STATUS OF THE FAIR PROJECT*

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Abstract

The acceleration of high intensity primary beams and the preparation of high quality secondary beams are the main goals of the accelerators of the FAIR project. Primary beams are either heavy ions used for the production of rare isotope beams or protons which are converted to antiprotons. Various cooling systems are planned which allow the preparation of the secondary beams for high precision experiments. The system of accelerators which has been recently documented in a set of technical design reports is passing through a final review. This report gives an overview of the FAIR accelerators and the status of the design of various systems and components.

INTRODUCTION

Acceleration of high intensity primary beams and their conversion to secondary beams is the main mission of the proposed Facility for Antiproton and Ion Research (FAIR) [1]. The existing GSI accelerator system with the UNILAC linear accelerator and the heavy ion synchrotron SIS18 will serve as injector complex for the new synchrotron SIS100. Two production targets, one for antiproton production using a primary proton beam and one for rare isotope production by fragmentation or fission of heavy ions, in combination with subsequent magnetic separators, will provide the secondary beams. In a complex of storage rings the secondary beams will be prepared for the users. Beam cooling will be crucial to prepare high quality secondary beams. Stochastic cooling will provide pre-cooling of the hot secondary beams, for antiprotons it is also employed in beam accumulation. Electron cooling is mainly a tool to perform experiments with high quality stored beams. Moreover, it is also employed in the accumulation of rare isotopes and in the deceleration of ions and antiprotons in order to increase the efficiency of these manipulations. Details of the new accelerators of the FAIR project were documented in technical design reports which are the basis for further planning of the accelerators and the general machine concepts [2].

UPGRADE OF THE EXISTING FACILITY

The main activity at the existing GSI accelerator facility is devoted to the improvement of the machines for high intensity operation. The low energy part of the UNILAC is being modified in order to increase the transverse acceptance and therefore to accelerate beams with larger efficiency. This is achieved by installation of new electrodes in the RFQ and new matching sections between RFQ and DTL section. The goal is the acceleration of beam intensities for the heaviest ions which are sufficient to fill the synchrotron SIS18 up to the space charge limit. Installation of new power converters in the linear accelerator as well as the recent addition of a large acceptance charge state separator between linear accelerator and synchrotron will significantly improve the performance with intense heavy ion beams.

The upgrade of SIS18 comprises various aspects. The problem of the dynamic vacuum has attracted high attention. The increase of the residual gas pressure during high intensity operation with low charge states at the SIS18 injection energy of 11.4 MeV/u is counteracted by various measures. Amongst others the pumping speed was increased by NEG coating of vacuum chambers, additional collimators for localized and defined beam loss at surfaces designed with special orientation and low desorption materials were installed. Various technical modifications will allow an increase of the ramping rate of SIS18 to 10 T/s which is beneficial with respect to high average intensity and which will reduce the losses in the residual gas during injection and acceleration. A new connection to the power mains has been installed. Some weak corrector magnet power converters are being replaced, an additional acceleration cavity operating at $h = 2$ will allow faster acceleration. A dedicated machine development program with beam dynamics investigations and hardware improvements is aiming at filling the synchrotron SIS18 with heavy ion beams up to the space charge limit.

NEW SYNCHROTRONS

It is planned to install two new synchrotrons with a circumference of 1083 m in a common tunnel. They can be either used for the acceleration of highest intensity beams of relatively low charge states, e.g. U^{28+} from SIS18 without any stripping between UNILAC and SIS18 or for acceleration to highest energies at the expense of intensity due to unavoidable losses in the stripper foil.

SIS100

For the achievement of high average intensities SIS100 is designed as a fast ramping synchrotron with a magnetic bending power of 100 Tm using super-ferric magnets [3]. With a maximum ramp rate of 4 T/s it can provide 5×10^{11} U^{28+} ions at 2.7 GeV/u every 1.5 s. With the same cycle time 2×10^{13} protons can be accelerated to 29 GeV.

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SIS100 is designed for slow and fast extraction. The fast extracted beams will be compressed into a short bunch of less than 50 ns length prior to extraction. For heavy ions a bunch compression scheme is applied at extraction energy. However, for protons at full energy the synchrotron period is too long, therefore a bunch merging scheme at intermediate energy resulting in a single bunch, which is accelerated to the final energy, is favorable.

The machine design is based on super-ferric magnets of the NUCLOTRON type [4]. Two straight full length dipole magnets of this type are available for testing and optimization at GSI. The manufacturing of a curved dipole prototype and of a quadrupole prototype is in progress. The cold vacuum chamber of this magnet concept will provide ultra-high vacuum conditions.

In order to alleviate the outgassing and dynamic vacuum problems during heavy ion operation the lattice is designed for controlled loss of ionized particles in specially designed beam catchers. A dedicated program to study desorption effects which will also guide the SIS100 design has been launched at the existing SIS18.

To accelerate the beam with the maximum ramp rate a total rf voltage of 400 kV at harmonic $h = 10$ will be needed. Ferrite loaded cavities operating in the frequency range 1.1 to 2.7 MHz are used for acceleration. The final bunch compression of heavy ions will be performed by magnetic alloy filled cavities operating in the frequency range 0.395 to 0.485 MHz. A total of 16 cavities with a voltage of 40 kV each will be needed to generate the required single short bunch for the injection of rare isotope beams into the collector ring and for plasma physics experiments.

SIS300

The second synchrotron SIS300 is aiming at highest energies for highly charged ions. The cos(θ)-dipole magnets are foreseen to be ramped with a rate of 1 T/s up to the maximum field of 4.5 T. A maximum energy of 34 GeV/u can be reached with highly charged ions. For lower charge states SIS300 can be used as a stretcher ring operated at fixed field delivering a nearly continuous beam by slow extraction of the ion beam from SIS300 after fast acceleration in SIS100 and transfer to SIS300. The present project schedule assumes that SIS300 will be added in a later stage of the project. Therefore the main activity is the design of the ring tunnel which can accommodate both synchrotrons. Hardware developments for SIS300 have a lower priority.

SECONDARY BEAM PRODUCTION AND SEPARATION

Antiprotons

Proton Linac The existing UNILAC accelerator is designed for the acceleration of heavy ions, the performance with protons is insufficient to serve as injector of high intensity proton beams which are needed for antiproton production. A new proton linac will accelerate protons from an ECR source to an energy of 70 MeV, which will be the energy for injection into SIS18 filling the two transverse acceptances by multiturn injection up to the space charge limit. A low energy RFQ section accelerates the protons to 3 MeV, a section with 12 Crossed-bar H-mode accelerating cavities (CH-DTL) operating at 325 MHz will allow the acceleration of short pulses ($\lessapprox 40\mu$s) with a maximum proton current of 70 mA to the energy of 70 MeV.

Antiproton Target A single bunch of 29 GeV protons from SIS100 will impinge on a nickel target of 60 mm length in order to produce antiprotons. Up to 2×10^{13} protons will be compressed into a bunch of less than 50 ns length in order to minimize the longitudinal heating in the subsequent target. The antiprotons which exit from the target with an energy of 3 GeV and large divergence will be first focussed by a magnetic horn and then be selected by a large acceptance magnetic separator. Chromaticity corrections as well as special collimators are part of the separator concept. The cycle of proton acceleration for antiproton production will be repeated every 10 s, which is close to the thermal limit of the target. The expected production rate is at least 1×10^8 antiprotons per pulse in the phase space volume which can be accepted by the magnetic separator and the subsequent Collector Ring. As the production target and the proton dump are located in close vicinity to the fragment separator for RIBs and some experimental installations, detailed FLUKA simulations have been performed in order to reduce the radiation during operation, but also to minimize the radiation level by activation of the target and proton beam dump area.

Rare Isotopes

For rare isotope production a heavy ion beam with an energy of about 1.5 GeV/u from SIS100 will be directed to the production target. The large acceptance of the fragment separator SuperFRS [5] for beams of divergence $\pm 40/20$ mrad horizontally/vertically and momentum spread ± 2.5 % requires the use of large acceptance superconducting magnets. Both slow extraction for fixed target experiments and fast extraction of a short bunch for experiments with rare isotopes in the storage ring complex of FAIR, can be provided. The combination of a pre-separator and a main separator with a bending power of 20 Tm provides high selectivity for fragment separation. If highest purity of the rare isotope beam is required, an additional degrader can be inserted between the two separator stages, thus allowing a $B\rho - \Delta E - B\rho$ separation technique. Three branches, for low and high energy experiments and a branch transferring the rare isotopes to the storage ring complex are foreseen after the fragment separator.

COLLECTOR RING CR

The Collector Ring (CR) has a circumference of 216 m and offers large acceptance which is important for the efficient use of the secondary beams injected from the production targets and separators. The design considerations of the CR are governed by the stochastic cooling system which will be applied to ions and antiprotons. The ion optical functions are chosen differently, such that proper mixing conditions are provided for both beams [6]. As the ring will be operated for both beam species at the maximum bending power of 13 Tm, the particle velocity is different for antiprotons ($\beta = 0.97$) and rare isotopes ($\beta = 0.84$). Consequently, different ion optical settings will be used, which give the best momentum slip factor for the respective beam species. Common to both ion optical modes are dispersion free straight sections for injection and extraction and for the installation of the rf system. The rf system is designed to perform a fast bunch rotation and debunching of the incoming short bunch. This longitudinal phase space manipulation reduces the momentum spread by about a factor of 5 which results in a reduction of the total cooling time for stochastic cooling.

The rf system of the CR is designed to provide the high voltage gradient over some hundred turns of the beam. The operation with high electric field in the frequency range 1.17 to 1.37 MHz is achieved by filling the cavity with magnetic alloy material. The 1 m long cavity has to be operated with a maximum voltage of 40 kV, but due to the short pulse needed for bunch rotation the average power dissipation is below 2 kW which requires only forced air cooling. Five such cavities are needed for the fast bunch rotation.

Stochastic cooling in the CR is used for a large range of beam parameters [7]. The velocity of rare isotopes and antiprotons and correspondingly the revolution time differs by 15 %. The cooling system also has to deal with a wide range of intensities, e.g. for rare isotope beams the intensity can vary from nearly single ions up to some 10^8. The signal from antiprotons, even if the full intensity of 10^8 is injected, is rather weak due to the low charge. A total cooling time of 1.5 s is needed for ions in order to make full use of the fast cycle of SIS100. This can only be reached for lower intensities due to the usual increase of the cooling time with particle number, if a certain beam intensity is exceeded. The cooling time for antiprotons should be 10 s at most, 5 s total cooling time will result in doubling the antiproton production rate. For cost reasons the bandwidth of the stochastic cooling system is presently limited to the range 1 to 2 GHz, an optional extension to 1-4 GHz will reduce the cooling time.

For the cooling of the low intensity ion beams and for the antiproton cooling high sensitivity of the pick-ups is indispensable. A new slot line structure for the band 1-2 GHz coupled to a micro-strip circuit has been developed [8]. The pick-ups can be cooled inside the vacuum tank to 20 K with cold heads mounted outside. A prototype tank is presently assembled in order to test the concept [9]. Pick-ups and kickers will be moved during the cooling process synchronously with the decreasing emittance of the beam in order to have best signal to noise ratio. Switchable delays allow matching the traveling time of the correction signal to the time of flight of the particles from pick-up to kicker. The designed system has been proven to provide good amplitude and phase flatness in the band from 1 to 2 GHz.

ACCUMULATOR RING RESR

The concept of antiproton production with high average rate requires a second ring after the pre-cooling ring for the accumulation of high intensity stacks. It has been shown at the former antiproton complex at CERN, particularly at the accumulator ring AA [10], and at FNAL with the Debuncher and Accumulator ring [11], that the combination of two rings results in highest production rate.

In order to make most efficient use of buildings and technical infrastructure the accumulator ring RESR and the pre-cooling ring CR will be installed in a common tunnel. The ion optical lattice of the RESR is optimized for the requirements of a dedicated stochastic cooling system which mainly manipulates the incoming pre-cooled beam from the CR. The concept is based on a large dispersion at the stochastic cooling pick-ups in order to adjust the cooling strength for injected particles and the accumulated stack. Different pick-up systems have high sensitivity either to the incoming beam on an inner orbit (lower momentum) or to the stack which is accelerated to an outer orbit (larger momentum).

The requirements to the ion optical layout of the RESR are best matched by a lattice with a hexagonal ring shape. The circumference of 240 m allows the installation of the RESR around the CR, conflicts between neighboring ring components of the two rings are avoided by installing the two beam axes with a vertical offset of 1.2 m. A dispersion free beam transport system between the two rings has been designed.

The required large momentum acceptance of $\Delta p/p = \pm 1\%$ for the accumulation of antiprotons is dominating the ring design. Another feature are small vertical beta functions at the location of the longitudinal cooling pick-ups in order to minimize an unwanted interference between injected beam and stack. The injected beams are pre-cooled in the CR, thus the required transverse acceptance of 25 mm mrad is very moderate. For the tuning of the stochastic accumulation system the transition energy can be varied by adjusting the focussing strength of the nine groups of quadrupole magnets, yielding a range for the transition energy γ_t from 3.3 to 6.4 [12]. This flexibility of the lattice has been used in simulations of the accumulation process and will also allow optimization during ring commissioning.

A detailed concept for the antiproton accumulation system of the RESR has been worked out [13]. The ion optical properties of the ring are integral part of the concept. It is foreseen to inject from the CR, which is located inside the RESR, onto an inner orbit of the RESR with a momentum offset $\Delta p/p = -0.8\%$. From the inner orbit the antiprotons are transported with the rf system to a central orbit. Finally, the stochastic cooling system drives the particles to an outer orbit at $\Delta p/p = +0.8\%$, where a high intensity stack is built up. The longitudinal cooling system in a basic version comprises two stack tail cooling systems in the band 1-2 GHz and a longitudinal core cooling system with the band width 2-4 GHz. For transverse core cooling two systems for horizontal and vertical cooling in the frequency range 2-4 GHz are foreseen. The small vertical beta function of 2 m allows the use of a vertical gap of only 20 mm in the momentum pick-ups which results in a well localized field distribution. The dynamic range of the cooling system is determined by the number of injected antiprotons of 1×10^8 per cycle and the maximum stack intensity of 1×10^{11}. According to simulations the influence of beam feedback for up to 10^{11} stored antiprotons is weak and should not adversely affect the beam stability.

The proposed accumulation mode requires C-shaped injection kickers which allow a displacement of particles in horizontal direction. A design with a ferrite yoke installed inside a vacuum tank can fulfill the requirements. The proposed injection of a single bunch from the CR can be achieved with rise times of the kicker field of 150 ns and a flat top time not exceeding 1 μs.

The RESR is not exclusively used with antiprotons, but is also a link in the chain of rare isotope accelerators. It can serve as a decelerator ring and as such it will be useful for both ions and antiprotons. For injection of antiprotons at the higher energy the transition energy of the RESR can be increased and consequently no crossing of the transition energy occurs during deceleration. For the much lower energy of ions this is achieved for the whole range of possible ion optical modes.

If rare isotopes below the production energy of 740 MeV/u are needed in the subsequent NESR, the RESR can decelerate them to energies between 100 and 740 MeV/u. This is most important for the collider mode of the NESR, when highest stability of the ion orbit is required and consequently deceleration in the NESR is not recommendable. The RESR therefore is equipped with magnets which allow a ramp rate of 1 T/s, the dipole magnets are identical with the NESR dipoles and also the other magnets have common design features with the NESR magnets. The power converters support the fast ramp rate. The rf system is based on the existing SIS18 system, installation of additional capacitors will allow an operation at harmonic $h = 1$ with a frequency range from 0.53 to 1.21 MHz. For the lowest ion energies a debunching and rebunching to harmonic $h = 2$ at an intermediate energy is necessary during the deceleration cycle.

STORAGE RING NESR

The NESR is designed for storage and internal experiments with ions, stable and unstable. It also allows a large variety of beam manipulations with ions and antiprotons which are supported by a powerful electron cooling system [14]. The strong requirement by experiments to study highly charged ions at lowest possible energy resulted in a concept of the NESR which allows fast ramping from the high injection energy needed for the production of highly charged and rare isotope beams to low energies. The present design of components is aiming at deceleration with a rate of 1 T/s. The fast ramp rate is most important for experiments with short-lived rare isotopes. The lowest energy for all kinds of ions is 4 MeV/u. The magnetic bending field is changed by a factor of about 25 from injection to lowest energy. The low energy beams are not only stored, they can also be extracted from the NESR.

Fast extraction is used for transfer into another low energy storage ring (the LSR of the FLAIR experiment). Slow extraction by resonant excitation of the beam or knockout with rf noise, and charge changing extraction by electron capture in the NESR internal target or its electron cooler are the available options, which governed the design of extraction components. The extraction components are designed for beams of a maximum magnetic rigidity of 4 Tm, that means that beam extraction is only available for decelerated beams. The extraction of decelerated beams is required for secondary beams or highly charged ions, all other ion beams can be provided directly from the synchrotron.

Antiprotons injected at 3 GeV from the RESR can be decelerated to a minimum energy of 30 MeV, which corresponds to the same variation of magnetic field strength as during ion deceleration. The low energy antiprotons can be extracted with slow resonance extraction or an adjustable fraction of the circulating low energy antiprotons can be transfered after fast extraction to FLAIR.

The NESR is designed with four 18 m long straight sections for the installation of special components and experimental equipment in the ring of 222.8 m circumference. The ion optical structure provides large acceptance, 150 mm mrad horizontally and 40 mm mrad vertically, for a momentum acceptance of $\Delta p/p = \pm 1.5\%$. Seven families of quadrupole magnets in the fourfold symmetric standard lattice result in horizontal and vertical tunes of $Q_x = 4.20$ and $Q_y = 1.87$. Twelve individually powered sextupole magnets are foreseen to achieve the required dynamic aperture, also taking into account higher order field errors in the main magnets. The large acceptance is required for experiments which need to simultaneously store particles with different momentum or, equivalently, particles with the same velocity, but different charge and mass. A large dispersion in the arcs results in a spatial separation of particles with different momentum, detectors can be placed in the dispersive sections for the observation of these particles.

The injection system is matched to the acceptance of the beamline from the fragment separator and allows direct injection of rare isotope beams from the SuperFRS with emittances of 50/20 mm mmrad, horizontally/vertically, and a momentum spread $\delta p/p = \pm 0.5$ %. This allows injection of fragments with large momentum spread or of multi-component beams with a corresponding range of charge to mass ratio.

For all operational modes of the NESR the availability of electron cooling over the whole range of ion energies is crucial, antiprotons can be cooled at energies below 800 MeV. Electron cooling provides high beam quality for experiments with stored beams. The deceleration profits from electron cooling, as the small beam emittance after cooling will allow almost loss free deceleration.

The NESR concept foresees the accumulation of heavy ion beams by longitudinal accumulation in combination with electron cooling. A wide band rf system which can be operated with variable voltage will compress the stored beam into a fraction of the circumference with a gap which can be filled with a new injection. The feasibility of such schemes has been confirmed in simulations and experimental investigations at the existing ESR storage ring [15].

For short-lived ions the cooling system is optimized to cool down beams, which were pre-cooled in the CR, with a total cooling time shorter than 1.5 s. The main application for this mode will be Schottky mass spectrometry [16], the determination of the mass of rare isotopes by measurement of their revolution frequency employing non-destructive Schottky noise detection. With momentum spreads of the cooled beam below 1×10^{-6} a mass resolution of at least the same order of magnitude can be achieved.

The NESR has long straight sections for the installation of the electron cooler, an electron target and an internal gas jet target, with additional space for detector systems. The northern straight section is reserved for collision experiment of rare isotopes with electrons circulating in an adjoining smaller storage ring. This electron ring allows collisions of rare isotope beams in a bypass of this straight section with electrons of up to 500 MeV energy. Although not funded in the start version of the FAIR project, this option is taken into account in all space considerations for the building concept and the preparation of infrastructure. The collision in the bypass is achieved by switching off the dipole magnets at the end of the straight section and installing two additional dipole magnets which bend the ion beam into and out of the bypass section.

HIGH ENERGY STORAGE RING HESR

The High Energy Storage Ring (HESR) with a circumference of 575 m and a magnetic bending power of 50 Tm will be the main user of the antiprotons accumulated in the RESR [17]. The antiprotons will be injected at 3 GeV and then be prepared according to the requirements of the experiment. The energy ranges from a maximum of 14.1 GeV down to a minimum of 0.83 GeV. The antiprotons are accelerated or decelerated in the HESR to the required energy with a ramp rate of 0.025 T/s. Experiments use an internal hydrogen target with a maximum thickness of 4×10^{15} atoms/cm^2. Stochastic and electron cooling are foreseen. The stochastic cooling supports operation in a high luminosity mode with 10^{11} stored antiprotons (luminosity 2×10^{32} cm^{-2}s^{-1}). For high resolution experiments electron cooling, which is presently planned for a later upgrade, would be operated at an order of magnitude smaller luminosity.

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