DESIGN OF THE NESR STORAGE RING FOR OPERATION WITH IONS AND ANTIPROTONS*

M. Steck, K. Beckert, P. Beller, C. Dimopoulou, A. Dolinskii, F. Nolden, J. Yang
GSI Darmstadt, Germany

Abstract

The NESR storage ring of the FAIR project is designed for versatile operation with ions and antiprotons. Ions, both stable and rare isotope beams, will be used for internal experiments. The ion beams can be decelerated to a minimum energy of 4 MeV/u and transferred to a low energy area. Antiprotons will be decelerated from 3 GeV to a minimum energy of 30 MeV and transferred to the FLAIR low energy area. Electron cooling will provide high quality beams for experiments. Cooling will also assist the deceleration process and will allow the accumulation of rare isotope beams in longitudinal phase space.

INTRODUCTION

The New Experimental Storage Ring (NESR) of the FAIR project [1] was originally proposed for a multitude of operational modes. Amongst them was the accumulation of antiprotons [2]. Due to severe constraints on the ion optical lattice and lack of space for stochastic cooling components, this idea was abandoned and the RESR storage ring was added to the FAIR concept as a dedicated accumulator ring for antiprotons [3]. Nevertheless, the variety of operational modes of the NESR is still large. Operation in both magnet polarities with ions and antiprotons is required. A special feature is the deceleration of all the particle species which are produced at high energy, i.e. highly charged ions, rare isotope beams (RIBs) and antiprotons.

Ion beams can be injected either directly from the synchrotrons SIS18 or SIS100 [4], where they are accelerated to the required energy, or as secondary RIBs which emerge from a production target and are selected in the magnetic separator SuperFRS [5]. The RIBs can be injected directly from SuperFRS or after pre-cooling in the collector ring (CR) [6]. At the maximum injection energy of 740 MeV/u the ions will be completely stripped. Injection at lower energy is also foreseen, if lower energy or lower charge states are required by experiments. Deceleration of ions to a minimum energy of 4 MeV/u requires a reduction of the magnetic field by a factor of 25. The maximum ramp rate of 1 T/s will allow a change of the bending field between 1.6 and 0.06 T in 1.5 s.

The main user of decelerated antiprotons is the FLAIR [7] facility of the FAIR project. Up to 1×10^9 antiprotons after pre-cooling in the CR and accumulation in the RESR will be injected at an energy of 3 GeV and decelerated to a minimum energy of 30 MeV.

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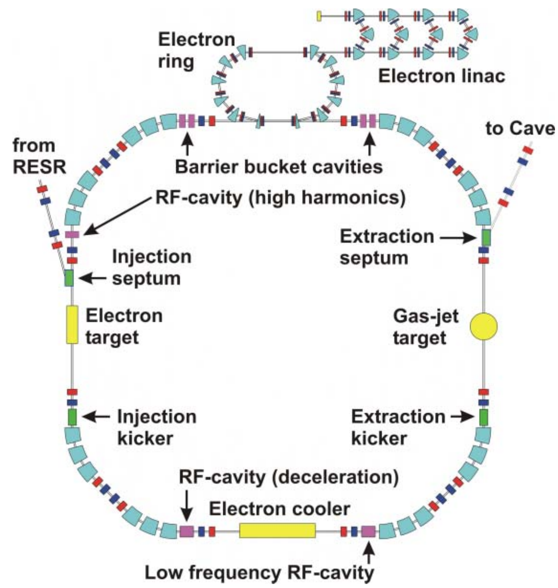

Figure 1: General layout of the NESR storage ring.

For precision experiments with stored beams an excellent stability of all components is required. Mass measurements of rare isotopes require a stability of the revolution frequency of 10^{-7} or better.

The operation with low energy or partially stripped ions and also the use as an antiproton decelerator impose stringent requirements on the vacuum system. For the achievement of a basic pressure below 10^{-11} mbar the whole vacuum system has to be bakeable at a maximum temperature of 300°C and all vacuum components have to comply with ultra high vacuum standards.

INJECTION INTO THE NESR

The beams to be stored in the NESR will be injected as a single bunch with a length between 20 and 80 % of the ring circumference. Three full aperture kicker magnets with a rise and fall time below 100 ns are foreseen, their polarity can be changed. They will allow injection of hot RIBs directly from the fragment separator SuperFRS. The fast rise and fall time offers two options. The use of more than 80 % of the ring circumference for injection, depending on the beam velocity, or a longitudinal accumulation method for an intensity increase, particularly for RIBs.

The favored method of longitudinal beam accumulation is based on a barrier bucket rf system in combination with electron cooling. Estimated cooling times below 1 s will allow optimum use of the fast cycling rate of the synchrotron where the primary heavy ion beam is accelerated. As an alternative, an $h = 1$ rf system for bunching of the circulating beam and injection of a new bunch onto the unstable fixed point in longitudinal phase space is considered. For both methods the maximum useful accumulation time is limited by the lifetime of the ion beam, either due to nuclear decay or due to recombination with electrons of the cooling system.

ION OPTICAL LATTICE

The ion optical parameters of the storage ring which have been described before [8] have been refined to a certain degree. The ring circumference is 222.1 m with four 18 m long straight sections in a basic lattice with fourfold symmetry based on doublet focusing. The maximum strength of the main magnetic ring elements up to a bending power of 13 Tm can be realized using normal conducting magnet technology. The option of super-ferric dipole magnets, which is expected to reduce the operation costs of these large aperture magnets, is under investigation.

For a maximum momentum deviation of ± 1.5 % the ring lattice offers a transverse acceptance of 160 mmmrad horizontally and 50 mmmrad vertically. The dynamic aperture has been calculated assuming the maximum higher order components of dipole and quadrupole magnets, according to previous experience with large aperture magnets at GSI. The results of such calculations with the SIXTRACK and the PTC code confirmed that the dynamic aperture significantly exceeds the size of a beam filling the full acceptance. The result of a SIXTRACK calculation is shown in Fig. 2 for optimized tunes of $Q_x = 3.37$ and $Q_y = 3.18$ and for various numbers of turns (1000, 10000 and 100000).

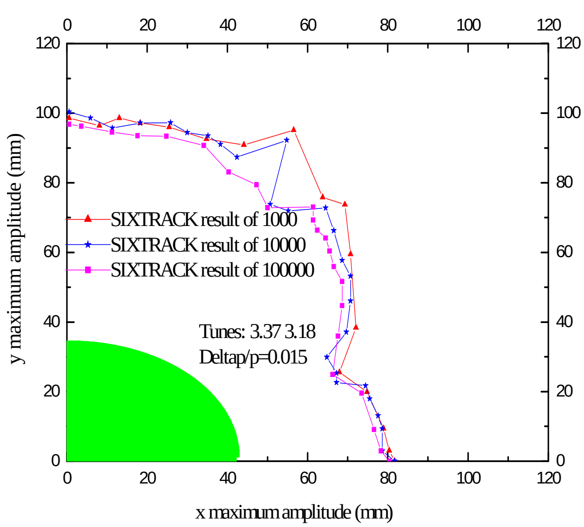

Figure 2: Dynamic aperture calculation with SIXTRACK for particles with a momentum deviation of 1.5 %. The dynamic aperture, which was tracked over different numbers of turns (1000, 10000, 100000), is much larger than the acceptance of the ring (green area).

The large momentum acceptance allows simultaneous storage of beam components with a large momentum deviation for experiments, e.g. different charge states of highly charged ions, rare isotopes with different charge to mass ratios, or products of internal reactions with large momentum change. The bending sections will be equipped with intercepting particle detectors which allow detection of particles produced in the straight sections, thus the bending sections can be operated as a spectrometer for reaction products.

ELECTRON COOLING

The required beam quality for precision experiments with stored ion beams will be achieved by electron cooling. Electron cooling will also support all beam manipulations involving rf systems, like beam accumulation and deceleration. The small momentum spread of the cooled beam will relax the requirements on the rf systems. For the antiprotons an intermediate cooling after deceleration from 3 GeV to 800 MeV is foreseen. Therefore, a cooling system for a range of electron energies from 2 to 450 keV has been designed [9]. Electron currents of up to 2 A will allow fast cooling of short lived isotopes. Short cooling times will crucially depend on the beam parameters after pre-cooling in the CR and RESR storage rings. This is particularly important because of the high beam velocity.

The dependence of the cooling time on the initial beam parameters has been demonstrated by simulations with the BETACOOL code [10] which has been applied to investigate cooling times for the injected beam and equilibrium values at high and low energy. The simulations confirmed the necessity of a magnetic field strength of 0.2 T and a field straightness in the cooling section of $B_\perp/B_\parallel = 5 \times 10^{-5}$ for fast cooling. For ion beams at the maximum injection energy of 740 MeV/u, cooling times of less than 0.5 s have been calculated, if the pre-cooled beam from the CR storage ring is cooled with an electron beam of 1 A. Even if the momentum spread and the emittance are larger by a factor of two than the design value of the CR, the cooling time will not exceed 1.5 s. Thus storage ring experiments with RIBs can benefit from the fast cycling of the synchrotron SIS100 without reservations.

At the lowest energy of 4 MeV/u for highly charged ions a maximum intensity of 5×10^7 cooled ions is estimated. This is, according to simulations, the emittance of a coasting beam of highly charged ions in equilibrium with intrabeam scattering and corresponds to a space charge tune shift $\Delta Q \simeq -0.1$. This intensity limit at low energy is further reduced, if the beam is compressed into a short bunch before transfer to the low energy experimental area.

The conditions for electron cooling are less favorable for antiprotons which are injected at 3 GeV and which have larger momentum spread and emittance [6]. Due to their low charge the cooling time easily approaches the order of minutes. The dependence of the cooling time on momentum spread and emittance for antiprotons injected at 3 GeV after pre-cooling in the CR and deceleration in the

NESR to 800 MeV are shown in Fig. 3. The cooling time for antiprotons with a deviation which corresponds to the 2σ-value of the distribution after stochastic pre-cooling in the CR is 180 s, even assuming a 2 A electron beam for cooling. As a consequence either better pre-cooling must be achieved or only a small fraction of the beam can be cooled, if deceleration cycle times below 1 minute are requested by experiments with low energy antiprotons.

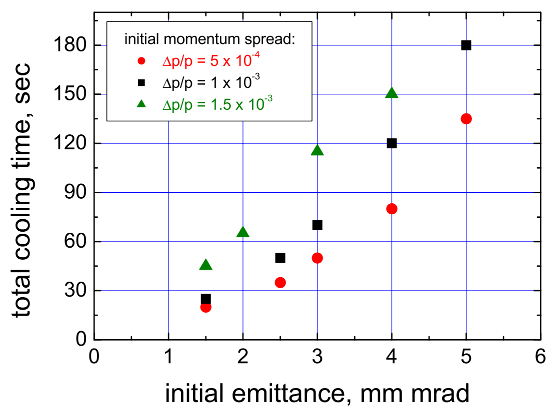

Figure 3: Total cooling time for antiprotons decelerated to 800 MeV as a function of transverse emittance and for different initial longitudinal momentum spreads.

A special requirement for the electron cooling system is fast ramping during deceleration. Whereas cooling after injection for ions and at the intermediate energy for antiprotons requires electron energies around 400 keV, after deceleration the electron energy must be lowered to a few keV. As a consequence an active method of discharging and charging the high voltage section is required to be able to ramp the accelerating voltage in 1.5 s between upper and lower value.

RF SYSTEMS

The operation of the NESR in various modes also requires pertinent rf systems. A ferrite filled cavity with a frequency swing between 1.1 and 2.8 MHz and a peak voltage of 20 kV will be installed, very similar to the existing SIS18 cavity. As the beams are cooled, the momentum spread is small and this voltage is sufficient for the fast ramp rate of 1 T/s. This cavity can decelerate all beams by changing the rf harmonic in the course of the deceleration process between $h = 1, h = 2, h = 4$ and $h = 8$. It will also allow debunching of single injected bunches in order to provide minimum momentum spread for fast cooling of the injected beam. If bunched beams are required for experiments this system can be used over the whole energy range by changing the harmonic number.

For beam accumulation at injection energy a broadband barrier bucket system is foreseen which provides single sine waves of 200 ns period. Four cavities, each equipped with a 3.5 kW solid state amplifier, result in a total voltage of 2 kV which, according to beam dynamics simulations, is sufficient to compress cooled beams. This system could also be used for compression of the decelerated beam into a bunch with a length of less than 30 m as required for transfer to a subsequent storage ring. It might make the installation of a dedicated low harmonic frequency system (down to 125 kHz) dispensable.

For the operation of the NESR in the collider mode with relativistic electrons an rf system operating at about 50 MHz will provide short ion bunches matched to the electron bunches in the electron storage ring. The parameters of this systems will be defined depending on the electron ring parameters.

EXPERIMENTAL INSTALLATIONS

The central parts of the straight sections will be mainly used for experimental installations (Fig. 1). An internal target, either a gas jet, cluster or a pellet target, allows a large variety of atomic and nuclear physics experiments. An electron target provides cold electrons at variable relative velocity for atomic physics recombination experiments.

After a first preliminary design [11], the fourth straight section is still being optimized as a collision section between electrons of up to 500 MeV and cooled RIBs. It has been proposed to store also antiprotons of up to 125 MeV in the electron ring for collision experiments requiring some modifications of the electron ring. The final layout of the electron ring and of the interaction region are under way regarding the requirements of the experiments.

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