THE ALTERNATIVE ION-OPTICAL MODE OF THE RECUPERATED EXPERIMENTAL STORAGE RING (RESR)*

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Abstract

The main purpose of the Recuperated Experimental Storage Ring (RESR) in the FAIR project is the accumulation of antiprotons coming from the Collector Ring (CR), where they are stochastically pre-cooled. The accumulation scheme of the RESR foresees longitudinal stacking in combination with stochastic cooling.

The stochastic cooling process strongly depends on the phase-slip factor (η) of the ring. Presently, the RESR is calculated to operate with small $\eta = 0.03$. In order to expand the area of application of stochastic cooling a new alternative ion-optical mode with higher $|\eta| = 0.11$ has been calculated in such a way, that the RESR can be operated in both modes easily. The study of the dynamic aperture of the nonlinear lattice has been performed in detail. The corresponding results are presented.

INTRODUCTION

The RESR is a symmetric storage ring with two arcs and two straight sections and a total circumference of 240 m [1]. The magnetic structure consists of 24 dipole magnets and a set of 9 quadrupole families (34 quadrupoles in total). For the chromaticity correction 2 sextupole families (8 sextupoles in total) will be installed in the dispersive regions of the ring. The RESR will be operated up to a maximum magnetic rigidity of 13 Tm. The momentum acceptance is $\pm 1.0\%$ and the transverse acceptance is 25 mm mrad in both planes.

The injection into the RESR will be performed onto the inner orbit with a momentum offset of $\Delta p/p = -0.8\%$ with respect to the central orbit, whereas the accumulation of antiprotons will take place on an outer, so called accumulation orbit with $\Delta p/p = +0.8\%$. The accumulation is realized by the accumulation of batches of 10^8 stochastically pre-cooled antiprotons delivered by the CR every 10 s at a beam energy of 3 GeV resulting in up to 10^{11} antiprotons within 3 hours [2]. The present CR/RESR complex is shown in Fig. 1.

The stochastic cooling process imposes certain requirements on the lattice with regard to transition energy or phase-slip factor, beta functions, phase advance between pick-ups and kickers of the stochastic cooling system and dispersion function to enable fast cooling and accumulation of the antiproton batches. The transition energy must be adjusted to a certain value range in order to obtain the desired mixing for efficient cooling.

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The present layout fulfills all these requirements and γ_t amounts to 6.4 ($\eta = 0.03$) [3]. However, according to recent simulations on the stochastic stacking process of the RESR, it was proposed to calculate an alternative ion-optical mode with higher η (lower γ_t) in order to optimize the stacking taking into account beam feed back effects [4].

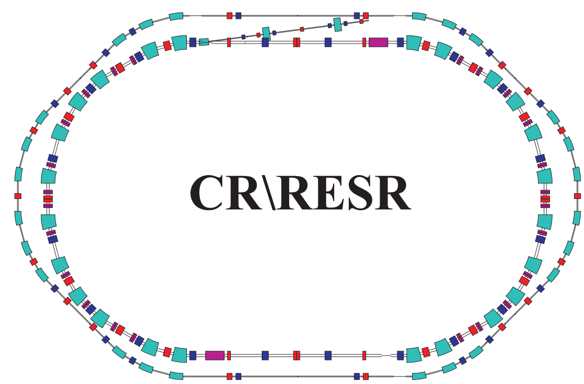

Figure 1: Layout of the CR (inner ring) and the RESR (outer ring) complex.

ION - OPTICAL CALCULATION

Detailed ion-optical calculations of the alternative setting have been performed with the ion-optical codes MIRKO [5] and GICOSY [6]. All 9 quadrupole families have been tuned in a special way to reduce γ_t down to 2.5 ($|\eta| = 0.11$) keeping the beam inside the magnet apertures and taking into account the requirements for the stochastic cooling described above. The longitudinal and transverse acceptances have been kept according to the normal RESR mode ($\gamma_t = 6.4$). The natural chromaticity has been efficiently corrected by 8 sextupole magnets. The calculated beam functions are illustrated in Fig. 2.

Dynamic Aperture

We have studied the investigation of the influence of nonlinear effects by computation of the dynamic aperture of the ring. The dynamic aperture gives us a conception of the maximal stable area in phase space depending on the different kinds of field imperfections of the magnets. It is usually determined by numerical particle tracking. In our caclulations we have used the Polymorphic Tracking Code (PTC) [7] integrated into MAD-X [8]. The field errors for the calculation (up to 9^{th} order) have been taken from Ref. [2], where multipole components for the quadrupole and sextupole magnets correspond to measured values of

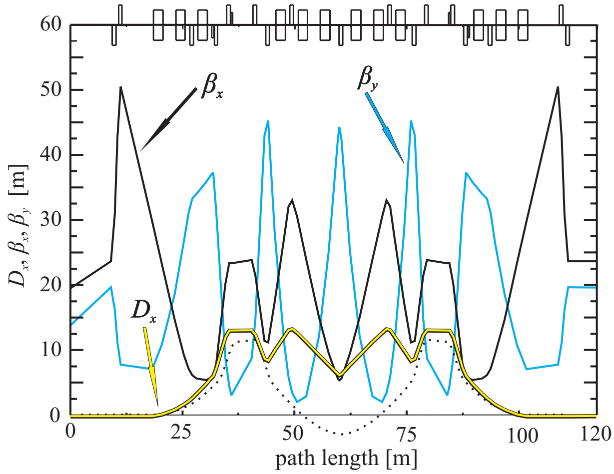

Figure 2: The calculated β-functions for one half of the RESR in horizontal (black curve) and vertical (blue curve) plane and the dispersion function (yellow curve) as a function of the path length. The dashed curve corresponds to the dispersion function of the normal RESR ($\gamma_t = 6.4$) mode. The magnet positions are indicated along the path length.

the existing ESR magnets. Errors for dipole magnets have been simulated with the OPERA code [9] using a circular multipole expansion. However, it is preferable to calculate dipole field errors using an elliptical multipole expansion, since the RESR dipoles have a large horizontal aperture [10]. This calculation has been performed with the OPERA-2D code, and the corresponding values are presented in Table 1. Since the elliptical errors provide more precise field information they were chosen as the errors for the dipole magnets. The dynamic aperture calculation has been performed for the injection, the reference and the accumulation orbits of the RESR. The corresponding results are illustrated in Fig. 3. One can see that the dynamic aperture is larger than the ring acceptance for all considered cases. Additionally, for the accumulation orbit the calculation using circular field errors was performed. It gives a result in the horizontal plane which is more optimistic by about 15% compared with the elliptical case (see Fig. 3).

Table 1: Systematic field harmonics of the RESR dipole magnet for the circular and the elliptical multipole expansion. The errors are expressed in units of 10^{-4} at a reference radius of 25 mm and 125 mm for the circular and the elliptical cases correspondingly. Harmonics of order 1 refer to a quadrupole, 2 to a sextupole component and so on.

Harmonic Number	Circular	Elliptical
1	0.0	0
2	0.12	1.26
3	0.0	0
4	-0.016	-0.9
5	0.0	0.0
6	0.017	1.19
7	0.0	0.0
8	-0.001	-4.78

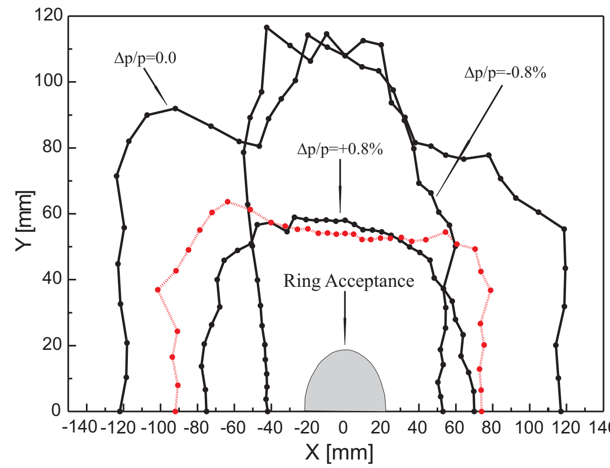

Figure 3: The dynamic aperture of the RESR for 1000 turns. The red dashed curve corresponds to the dynamic aperture of the accumulation orbit ($\Delta p/p = +0.8\%$) calculated with circular errors of the dipoles. The black solid curves are calculated with elliptical errors of the dipoles.

Frequency Map

In order to come to a better understanding of the complex structure inside the dynamic aperture (resonances) the tune as a function of the betatron amplitude was computed and Laskar's frequency map [11] has been calculated for three orbits of the RESR. The calculations have been performed with the ELEGANT code [12]. The corresponding plots are shown in Figs. 4-6. In order to see the real strength of the resonances which can disturb the dynamic aperture, and at which amplitude they act, one has to consider a stability index which characterizes the tune variation. The stability index can be described by the diffusion coefficient D:

$$D = \lg\left(\sqrt{\left(Q_x^{(2)} - Q_x^{(1)}\right)^2 + \left(Q_y^{(2)} - Q_y^{(1)}\right)^2}\right), \quad (1)$$

where $Q_{x,y}^{(1)}$ are the transverse tunes computed over the first 500 turns, and $Q_{x,y}^{(2)}$ are the tunes computed over the next 500 turns. In all figures this diffusion rate is depicted by a color scale from red (for very stable betatron motion) to violet (for chaotic betatron motion).

From these figures one can see that the working point is found in the stable area of the frequency map and there are no dangerous resonances within the ring acceptance.

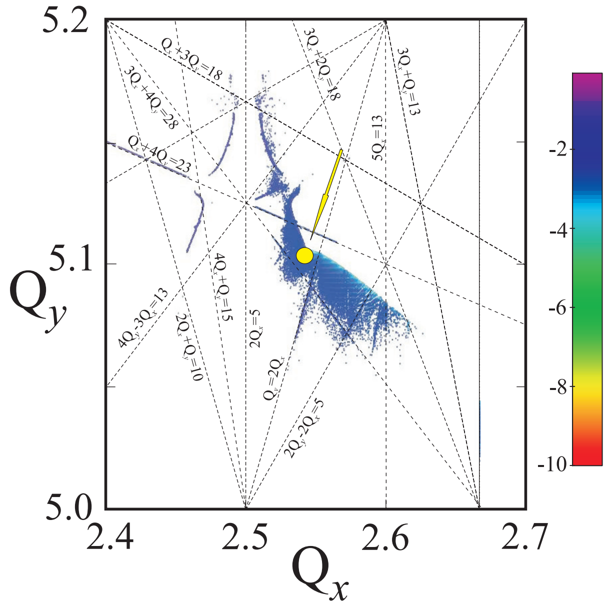

Figure 4: The frequency map computed for the reference orbit ($\Delta p/p = 0$). The arrow shows the working point and the area corresponding to the ring acceptance.

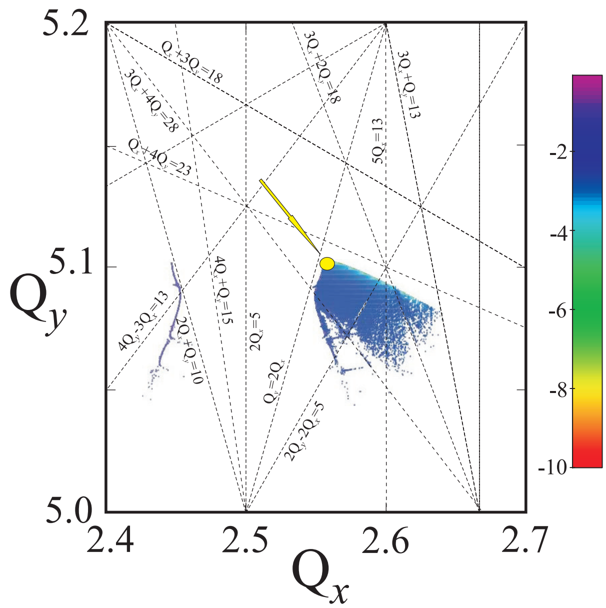

Figure 5: The frequency map computed for the injection orbit ($\Delta p/p = -0.8\%$). The arrow shows the working point and the area corresponding to the ring acceptance.

SUMMARY AND OUTLOOK

We have studied that the alternative mode of the RESR is functional and is not different from the normal one with respect to the stochastic cooling process. However, further simulations of the dynamic aperture including all kinds of field imperfections such as random errors of the magnets, fringe fields of the quadrupoles and magnet misalignments are needed. Thus the flexibility of the RESR for stochastic

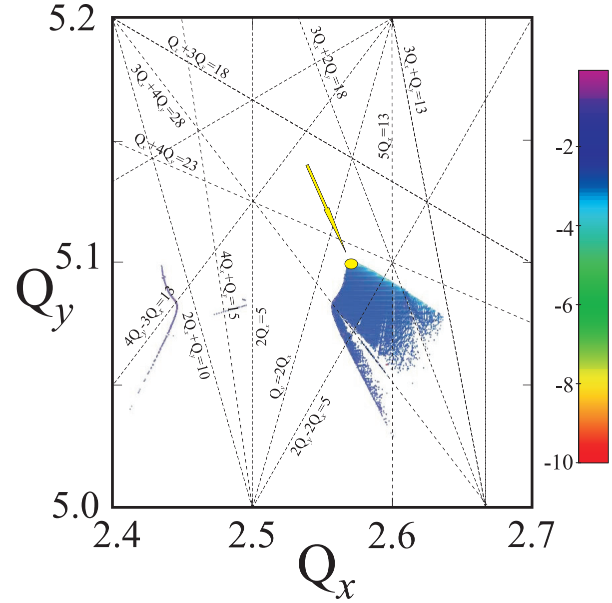

Figure 6: The frequency map computed for the accumulation orbit ($\Delta p/p = +0.8\%$). The arrow shows the working point and the area corresponding to the ring acceptance.

cooling can be increased by controlling the γ_t via an additional sextupole family in the arc of the ring. Space for installation of the additional sextupoles is available.

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