

ADVANCED DESIGN OF THE FAIR STORAGE RING COMPLEX*

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Abstract

One of the main features of the planned FAIR facility will be the availability of high quality secondary beams of antiprotons and rare isotopes. The preparation of these beams is achieved in the complex of the three storage rings CR, RESR and NESR. These rings are equipped with beam cooling systems for pre-cooling, accumulation and final cooling of the secondary beams. The ion optical design of the storage rings is guided by the requirements of the cooling systems. Other systems, like rf systems are integrated into the cooling procedures. Deceleration will offer secondary beams over a large range of energies down to particles at rest. The status of the storage ring design and component development is summarized.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) [1] is aiming at providing higher beam energies and higher beam intensities compared to the existing GSI facility. High intensity ion beams over the whole range of stable isotopes will be accelerated in the new heavy ion synchrotron SIS100 to energies around 1.5 GeV/u. They will serve as primary beams for the production of rare isotope beams (RIBs) by in-flight separation in the new fragment separator SuperFRS. A high intensity proton beam compressed to a 50 ns short bunch of 2×10^{13} protons at 29 GeV from SIS100 will produce antiprotons by bombardment of a nickel target. Subsequently the antiprotons are selected in a magnetic separator.

For the phase space compression of the secondary beams a set of storage rings equipped with beam cooling systems have been designed. The hot secondary beams emerging from the production targets will be collected in the large acceptance Collector Ring (CR). The accumulator ring RESR is mainly designed to accumulate high intensity antiproton stacks for experiments in the High Energy Storage Ring (HESR) or for experiments with low energy antiprotons in the Facility for Low-energy Antiproton and heavy-Ion Research (FLAIR). The New Experimental Storage Ring (NESR) can be used to store stable ion and rare isotope beams for experiments. Moreover, it can decelerate antiprotons and ion beams for experiments in the FLAIR experimental area.

All three storage rings CR, RESR and NESR are designed for the same maximum magnetic rigidity of 13 Tm, which allows storage of antiprotons at 3 GeV, matched to

the maximum antiproton production rate from a 29 GeV proton beam, and for storage of RIBs at 740 MeV/u. The various technical systems of the storage rings are optimized for operation at these energies. Operation with both polarities, particularly demanding for the magnetic components, is taken into account. It was decided to use normal-conducting magnets for the storage rings in order to get best field quality at moderate investment cost.

COLLECTOR RING CR

The lattice of the CR with a circumference of 216 m was from the beginning optimized to support stochastic cooling of both antiproton and rare isotope beams [2]. Antiprotons and RIBs have different velocity, but there is the need to have proper mixing conditions for stochastic cooling. Therefore, two different working points are foreseen with optimized transition energy and proper mixing. Recently the ion optical lattice and the working point for both modes was further optimized for efficient injection and extraction without changing the focusing structure in the arcs which determines the amount of mixing, both desired mixing between kickers and pick-ups and undesired mixing between pick-ups and kickers. For fixed arc sections this final optimization was addressing the choice of the focussing structure in the straight sections. In the drift spaces between the quadrupoles the straight sections will accommodate pick-up and kicker tanks of the stochastic cooling system, the rf cavities, and the injection and extraction components.

For fast rotation and debunching of the injected short bunch five magnetic alloy filled cavities at harmonic number $h = 1$ with a total voltage of 200 kV will be installed in the dispersion free straight section. The rf manipulations result in a small momentum spread which is a prerequisite for fast stochastic cooling.

As the production rate of antiprotons is dominated by the efficiency of the transport from the production target into the CR, the complete beam line from the target to the CR was optimized for maximum acceptance. Chromaticity corrections were calculated and the beam envelope was finally matched to the ion optical functions of the CR at the injection point. The layout of the CR was optimized for the injection of antiprotons. According to ion optical tracking simulations up to 70 % of the antiprotons, which are matched to the CR acceptance, can be stored with the optimized system. This confirms that the goal of injecting 1×10^8 every 10 s can be reached reliably. The injection and efficient storage of rare isotopes, which are injected along the same beam line after a common inflector magnet, was studied, too, but this mode is generally less demanding.

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The number of injected rare isotopes which is determined by the production cross section can vary from single ions up to 10^9 for the most abundant species.

As stochastic cooling will be applied to beams with significantly different velocity ($\beta = 0.83$ for RIBs and $\beta = 0.97$ for antiprotons) a new slot line structure coupled to a micro-strip circuit has been developed [3]. Switchable delays allow matching the signal to the velocity of the beam. This system provides good amplitude and phase flatness in the band from 1 to 2 GHz. In order to increase the signal to noise ratio the pick-up electrodes will be cooled by cold heads to 20 K and pick-ups and kickers will be moved during the cooling process synchronously with the decreasing emittance of the beam. A prototype vacuum tank for testing of the new electrode structures in combination with the cryogenic equipment has been ordered and will be ready before the end of 2008.

ACCUMULATOR RING RESR

The main task of the RESR [4] is the accumulation of antiprotons after stochastic pre-cooling in the CR. This is achieved by a dedicated stochastic cooling system which determines the ion optical layout of the storage ring. The original ring design with a rectangular footprint did not provide the required flexibility, therefore, it was replaced by a new design with a hexagonal shape. The new lattice allows operation with a transition energy in the range $\gamma_t = 3.3 - 6.4$ which gives large flexibility in the design of the stochastic accumulation system. For the deceleration of both ions and antiprotons it allows injection below transition energy and consequently deceleration without crossing transition energy. The RESR with a circumference of 240 m and the CR will be installed in a common building with the larger RESR surrounding the smaller CR.

The dipole magnets of the RESR will be identical to the NESR dipoles which offer a large aperture. The large aperture is also a feature of the existing ESR quadrupoles which will be reused for the RESR. This choice of the main magnets results in a momentum acceptance of $\Delta p/p = \pm 1.0\%$ as required for the accumulation in longitudinal phase space with a stochastic cooling system. The transverse acceptance of 25 mm mrad, both horizontally and vertically, is adequate for the injection of pre-cooled beams from the CR. The injection and extraction systems will employ partial aperture C-shaped magnetic kickers which allow an acceleration of the beam out of the magnetic field region of the kicker. The beam will be injected onto an inner orbit (momentum offset $\Delta p/p = -0.8\%$) and in the course of the accumulation procedure shifted to the stack orbit (momentum offset $\Delta p/p = +0.8\%$). The rf system shifts the beam from the injection orbit to the tail of the accumulated stack from where the stochastic cooling system forces the particles towards the core. For extraction the shift in momentum is reversed, either for a fraction of the stack or for the entire stack. The beam is ejected by the kicker system from the same orbit used for injection.

The accumulation will be performed by an AA-like accumulation system [5]. Electrode systems for tail and core cooling with a vertical gap of 20 mm can be installed due to the small beta function in this location of less than 2 m. 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} . Detailed design studies for the choice of electrodes and the gain function versus revolution frequency are under way.

As the antiprotons will be delivered to two main users, the HESR storage ring and the FLAIR facility, it is foreseen to separate an adjustable fraction of the stack by the application of rf at harmonic number $h = 1$ with a variable amplitude. The bucket height determines the amount of beam which is captured from the stack and transported to the extraction orbit, from there the bunch is kicked out. 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.

STORAGE RING NESR

The basic concept of the NESR [6], a 222.8 m circumference storage ring with fourfold symmetry and four 18 m long straight sections for experimental installations, remained unchanged. During optimization of the ion optical structure for large acceptance the focussing structure was modified providing additional space for chromaticity corrections by sextupole magnets and increased longitudinal acceptance. The injection and extraction systems were adjusted to the new focussing structure resulting in more relaxed parameters for the injection components. The present design provides a maximum acceptance of 150 mm mrad horizontally and 40 mm mrad for particles with a maximum momentum deviation of $\Delta p/p = \pm 1.5\%$. This allows direct injection of rare isotope beams from the SuperFRS, but also storage of multi-component beams with a corresponding range of beam momenta or charge to mass ratio of the stored ions. The ion optical lattice is the same for ion and antiproton operation and during beam deceleration.

For the collision of rare isotope beams with electrons in one straight section a new set-up is foreseen. In a bypass mode the ion beam will be transferred to a straight section parallel to the standard ring straight section. This 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. The main advantage of the bypass mode is a reduced focussing strength of the quadrupole magnets in the collision region and easier access for experimental installations in the collision zone. At the same time the injection into the electron ring was modified now employing a design which does not only allow the injection of electrons from a linac, but also injection of antiprotons from the RESR after deceleration to energies in the range 30-125 MeV (Fig. 1).

The NESR magnets and rf systems are designed to decel-

erate 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. This corresponds to the maximum rigidity of 13 Tm and deceleration of all ion species to a minimum energy of 4 MeV/u.

For experiments in the NESR various installations are planned, an internal target, an electron target and the collision section with electrons. All experiments as well as the deceleration of ions and antiprotons rely on an electron cooling system. This system can provide electrons at a maximum energy of 450 keV down to 2 keV with an electron current up to 2 A. This cooling system will be instrumental for both experiments and beam manipulations. For precision mass determination of rare isotopes by measurement of their revolution frequency with a Schottky noise technique the cooling system has to stabilize the beam energy to better than 10^{-6} .

As the intensities of RIBs can be rather low it is considered to accumulate the pre-cooled beams by a combination of rf potentials and electron cooling. Two schemes have been identified as promising candidates, a barrier bucket system with a maximum rf voltage of 2 kV and an upper frequency limit of 5 MHz and accumulation by injection of the bunch onto the unstable fixed point of the rf operated at harmonic number $h = 1$. Simulation tools have been developed and compared to the results of benchmarking experiments in the ESR storage ring, good agreement has been found. Therefore, the simulations for the accumulation of RIBs in the NESR have a high predictive power. The simulations predict that the electron cooling system will be capable to cool the RIBs after stochastic pre-cooling in the CR with total cooling times below 1.5 s.

COMMON DESIGN ISSUES

For all storage rings detailed dynamic aperture studies were performed. They provide guidelines for the specification of magnets which are required for the large acceptance of the storage rings. Closed orbit correction schemes were determined in ion optical calculations. The location of the beam position monitors and the required strength of the orbit correction magnets was defined accordingly. Orbit errors due to typical alignment and production error of the main magnets can be reduced by more than one order of magnitude, typically to orbit deviations of less than 1 mm, which is sufficient for storage rings with large acceptance.

Although the circumferences of the three storage rings are different, the transfer of beam bunches is eased by the fact that all rings are equipped with an rf system operating at harmonic number $h = 1$. The synchronization of the rf systems of the rings will be done by a fast timing system which is under development for the FAIR project.

The typical cycle time for the various systems is governed by the lifetime of short-lived rare isotopes and high

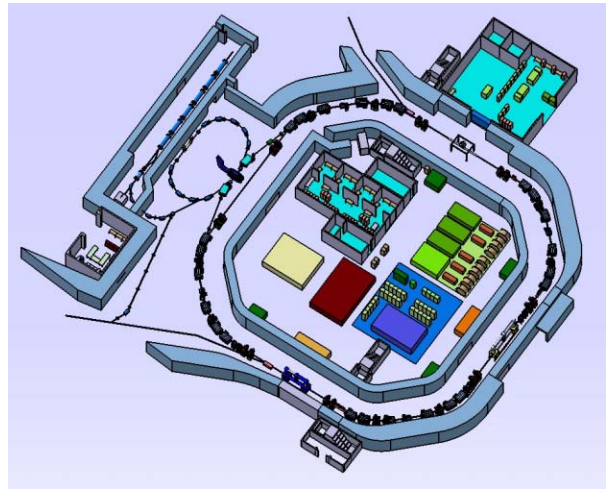


Figure 1: Layout of the NESR building, injection from RESR is on the left, top is extraction to FLAIR. The center of the building is used for technical installations.

overall production rate for antiprotons. For antiprotons the minimum cycle time is determined by the cooling time in the CR, with the stochastic cooling system operating between 1 and 2 GHz a total cooling time of 10 s is expected. This defines the time for shifting the antiprotons from the injection to the stack orbit in the RESR. The CR can cool highly charged rare isotopes from SuperFRS in less than 1.5 s matched to the cycle time of SIS100 for the primary heavy ions and the time needed for electron cooling in the NESR.

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