ADVANCED DESIGN OF THE FAIR STORAGE RING COMPLEX*

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Abstract

The preparation of high quality secondary beams in the new FAIR facility is founded in a system of three storage rings equipped with various beam cooling systems. Depending on the beam species, which can be either rare isotope beams or antiprotons, the storage rings have different tasks such as pre-cooling, accumulation or deceleration of secondary beams. Operation with stable highly charged ions is another mode of the storage rings. The ion optical design has been refined in order to have optimum performance for the planned applications. Beam cooling systems for the storage rings were specified in detail and a hardware development program has been launched. In parallel, the civil engineering design and the design of the technical infrastructure for the FAIR project is progressing.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) [1] will use the existing GSI accelerator complex to build a new facility for the production of high intensity secondary beams as well as for experiments with high energy or high intensity heavy ion beams (Fig. 1). Details of the accelerator complex were recently documented in technical design reports of the various machines [2]. For the production of high intensity secondary beams a complex of storage rings was designed which will be used to prepare the secondary beams. The three storage rings CR, RESR and NESR will have a maximum bending power of 13 Tm in common, which allows beam transfer at fixed energy and the use of standardized components. The secondary beams will be either antiprotons or rare isotope beams. The primary beams will be protons in the case of antiprotons and heavy ion beams for the production of rare isotopes by projectile fragmentation or fission. The primary beams will be accelerated in the new fast-cycling synchrotron SIS100 using superconducting magnets [3]. The final energy, 29 GeV for protons and around 1.5 GeV/u for heavy ions in low charge states, is optimized for maximum secondary beam production at relatively moderate cost of the accelerator facility. Compression of the primary beam to a less than 50 ns short bunch is mandatory to collect the secondary beams after the production target with high efficiency in a storage ring. The manipulations of the beams in the storage rings, like accumulation and deceleration are vitally based on beam cooling, both stochastic and electron cooling, which were studied in great detail at the existing ESR storage ring [4].

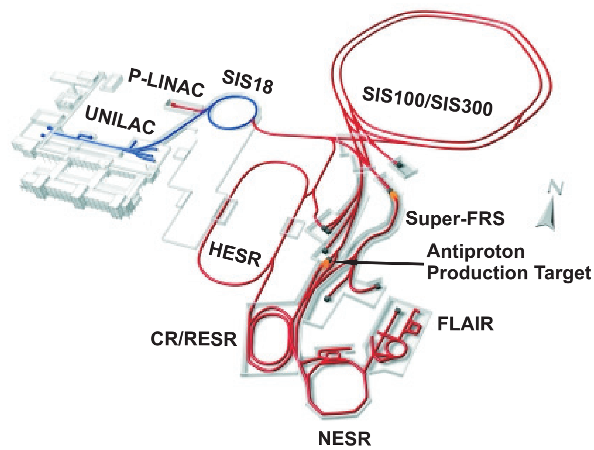

Figure 1: Overview of the new FAIR accelerator complex. In blue the existing UNILAC and SIS18 accelerators, the accelerators in red will be added.

PRODUCTION OF SECONDARY BEAMS

Antiprotons

The concept of antiproton production is similar to the scenario that was developed at CERN. The primary proton energy of 29 GeV allows efficient production, collection, cooling and accumulation of antiprotons at an energy of 3 GeV with storage rings of magnetic bending power 13 Tm. The short proton bunch from SIS100 is directed onto a nickel target followed by a magnetic horn, which focusses the diverging antiprotons, and a large acceptance antiproton separator. The optical design of the separator is aiming at the transport of the large momentum spread antiproton bunch with high efficiency into the subsequent Collector Ring (CR), where bunch rotation of the short bunch reduces the momentum spread and prepares the antiprotons for stochastic pre-cooling. The transport of the antiproton bunch from the production target through the antiproton separator into the collector ring was optimized including chromaticity corrections in order to be able to transport a momentum spread $\delta p/p = \pm 3$ %. The small emittance and momentum spread after stochastic cooling in the CR allows the accumulation of a high intensity antipro-

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ton stack in the accumulator ring (RESR) by a longitudinal stacking method employing stochastic cooling.

From the RESR the antiprotons can be transferred to two different users. The High Energy Storage Ring (HESR) allows the acceleration or deceleration of the antiprotons to energies in the range 1.5 to 15 GeV [5]. Stochastic cooling and, in a later stage, electron cooling will provide high luminosity or high resolution for investigations of the interaction of the antiprotons with an internal hydrogen target. The second branch after the RESR uses the New Experimental Storage Ring (NESR) as a decelerator to reduce the antiproton energy from 3 GeV to a variable end energy with a minimum value of 30 MeV. These low energy antiprotons can be transferred to the low energy antiproton experimental area FLAIR for deceleration to even lower energies.

The performance of antiproton production is quantified by the production rate. Therefore all subsystems are optimized for this goal. The present production rate of 1×10^7 antiprotons per second is limited by cost considerations. The SIS100 will provide a bunch of 2×10^{13} protons every 10 s. The conservatively estimated conversion rate of 5×10^{-6} corresponds to 10^8 antiprotons injected into the acceptance of the CR. If the beam transport through the separator works with the calculated efficiency of better than 70 %, the production rate will be finally limited by the rf and the stochastic cooling system in the CR. For cost reasons the rf voltage was limited to 200 kV and the stochastic cooling systems operates in the frequency band 1-2 GHz. Doubling the rf voltage and extending the cooling band width to 1-4 GHz will approximately result in half the cooling time and consequently will increase the production rate to 2×10^7 antiprotons per second assuming that the SIS100 provides a proton bunch every 5 s. Space for the additional hardware is reserved in the CR. The production target is designed to stand the increased thermal load.

Rare Isotope Beams

The preparation of rare isotopes follows a similar sequence of accelerators as antiproton production. The storage rings have to be operated with opposite polarity of most components which consequently have to be designed and tested for operation with both polarities. The short bunch of primary heavy ions bombards a production target followed by the new Superconducting Fragment Separator (Super-FRS) which offers large acceptance for the in flight separation and further transport of rare isotopes [6]. The rare isotopes are injected into the CR for bunch rotation and stochastic pre-cooling, as the antiprotons. Afterwards the rare isotopes can be transferred to the NESR via RESR. In the NESR electron cooling allows a further improvement of beam quality and offers the option to accumulate rare isotopes to higher intensities. NESR as well as RESR will be equipped to decelerate the rare isotopes with a ramp rate of 1 T/s which is most important for short-lived species. After the NESR ion energies as low as 4 MeV/u are envisaged.

Other Modes of Operation

The storage rings can also be used to perform experiments with stable heavy ion beams. In the NESR various experimental installations are available. An electron cooling system will give significantly improved beam quality for the whole range of energies between 4 MeV/u and about 800 MeV/u. The main interest is in highly charged ions which are produced in a stripping section after acceleration in the synchrotron. For a number of experiments the highly charged ions will be decelerated to a variable energy. For dedicated experiments the NESR can be filled with low charge state ions.

A special mode, the so-called isochronous mode, is planned for the CR. As the CR is designed for operation with small momentum slip factor, due to the requirements of stochastic cooling, the lattice structure is suitable for tuning it to the transition energy. This is beneficial for the isochronous mode which is used for mass measurements of short-lived radioactive nuclei. Masses of nuclei with lifetimes down to a few hundred microseconds can be measured by installing a dedicated time of flight detector. This is not a normal storage mode as the ions lose energy when passing the detector and are lost at the longitudinal acceptance. Nevertheless, after some thousand passages of the detector the mass of the ions can be detected with an accuracy of the order of 10^{-6}.

COLLECTOR RING CR

The CR is the first storage ring after the production targets for secondary beams. Due to the large emittances, both transversely and longitudinally, the ring is designed with large acceptance in all phase space planes. The ring lattice is governed by the large acceptance and the use of a stochastic cooling system, which needs proper mixing conditions and beta functions [7].

Both beams, antiprotons and rare isotopes, are injected at the maximum bending power of 13 Tm. The velocities of the two species differ significantly, the relativistic velocity is $\beta = 0.84$ for ions and $\beta = 0.97$ for antiprotons. The rf system and the stochastic cooling system are designed to cope with the corresponding revolution frequency. However, in order to provide the best conditions for stochastic cooling different ion optical settings have been calculated to provide a momentum slip factor between pickups and kickers of the stochastic cooling system for both good wanted and small unwanted mixing. Dispersion free straight sections for injection and extraction and for the installation of the rf system are another feature of the lattice.

The circumference of the CR is 216.3 m. Large aperture dipole and quadrupole magnets provide the required acceptance. In the antiproton operation mode tunes of $Q_x = 4.26$ and $Q_y = 4.84$ correspond to transverse acceptances of 240 mm mrad in both planes and a momentum acceptance $\Delta p/p = \pm 3\%$, the RIB mode is tuned to $Q_x = 3.21$ and $Q_y = 3.71$ with transverse acceptances of 200 mm mrad and a momentum acceptance $\Delta p/p =$

$\pm$ 1.5%. In both cases the momentum slip factor is rather small ($\eta = -0.0228$ for antiprotons, $\eta = 0.1745$ for RIBs). The large acceptance was confirmed in dynamic aperture calculations including higher field components in the main ring magnets and additional sextupole magnets for chromaticity correction and compensation of sextupole components in the main dipoles [8].

Before stochastic cooling is applied a bunch rotation and debunching systems reduces the momentum spread of the short bunch of secondary particles by at least a factor of 5. This results in better initial conditions for stochastic cooling and in a shorter total cooling time. The rf system of the CR [11] is designed for high voltage gradient during bunch rotation, but it acts only over some hundred turns on the beam. Although each 1 m long cavity has to provide a voltage of 40 kV, the average power dissipation will not exceed 2 kW. The use of magnetic alloy material is foreseen in order to achieve the high electric field strength. Due to the small average power dissipation forced air cooling of the magnetic alloy rings will be sufficient. No change of the beam energy with the rf system is foreseen in the CR, therefore the frequency range for the operation at harmonic number $h = 1$ from 1.17 to 1.37 MHz is only determined by the difference in velocity of ions and antiprotons when injected at their specific energies.

The stochastic cooling of the CR will be applied to beams with significantly different velocity [9]. The intensities, particularly of rare isotope beams, can vary from very low intensity (a few ions) up to some 10^8. The goal for low ion intensities is a total cooling time of 1.5 s in order to make full use of the fast cycle of SIS100. 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 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 [10]. Cooling of the pick-ups to 20 K with a cold head is included in the design of the vacuum tank. A prototype tank is presently assembled in order to test the concept. 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.

The antiprotons will be stored for about 10 s and rare isotopes for a few seconds. The required beam lifetime for these high energy secondary beams can be achieved in metal sealed ultrahigh vacuum system without baking.

ACCUMULATOR RING RESR

The design of the accumulator ring for antiprotons has gone through several iterations. Starting from a concept based on the idea to reuse components of the existing ESR storage ring [12] (which gave the name RESR), the ring layout has been optimized for the accumulation of antiprotons. The accumulation is performed with a stochastic cooling system accumulating the antiprotons by longitudinal beam manipulations in a similar manner as in the former AA ring at CERN [13]. The ion optical layout of the storage ring has to meet the requirements of this dedicated cooling system. It requires a large dispersion at the pick-ups in order to provide discrete cooling for injected particles and the accumulated stack which are separated spatially because of their different momentum. This results in a high selectivity with respect to the particle momentum.

The latest lattice of the RESR is based on a ring with hexagonal shape and a circumference of 240 m. A large momentum acceptance of $\Delta p/p = \pm 1\%$ is needed for the accumulation of antiprotons. As the injected beams are pre-cooled in the CR, a transverse acceptance of 25 mm mrad is sufficient. A transition energy which is adjustable in the range $\gamma_t = 3.3 - 6.4$ gives a large flexibility for the ongoing optimization of the lattice design for the stochastic accumulation system [14].

The RESR will be accommodated in a common ring tunnel with the CR, its larger circumference allows their installation in one another. The beam axis height is different which requires a beamline from the CR to the RESR with vertical deflection.

For the deceleration of both ions and antiprotons the RESR allows injection below transition energy and consequently deceleration without crossing transition energy.

The recent design considerations of the accumulation system have resulted in a set of parameters, which is matched to the ion optical properties of the lattice. The antiproton beam is injected from the CR onto an inner orbit with a momentum offset $\Delta\ p/p = -0.8\%$, then it is transported with the rf system to a central orbit. Finally the stochastic cooling system drives the particles to an outer orbit at $\Delta\ p/p = +0.8\%$. The longitudinal cooling system comprises a stack tail cooling system 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 of the core 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}. A longitudinal distribution according to a simulation is shown in Fig. 2. The effects of beam feedback for up to 10^{11} stored antiprotons and the resulting beam stability are under investigation.

The proposed accumulation mode requires C-shaped in-

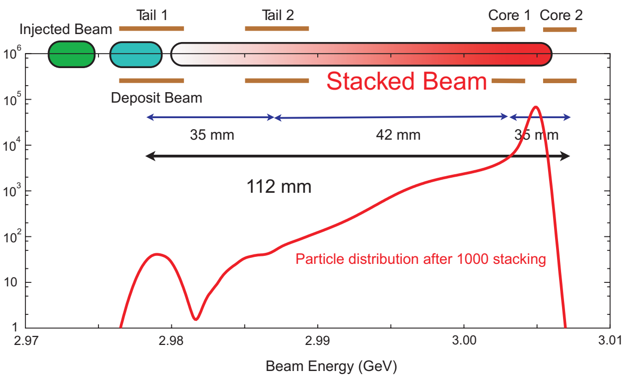

Figure 2: Geometry of the electrode system used in a simulation of accumulation in the RESR. The distribution after the accumulation of 1000 injections is shown.

jection kickers which allow horizontal motion of the beam during the longitudinal beam manipulations. 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 accumulated antiprotons will be delivered to two main users, directly to the HESR storage ring and to the FLAIR facility via the NESR. Fractions of the accumulated beam or the full stack can be provided to the users. By the application of rf at harmonic number $h = 1$ with a variable amplitude an adjustable fraction of the stack can be separated for extraction. This method will allow the creation of low intensity pilot pulses to test the beam transport setting prior to the transfer of a high intensity antiproton pulse to the HESR.

The RESR is used in a second mode for rare isotope experiments. 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 magnet system. 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. The growth of emittance during deceleration would conflict with the small gap of the stochastic cooling electrodes. As these electrodes cover only about half of the horizontal ring acceptance, the ion beam has to be kept in that part of the acceptance which is not limited by the small vertical gap of the cooling electrodes.

STORAGE RING NESR

The NESR can be used for a variety of beam manipulations. For ions, stable and unstable, it is, first of all, a storage ring for internal experiments. As many experiments prefer lower energies than the one needed for production of highly charged or radioactive ions, the ring is designed for ramping with a rate of 1 T/s. With a lowest energy of 4 MeV/u the magnetic fields have to be changed by a factor of about 25 between injection and lowest energy. The lower energies are not only available with stored beams, but various methods for extraction are foreseen. 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 can be utilized. The various extraction components are integrated into the ring design.

For operation with antiprotons the NESR will serve as a decelerator reducing the antiproton energy from 3 GeV to a minimum value of 30 MeV. The low energy antiprotons can be extracted with slow resonance extraction or will be transferred after fast extraction to FLAIR. The antiproton deceleration will be applied to a variable fraction of the antiproton stack accumulated in the RESR.

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 store particles with different momentum or, equivalently, particles with the same velocity, but different charge and/or 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 NESR magnets and rf system are designed to decelerate ion and antiproton beams with a maximum ramp rate of 1 T/s, which is most important for the deceleration of short-lived rare isotopes. The dipole magnets are designed for good field quality (integral contributions of multipole components less than $\pm 1 \times 10^{-4}$) in the range of magnetic field strength from 0.03 to 1.6 T corresponding to the maximum rigidity of 13 Tm and deceleration to a minimum energy of 4 MeV/u.

The injection system is matched to the acceptance from the fragment separator allowing 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 fragment with large momentum spread or of multi-component beams with a certain range of charge to mass ratio. The extraction components are designed for beams of maximum magnetic rigidity 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.

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 available beam quality after electron cooling was determined in simulations [15].

The small momentum spread after cooling offers the possibility to apply longitudinal accumulation methods. The most favorable schemes consider to capture the accumulated stack in a fraction of the circumference and to inject new beam into the empty fraction. Accumulation by application of barrier buckets or by using a sinusoidal rf operating on harmonic number $h = 1$ were studied in computer simulations [16] and in beam dynamics experiments at the ESR [17]. Both methods are very promising for the application in the NESR. Accumulation in the NESR will be applied to rare isotope beams which cannot be produced in sufficient quantity with a single primary beam bunch [18]. If the beam lifetime is long compared to the cycle time of SIS100 (1.5 s), the intensity of the stored beam can be increased.

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 s. The main application for this mode will be Schottky mass spectrometry [19], 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 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 one 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 this straight section and installing two additional dipole magnets which bend the ion beam into and out of the bypass section.

OUTLOOK

As the FAIR facility will be constructed as an international facility a new company owned by the partner countries is expected to be established this summer. Afterwards the different systems of the facility will be provided, to a large extent, by the partner countries. As the facility will be built as an extension of the existing GSI facility, the civil construction division at GSI has started to work out the buildings and infrastructure for the new facility in a collaboration with a consortium of external civil engineering offices. A building concept is already available and is presently being refined.

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