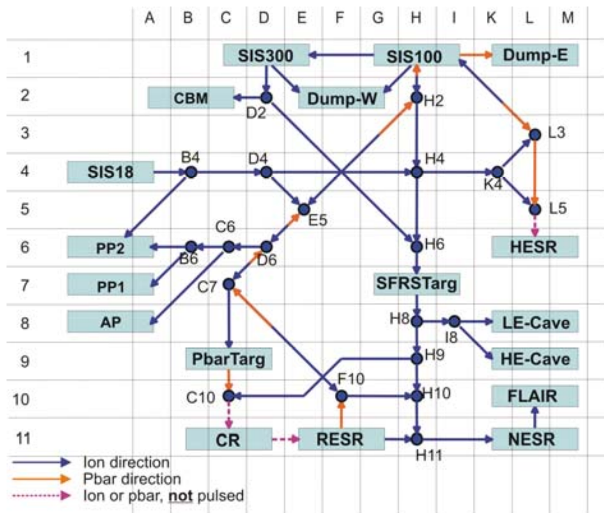

Figure 2: FAIR beam line system.

Because of shielding requirements, the vertical position of SIS100 is situated underground at -13.5m relative to SIS18. Three vertical beam lines connect the synchrotron tunnel level to the ground level; one for the injection beam line and two for the extracted beams from SIS100 and SIS300 respectively. The concept of a two-level accelerator complex is taken over from the synchrotrons to the beam line system. The extraction lines from SIS100 and SIS300 and the lines to the SUPER-FRS are guided in parallel on top of each other. In front of the SUPER-FRS final focus system these lines are merged by a vertical transition from SIS100. In summary the SUPER-FRS, pbar-Target, CR and the CBM-Cave share the upper plane at +1.3m relative to SIS18. The SIS18, AP-Cave, PP-Cave, RESR, NESR, FLAIR and the HESR are located in the lower plane. Four vertical transitions are needed; two for the SIS100 beam in front of the SUPER-FRS and in front of the antiproton target, one for the 13Tm beam in the transition from CR to the RESR and one in the beam line from the SUPER-FRS to the NESR.

CR

The CR is a storage ring with three major tasks:

- Stochastic pre-cooling of antiproton beams at a fixed energy of 3 GeV, to be deliverd to RESR.
- Stochastic pre-cooling of rare isotope beams at a fixed energy of 740 MeV/u, to be delivered to RESR.
- Mass measurements of short-lived secondary rare isotope beams in an isochronous mode.

The CR is a high acceptance ring with a full aperture injection and extraction kicker, RF cavities for bunch rotation, adiabatic debunching and rebunching, and a sophisticated stochastic cooling system. In order to fulfill its three purposes, its ion optics can be set to three different modes. A special procedure to shorten the cooling time is foreseen in the longitudinal phase space. In order to generate a beam with small initial momentum spread, a fast rotation of the phase space of the short bunches of secondary beams will be performed. The phase space rotation will be generated by means of a powerful (440 kV) RF decompression system, followed by a subsequent adiabatic debunching. The initial beam parameters for the two cases of stochastic cooling are determined by the longitudinal and transverse acceptance of the beam lines behind the antiproton separator and the Super-FRS.

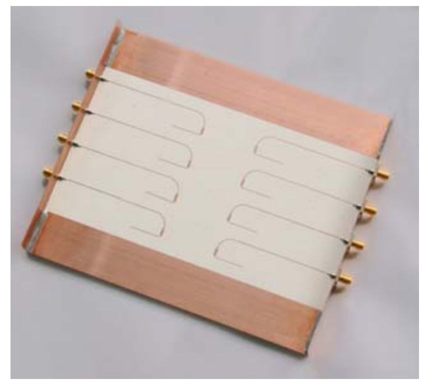

Figure 3: Test array of slot line pick-ups (rear side).

A major effort was put into the development of electrode structures which are applicable both for rare isotope and for antiproton beams. Detailed field theoretical investigations have shown that slot line couplers are versatile enough, and have a good sensitivity-bandwidth product (fig.3). The beam parameters at extraction are determined by the requirements for efficient antiproton accumulation in the RESR, and for fast electron cooling of RI beams in the NESR, respectively.

RESR

The main task of the accumulator and decelerator ring RESR is the accumulation of high intensity antiproton beams and the fast deceleration of rare isotope beams. The first task foresees the accumulation of up to 1×10^{11} antiprotons within 0.5–2 hours. This is accomplished by accumulating batches of 1×10^{8} stochastically pre-cooled antiprotons delivered by the CR every 5 seconds at 3 GeV. Accumulated antiprotons could either be re-injected into SIS100 for further acceleration or transferred to NESR for experiments with low energy antiprotons at FLAIR. The accumulation scheme foresees longitudinal stacking in combination with stochastic cooling. The second task of the RESR is the fast deceleration of rare isotopes to energies between 100 MeV/u and 500 MeV/u within 1 s which requires a dipole ramp rate of 1 T/s.

The RESR is designed as a racetrack shaped storage ring with a circumference of 245.5 m and a magnetic bending power of 13 Tm. In order to minimize the design effort, the RESR uses the same type of superferric dipole magnets as the NESR. To keep the additional costs of the RESR low, it is foreseen to recycle as many parts as possible from the existing Experimental Storage Ring ESR. The RESR layout is dominated by the requirements of the stochastic cooling system. The actual lattice is optimized for momentum stacking. The stochastic cooling system is used for antiproton accumulation only. The RESR will be equipped with two transverse cooling systems and up to three momentum cooling systems. The momentum cooling systems are a stack core, a stack tail and an intermediate cooling system. Optionally the installation of a pre-cooling system is being discussed.

HESR

The high energy storage ring HESR is used to stack and cool antiproton beams accumulated in the RERS and provides a maximum luminosity of 10^{32} $cm^{-2}s^{-1}$ for the in-ring experiment. Antiproton experiments are foreseen in the energy range between 0.8 and 15 GeV. At present, two different schemes for injection are under discussion, a) top-off injection at final energy via SIS100 or b) top-off injection at low energies directly from RESR. For the second option, HESR must be ramped and operated as a synchrotron. Both options are being compared with respect to cost savings and the achievable average luminosity taking into account the transverse damping times for cooling at the relevant energies. An intermediate energy electron cooler operated at the reference energy acts against the target heating and maintains the desired emittance equilibrium. A technical study, using an electrostatic accelerator charged by a proton cyclotron was performed by BINP.

SUPERCONDUCTING MAGNETS IN FAIR

Synchrotron Magnets for SIS100

GSI decided to adopt the Nuclotron design for the SIS100 magnets and established a collaboration with LHE (JINR Dubna). The superferric window-frame type dipoles and quadrupoles have a compact low cost design. The Nuclotron conductor was especially developed to be suitable for a high 'steady state' AC loss application. The main R&D goals are:

- Reduction/minimization of the losses at the 4K level in yoke, coil, and beam pipe,
- Improvement of the 2D and 3D field quality,
- Strengthening the mechanical structure, i.e. search for an optimal design for the coil structure to ensure a cycle rate of about10^8 within a life time of 20 years.

At 4 K the AC losses of the original Nuclotron dipole amounted to 9 W/m (coil) and 29 W/m (yoke) for the standard cycle (4T/s, 2T, 1Hz; no beam pipe).

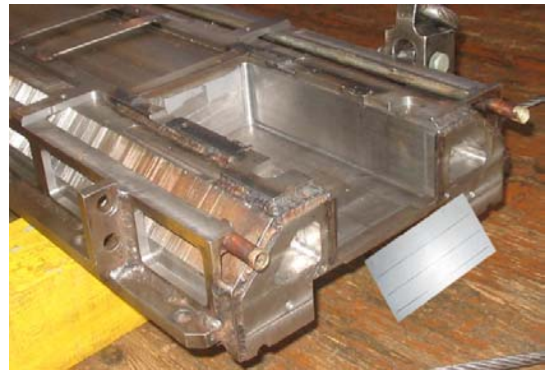

Figure 4: Preparation of the SIS100 test model PDP2 with improved yoke ends (laser-cut slits, reduced stainless steel end plate and minimized brackets).

This was clearly too high for the intended operation conditions of SIS100. The R&D results obtained up to now on our test magnets lead us to expect a final loss reduction in the SIS100 dipoles to 6+/-1 W/m (coil) and 7+/-2 W/m (yoke). So, we have reduced the dynamic losses at cryogenic temperatures by a factor of 3 and the corresponding overall AC loss in the SIS100 dipole magnets will not exceed 7 W/m at intended operating cycles [5]. Furthermore the iron lamination cross section was optimized by introducing negative shimming and slots. Model coil samples with a reinforced internal coil structure were built.

Synchrotron Magnets for SIS300

The SIS300 6 T, 1 T/s ramp rate, 100 mm coil aperture dipole design evolved from the earlier work on a SIS 200 4 T dipole design, which was based on a modified version of the BNL 80 mm coil aperture RHIC dipole design, but with a higher 4 T central field, rather than the RHIC 3.5 T value. The distinguishing new feature of both of these magnet designs is the required fast magnetic field ramp rate of 1 T/s, so that AC loss reduction concepts had to be developed for the magnet. The AC loss reduction concepts which were developed during the SIS200 program were tested in the 1 m long dipole model magnet GSI001 which was built and tested by BNL. It reached its design field of 4 T at a ramp rate of 4 T/s [6].

The effect of the high magnetic field ramp rate on the field quality during ramping has been investigated for GSI001 as well and analysis of test results and comparison with calculations is underway. The new 6 T dipole for SIS 300 requires a two layer coil, as opposed to the one layer RHIC coil design, upon which GSI001 was based. Therefore, the UNK 5.1 T dipole, built by IHEP in Protvino, Russia, was taken as the starting point for the SIS300 6 T dipole design. A collaboration was launched in 2002 to design this magnet and build test models. A conceptual design report was completed by June 2004, and a technical design report is now being prepared by IHEP. This will include information needed to design tooling, fabricate components, and build model magnets.

Storage Ring Magnets for HESR

The arcs of this DC-operated ring will have superconducting magnets very similar to the magnets used for RHIC at BNL. This will reduce the development effort.

Storage Ring Magnets CR

The main parameters of the 24 dipoles are: DC, warm bore, very large aperture, moderate field (≤ 2 T). This leads to the design choice of a superferric magnet with a warm iron yoke (minimum cold mass option → reduced cool down time) and a potted (or vacuum-impregnated) low-current coil, wound with monolith wire. Dipoles of this type are installed in the A1900 Fragment-Separator at MSU. All CR dipoles will be connected in series. Therefore, despite the solutions at MSU and RIKEN we want to use a laminated iron yoke allowing iron shuffling for mixing the steel properties.

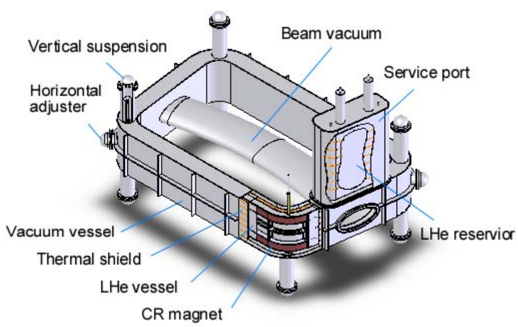

Figure 5: Cryostat structure of a CR dipole.

Originally the lattice was equipped with quadrupoles with embedded independent sextupoles. Since this option is rather difficult and tedious to realize, separated resistive quadrupoles and sextupoles are considered.

Super-FRS Magnets

The Super-FRS structure was chosen such that the dipole parameters are almost the same as those of the CR dipoles. Superferric quadrupoles are absolutely necessary for this particular application, due to the required high pole tip fields (aperture radius multiplied by field gradient). The 3 dipoles downstream from the target are in a high radiation area. To avoid a high heat load on the cryogenic system, these magnets will be designed as resistive magnets, using a high-radiation resistant conductor. The magnets of the so called energy buncher are specified to be superferric as well.

Storage Ring Magnets for NESR /RESR

Only the dipoles are designed to be superconducting. A ramp rate of 1 T/s requires a coil design different to that of CR and Super-FRS. The cryostat design will prevent large eddy current losses. The important differences to the magnets of the CR and Super-FRS are:

- They are pulsed with a maximum ramp rate of 1 T/s
- The useable gap volume is smaller, 250mm x 70 mm compared with the 380mm x 140 mm of the CR and Super-FRS main dipole.

In order to keep the inductance low one can either use the Nuclotron-conductor (designed for large steady-state-AC losses) or a standard Cable-in Conduit Conductor (CICC). The choice depends strongly on the operating cycles of the magnet. In both cases helium containment is not needed. GSI made a preliminary design based on the following assumptions:

- Coil window: as for CR dipole (assuming that only the coil is in the cryostat)
- Maximum engineering current density of the coil 150 A/mm^2
- Current: 6000A.

A low number of turns (10 only, 2 layers) makes a curved magnet with negative coil curvature possible. An air filter and a hole near the pole guarantee the field quality over the large dynamic field range of the magnet between 0.06 and 1.6T.

High Energy Beam Line Magnets

For synergy reasons, the policy was to use to a large extent magnets already developed for the rings. Since the magnet parameters are almost identical, as far as field level, aperture and cycle time are concerned, this policy saves a lot of development and production costs. Only the sc magnets for the target final focusing systems require special developments. Most of the low energy beam lines for the injection from SIS18 and the 13 Tm beam lines between after the targets are equipped with resistive magnets.

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