LATTICE CONSIDERATIONS FOR THE COLLECTOR AND THE ACCUMULATOR RING OF THE FAIR PROJECT*

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Abstract

Two storage rings (Collector Ring (CR) and Recycled Experimental Storage Ring (RESR)) have been designed for efficient cooling, accumulation and deceleration of antiproton and rare isotopes beams at the FAIR project (Darmstadt, Germany). The large acceptance CR must provide efficient stochastic cooling of hot radioactive ions as well as antiproton beams. The RESR will be used as an accumulator of high intensity antiproton beams and as decelerator of rare isotopes. Different lattice structures have been considered in order to achieve good properties for the stochastic cooling and at the same time the maximum dynamic aperture. The structure of the ring lattices and its ion optical properties are described in this contribution. The beam dynamics stability and flexibility for operation in the different modes are discussed.

INTRODUCTION

Production, fast cooling, and accumulation of intense secondary beams, antiprotons and rare isotopes are key issues of the FAIR accelerator facility [1]. The rather hot secondary particles, rare isotopes coming out of the Super-FRS [2] or antiprotons coming out of the antiproton separator will be injected into the Collector Ring (CR), where fast RF bunch rotation and debunching followed by fast stochastic pre-cooling in all phase planes is foreseen. The envisaged total precooling times are 10 s for 3 GeV antiprotons and 1.5 s for fully stripped radioactive isotopes at 740 MeV/u. The CR will be operated at static magnetic field corresponding to the magnet rigidity of 13 Tm. After precooling in the CR the batches of 10^8 antiprotons will be delivered to the RESR, where the accumulation up the 10^{11} particles takes place during several hours at the beam energy of 3 GeV. Then accumulated antiprotons are either transferred to the HESR [3] for further acceleration/ deceleration or transferred to the NESR [4] for experiments with low energy antiprotons at FLAIR [5]. The accumulation scheme in the RESR foresees longitudinal stacking in combination with stochastic cooling. This will be achieved by a momentum stacking scheme. The RESR will be used also as the fast decelerator of rare isotopes from an energy of 740 MeV/u to energies between 100 MeV/u and 500 MeV/u within 1 s in order to be able to provide short-lived rare isotope beams at low energy for electron-ion collision experiments in the NESR. As an

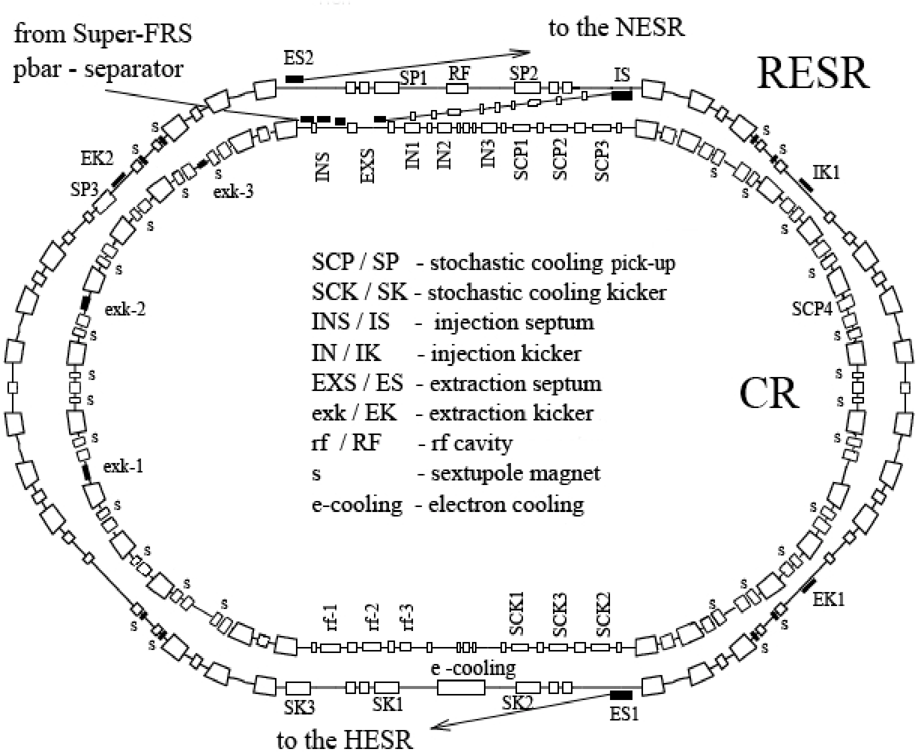

Figure 1: Layout of the CR – RESR rings.

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option the RESR can be used to decelerate antiprotons as well. This will be necessary if antiprotons for antiproton-ion collision experiments have to be provided to the NESR. For this mode the antiprotons are cooled and accumulated below the RESR transition energy to avoid crossing of the transition energy during deceleration. An additional electron cooling system in the RESR then compensates diffusion during deceleration. As this option is expected to be realized at a later stage of the FAIR project, the required space for the installation is taken into account during the present planning.
Here we consider the lattices of the two rings: the CR and RESR, where the stochastic cooling technique will be used for efficient cooling and accumulation of antiprotons. The RESR and CR are located in a common building as depicted in Figure 1.

THE COLLECTOR RING

The Lattice Consideration

On an early stage of the CR design we have considered two solutions for the CR lattice: a "symmetric ring" with identical lattice functions in the arcs and the "split ring" with different lattice functions in the arcs. The detailed consideration of both lattices is given in ref.[6]. In both cases the CR ring layout should follow these requirements

- setting different γ_{tr} values for antiprotons and radioactive ion beams to reach optimized mixing parameters for stochastic cooling, both for desired and undesired mixing;
- setting γ_{tr} value exactly equal to the energy of radioactive isotopes to have the so-called isochronous condition in the ring for TOF mass measurements [7];
- accommodation of stochastic cooling pick-up and kickers as well as the RF cavities in regions of zero dispersion;
- controlling the horizontal and vertical betatron phase advance between pickups and kickers of the transverse stochastic cooling systems;
- reducing chromaticity over the whole momentum range;
- the arrangement of sextupoles and higher order correctors has to be applicable for all three (different) ion optical settings;
- sufficient places to house the injection/extraction devices.

One can see that the ring must operate in three different optical modes in order to have good properties for stochastic cooling. In this paper we call the optics of the CR needed for antiproton cooling as "pbar-mode", for radioactive isotope beams – "rib-mode", and for the isochronous condition – "iso-mode". After many optimisations it was found that the "symmetric ring" lattice is much favourable because of different reasons. This layout of the CR gives the possibility to choose optimal ring optics for both pbar and rib-modes and the CR can be easily adjusted to iso-mode with relatively large transverse and momentum acceptance. Table 1 lists the main specification of the symmetric ring and the beam parameters before and after cooling.

Table 1: Main Specifications of the CR

Circumference	215 m	
Magnetic rigidity	13 Tm	
	antiprotons	Rare Isotopes
Max. number of particles	10^8	10^9
Kinetic energy	3 GeV	740 MeV/u
Transition, γ_{tr}	3.6	2.7
Betatron tunes Q_h/Q_v	4.42 / 4.44	3.11 / 3.10
Natural chromati., ξ_x / ξ_y	-7.8 / -8.4	-5.6 / -4.6
Revolution frequency	1.38 MHz	1.18 MHz
RF amplitude	100 kV	200 kV
Beam emittance (2σ) after injection after cooling	 240 mm mrad 5 mm mrad	 200 mm mrad 0.5 mm mrad
Momentum spread (2σ) after injection after cooling	 3 % 0.1 %	 1.5 % 0.05%
Overall cooling time	10 s	1.5 s

The Chromatic Correction

Since hot ion beams must be injected into the CR efficient chromatic correction must be done for a large off-momentum dynamic aperture. Therefore the CR lattice requires strong sextupole correctors. In the present layout of the CR design normalconducting quadrupole magnets with a number of separate sextupoles are considered. A method to control the natural chromaticity of a synchrotron, while keeping the tunes $Q_{x,y}$ constant, is to introduce two families of sextupoles for example placed at location of the ring, where the values of the function $\beta_{x,y}$ and D_x are high. But two sextupole families however may strongly affect the first and second order dependence on the momentum spread of the $\beta_{x,y}$ and D_x functions as well as of the chromaticity. This dependence of the functions $\beta_{x,y}$ and D_x on $\delta p/p$ introduces strong "beta/dispersion waves", which reduces the dynamic aperture of the ring. In addition the beta/dispersion waves will affect the horizontal and vertical chromaticities $\xi_{x,y,t}(\delta p)$ through the first and higher order terms of the chromaticity expression [8]. In order to minimize the dependence of $\beta_{x,y}$, D_x and the chromaticity on the $\delta p/p$, several sextupole families are required. Presently 6 independently powered sextupole families (totally 24) are foreseen in order to control the chromaticity and at the same time to minimize the dependence of the $\beta_{x,y}$ and D_x on $\delta p/p$. The side effect of using such a large number of sextupoles is the introduction of additional non-linearities in the ring such as increasing the amplitude dependence and nonlinear chromatic aberration. These effects tend to reduce the dynamic aperture. In case of the split optics in the CR the dynamic aperture is smaller then the required ring acceptance in pbar-mode operation [6]. The symmetric ring layout gives optimal properties of the optics for the stochastic cooling and at the same time the maximum dynamic aperture in all modes of operation.

Stochastic Cooling in the CR

The injection and extraction beam parameters (Table 1) for both stochastic cooling tasks in pbar and rib-modes are determined by the longitudinal, horizontal and vertical beam emittances at the end of the transport lines from the antiproton target and from the Super-FRS. The optical layout of the ring is chosen to meet the requirements for most efficient cooling. It has turned out that flexibility in setting transition γ_{tr} to an optimal value is extremely important. This is due to the necessity to find a compromise for the required mixing between kicker and pick-up (which should be large) and the undesired mixing between pick-up and kicker (which should be small). In a simplified model, one can write the stochastic cooling rate

$$\frac{1}{\tau} = \frac{W}{2N}\left[2gB - g^2\left(M + U\right)\right], \qquad (1)$$

where W is the electronic bandwidth, N is the number of particles in the beam, g is the system gain, B is the undesired mixing parameter, which can be written in the form

$$B = \cos\left(m_c \varphi_u\right), \qquad (2)$$

here m_c is the central harmonic in the cooling frequency band, φ_u is undesired mixing phase angle

$$\varphi_u = k\eta_{pk}\frac{\delta p}{p}. \qquad (3)$$

k is the ratio between the path from pickup to kicker and the circumference, $\delta p/p$ is the maximum momentum width to be cooled, η_{pk} is the local frequency slip factor between pick-up and kicker

$$\eta_{pk} = \left|\frac{1}{\gamma^2} - \frac{1}{\gamma^2_{tr,pk}}\right|, \qquad (4)$$

with the local $\gamma_{tr,pk}$

$$\frac{1}{\gamma^2_{tr,pk}} = \frac{1}{\Delta L_{pk}}\int_{s_p}^{s_k} D(s)\frac{ds}{\rho(s)}. \qquad (5)$$

In this equation s_p and s_k denote the azimuthal positions of the pick-up and the kicker, $D(s)$ is the dispersion function, and $\rho(s)$ is the radius of curvature. The desired mixing parameter can be approximated by

$$M = \left(m_c \eta_{kp}\frac{\delta p}{p}\right)^{-1}. \qquad (6)$$

U is the noise to signal ratio. If the parameter $m_c\varphi_u$ becomes larger than $\pi/2$, the cooling force changes sign,

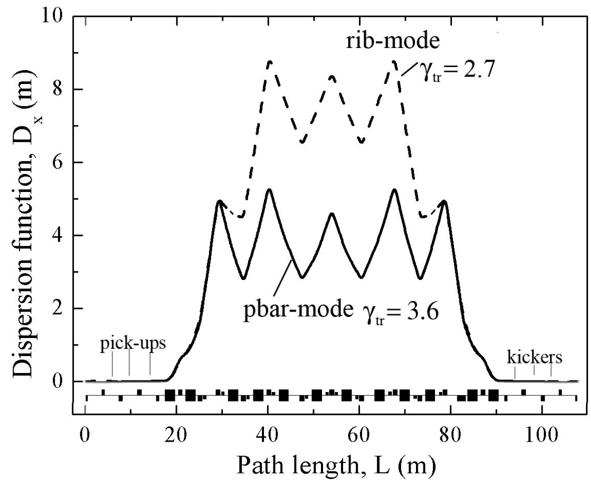

Figure 2: Dispersion function of the CR over half of the ring.

i.e. heats up the beam. This is minimized by making γ_{tr} as low as possible by increasing the dispersion in the dipole magnets. Also, the ratio k is minimized by placing pick-up and kicker as close together as possible. Rare isotope beams (γ = 1.79) and antiproton beams (γ = 4.2) require different γ_{tr}. For the antiproton beams one has to keep a certain distance between γ and γ_{tr} in order to make the mixing parameter M small enough. For antiproton cooling, the CR will be operated above transition with γ_{tr} = 3.6. In rib-mode the CR will be operated bellow transition with γ_{tr} = 2.7. In Fig.2 the shape of the dispersion functions over half of the ring for both pbar-mode and rib-mode is shown. For the rare isotope beams, the undesired mixing effect limits the momentum acceptance of the system because of the larger dispersion function in the arcs (Fig.2).

THE RECYCLED EXPERIMENTAL STORAGE RING

The RESR layout is dominated by the requirements of the stochastic cooling system in combination with momentum stacking. Beams are always transferred from the CR. This means the injection septum has to be positioned on the inner side of the RESR (Fig.1). The momentum stacking scheme requires a kicker which covers only half of the RESR aperture at a location in a dispersive section of the ring. The beam is injected on an inner orbit at a momentum offset of approximately $\Delta p/p$ = -0.8 % with respect to the central orbit, while the stacked beam circulates on an outer orbit with $\Delta p/p$ = +0.8 %. Although no stacking for rare isotopes is foreseen, the injection scheme is the same as for antiprotons.

The new version of the RESR has been designed with emphasis on strong stochastic accumulation rate. The structure of the ring is sketched in Fig. 1. The boundary conditions follow the requirements

- adjustable transition energy to provide good ion optical properties of the ring for antiproton

accumulation as well as for radioactive ion deceleration;
- to have a large dispersion function at the longitudinal stochastic pick-up to provide the good separation between injection and stacking orbits;
- small vertical beta function at longitudinal pick-up position
- long drift sections to provide injection from the CR as well as extraction from the RESR
- the phase advance in all pairs between kicker and septum for inj/ext must be close to $\pi/2$.

The current layout shown in Fig.1 fulfils all these requirements. This lattice is also suitable for fast deceleration of rare isotopes. Therefore, the optical mode of the RESR can remain unchanged for this task. Required acceptances of the RESR are moderate since only pre-cooled beams are injected from the CR. The actual RESR lattice and beam parameters are given in the Table 2.

Table 2: Main Specifications of the RESR

Circumference	240 m	
Magnetic rigidity	13 Tm	
	Antiprotons	Rare Isotopes
Max. number of particles	10^{11}	10^{9}
Accumulation time	up to 3 h	no accum.
Kinetic energy	3 GeV	740 MeV/u
Transition, γ_{tr}	6.0	3.3
Betatron tunes Q_h/Q_v	3.11 / 4.10	
Momentum acceptance	1.6 %	
Trans. acceptance, H/V	40 / 35 mm mrad	
Revolution frequency	1.17 MHz	1.0 MHz
Beam emittance (2σ) after extraction	5 mm mrad	1 mm mrad

The chromaticity correction is done by two families of sextupole magnets. Each family consists of 4 sextupole magnets. The lattice functions have a basic superperiodicity of 2. The adjustment of γ_{tr} is obtained by tuning the quadrupoles, which are located between injection (IK1) and extraction kickers (EK1, Fig.1). Using 6 independently powered quadupoles families in arc one can create a local dispersion bump in 6 dipole magnets as shown in Fig.3 such that the γ_{tr} can be chosen in the range of 3.3 – 6.4 and the betatron tunes remain unchanged.

Stochastic Cooling in the RESR

A crucial point of the accumulation scheme is the reduction of emittance and momentum spread of the injected antiproton beam within the time between successive injections. The stochastic cooling system therefore must be capable of cooling a batch of 10^{8} antiprotons to its final values with respect to emittance and momentum spread within 10 s. The foreseen momentum stacking scheme is very similar to the CERN AA stacking scheme [9], where such as system has been used successfully. A study on a CERN AA like system for the RESR has shown that the RESR lattice is well suited for this task. Furthermore, the results led to the definition of the gain profile for the pickups of the longitudinal cooling system. The momentum cooling system is divided into three different systems: the hand-over system, the stack-tail system and the stack-core system. An injected beam will be transferred from the injection orbit to an orbit which is covered by the hand-over system using the standard RF-cavity of the RESR. The different cooling systems then are cooling this beam towards the stack-core [10].

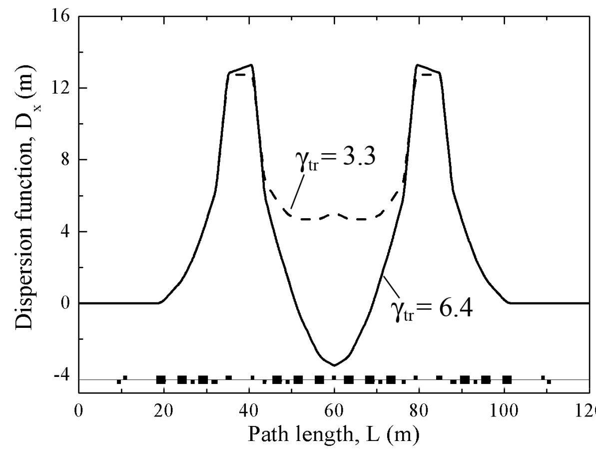

Figure 3: Dispersion function bump in the RESR arc.

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