# BEAM DYNAMICS AND CLOSED ORBIT CORRECTION AT THE COLLECTOR RING

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## *Abstract*

Ion-optical layout and system design of the Collector Ring (CR) has been recently finalized after careful optimizations aiming at improvement of the beam parameters and machine performance. Nonlinear beam dynamics is discussed in this paper. Particle tracking calculations have been performed to evaluate the dynamic aperture for the different ion-optical modes of the machine. The technique of frequency map analysis allowed us to reveal more details about the influence of the magnet imperfections on the dynamic aperture. Closed orbit distortions due to the magnet misalignments and the dipole field errors have been studied with the MAD-X code [1]. We used the SVD algorithm for the closed orbit correction based on the present layout of the beam position monitors and dipole correctors. Requirements to the strengths of the correctors are also discussed here.

## INTRODUCTION

CR is a dedicated large acceptance storage ring designed for stochastic cooling of hot antiprotons or rare isotopes at FAIR [2]. Coming directly from the antiproton (or fragment) separator, the injected beams will have a large emittance of 240 mm mrad for antiproton beam and 200 mm mrad for heavy ions. The momentum spread is 6% and 3% for antiproton and ion beams, respectively. Sextupole correction is therefore an essential issue for compensation of the natural chromaticity. In the CR, six families of sextupoles will be used for this purpose. Calculations show that the sextupoles are themselves the main source of a nonlinear particle motion due to amplitude dependency [3]. Therefore, an optimal choice of the sextupole correction scheme aims to find a compromise between the corrections of chromatic and amplitude dependent effects. To examine carefully the nonlinear beam behaviour, dynamic aperture has to be analysed at discrete values for the full range of the momentum spread. Realistic magnetic field imperfections have to be considered as they can generate the beam instabilities due to resonances and restrict the dynamic aperture, especially for off-momentum particles [4]. Other sources of the dynamic aperture squeeze are the magnet misalignments and dipole field errors. Quadrupole and sextupole rotation errors generate skew field components which can amplify nonlinear behaviour due to coupling resonances. Orbit distortions in the sextupole magnets result in amplitude growth and tune shift which can lead to unstable motion of particles. Beam position monitors and dedicated dipole correctors are then used to observe and correct the closed orbit deviations.

## LATTICE

The CR has a circumference of 221 m and a maximum magnetic rigidity of 13 Tm. It consists of 24 dipoles, 40 quadrupole and 24 sextupole magnets distributed in the two arcs and two long straight sections. An overview of the present ion-optical layout and properties of the ring has been presented in [5]. In the arcs, 13 vertical corrector magnets with the embedded beam position monitors (BPM) will be installed. All 24 main dipoles will have the correction coils embedded into the main dipole coils for closed orbit corrections. In the straight sections, 4 combined correctors, 1 horizontal corrector and 2 vertical correctors with the embedded BPM will be installed. The positions of the BPMs and correctors in one quarter of the CR are indicated in Fig. 1.

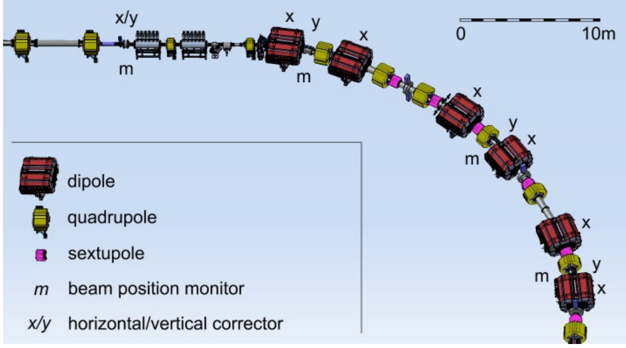

Figure 1: Positions of the beam position monitors (*m*) and horizontal/vertical correctors (*x/y*) in the CR quarter.

## NONLINEAR BEAM DYNAMICS

### *Sextupole Correction*

The natural chromaticity of the CR is (-6.2, -4.7) for the antiproton optics and (-3.1, -3.0) for the ion optics. Optimal values of the sextupole strength parameters have been defined taking into account the estimated higher-order multipole contribution of the CR magnets. Particle tracking calculations have been performed to evaluate the resulting chromatic dependence of the betatron tunes and the tune variation with initial transverse amplitudes (see Fig. 2). The horizontal and vertical tune variation after the sextupole correction is within the range of ±0.02 for antiproton and ion optics.

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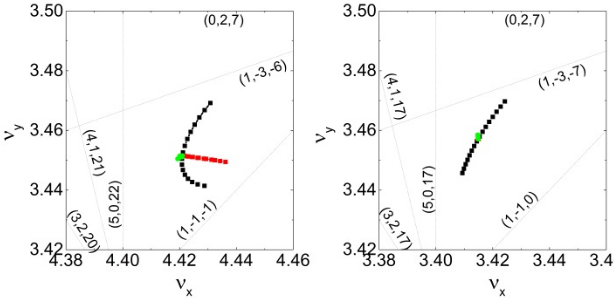

Figure 2: Betatron tune variation with momentum deviation (black), horizontal amplitude (red) and vertical amplitude (green) for the antiproton (left) and ion (right) optics. Resonance lines *(m, n, l)* defined as $m\nu_x + n\nu_y = l$ are shown up to order $|m| + |n| \leq 5$.

### *Dynamic Aperture*

Multipole field components from the electromagnetic field simulations for the dipole, quadrupole and sextupole magnets have been used to evaluate the impact of the field imperfections on the dynamic aperture (DA). Figure 3 shows the DA calculated by particle tracking over 1000 turns as dictated by the time required for the bunch rotation (typically 1-2 ms) prior to the stochastic cooling.

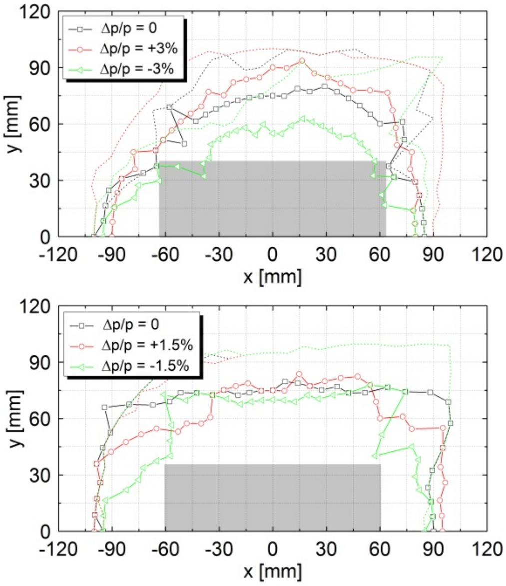

Figure 3: Dynamic aperture calculated at the middle of the CR straight section for the antiproton (top) and ion (bottom) optics. Dotted lines correspond to DA due to only sextupoles. Lines with symbols are DA due to sextupoles and multipole field errors of the CR magnets.

To study the DA in a more detail, the technique of frequency map analysis has been applied [6]. For the antiproton optics, the tune map is split into two parts by the quadrupole coupling resonance (1,-1,1) as shown in Fig. 4. Other resonances which may disturb the particles inside the ring acceptance are of 9th order corresponding to the 18-pole field components of the dipole and quadrupole magnets. The most serious resonances for the ion optics are due to the 10-pole and 14-pole field components, especially the (5,2,24) resonance which disturbs the ring acceptance for off momentum particles (see Fig. 5).

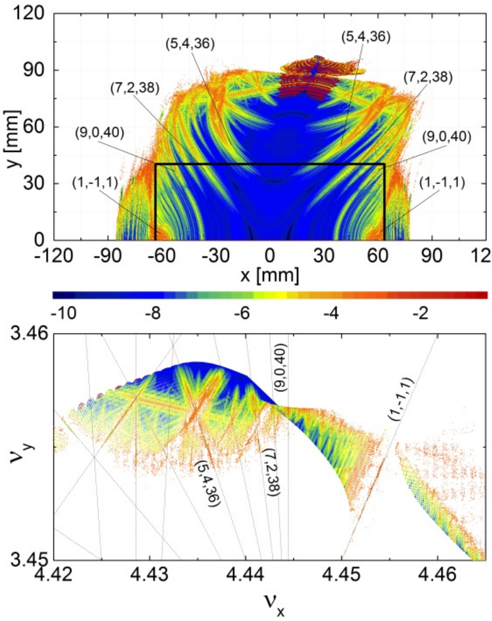

Figure 4: Dynamic aperture (top) and tune map (bottom) for particles with the momentum deviation Δp/p = 3% in the antiproton optics. Black line is the acceptance.

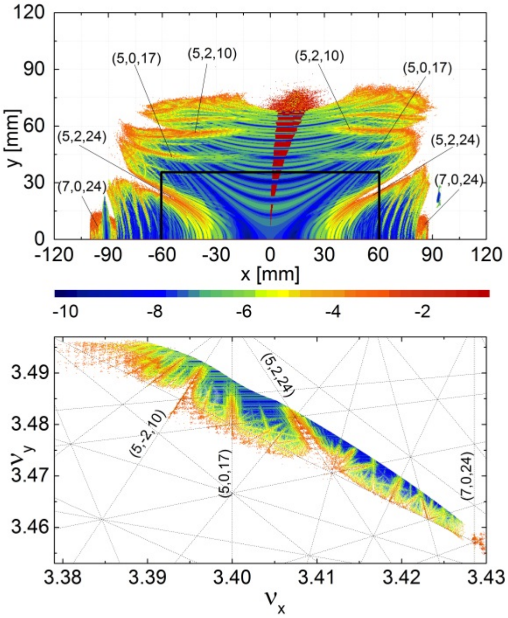

Figure 5: Dynamic aperture (top) and tune map (bottom) for particles with the momentum deviation Δp/p = -1.5% in the ion optics. Black line is the acceptance.

### *Impact of Closed Orbit Distortions*

To study the influence of the closed orbit (CO) distortions on nonlinear beam dynamics, DA has been calculated taking into account the integrated dipole field error δB/B, magnet displacement errors Δx, Δy, Δz and magnet rotation errors Δφ, Δθ, Δψ listed in Table 1. The Gaussian distribution with mean value of 0 and a cut-off at 2.5σ has been used to generate 20 different error sets.

Table 1: Alignment and Field Quality Tolerances

| | Dipole | Quadrupole | Sextupole |
|---|---|---|---|
| δB/B, rms | $5\cdot10^{-5}$ | - | - |
| Δx, Δy, Δz, rms | 0.3 mm | 0.3 mm | 0.3 mm |
| Δφ, Δθ, Δψ, rms | 0.3 mrad | 0.3 mrad | 0.3 mrad |

Figure 6 shows the DA and tune map calculated for an averaged CO distortion with the rms horizontal (vertical) deviation of 12 mm (8 mm) for off-momentum particles in the antiproton optics. Comparison of Fig. 6 with Fig. 4 demonstrates that the DA is reduced due to the simulated orbit distortion.

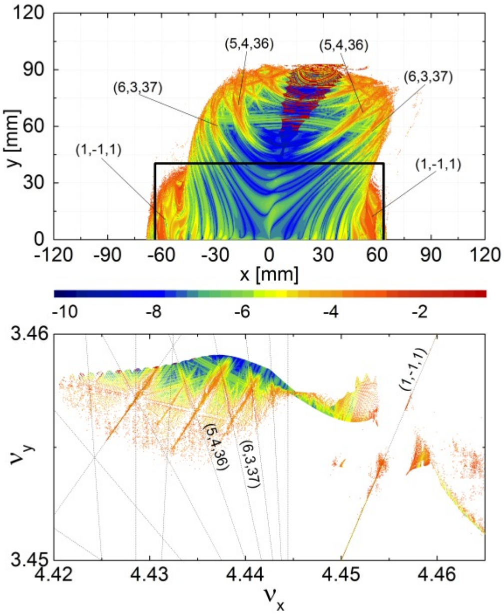

Figure 6: Dynamic aperture (top) and tune map (bottom) for particles with the momentum deviation Δp/p = 3% in the antiproton optics. Magnet misalignments and dipole field error are considered. Black line is the acceptance.

Even inside the ring acceptance some particles are lost within the 1000 turns due to the tune shift generated by the CO displacement in the sextupoles. The tune map shows an amplification of the quadrupole coupling resonance (1,-1,1) which is due to the quadrupole and sextupole rotation errors creating skew multipole contributions.

## CLOSED ORBIT CORRECTION

CO distortions in the CR can be observed by 19 beam position monitors (BPM). It is assumed that the BPMs have the absolute measurement accuracy of 1 mm. 29 horizontal and 19 vertical correctors distributed in the arcs and straight sections have been used to correct the CO distortions for 5000 different sets of errors. The horizontal (vertical) CO distortions have been corrected from peak-to-peak rms value of 12.3 mm (9.2 mm) to 1.5 mm (1.2 mm) for the antiproton optics as shown in Fig. 7. In the rare isotope mode, the CO distortions can be reduced to peak-to-peak rms values of 0.7 mm and 1.2 mm in the horizontal and vertical plane, respectively. This is due to a slightly smaller average horizontal β-function in the ion optics.

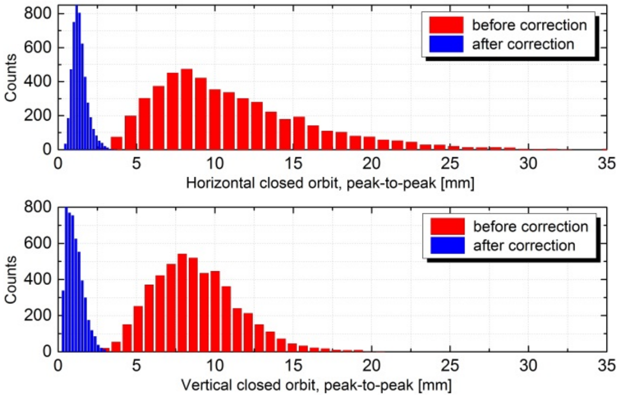

Figure 7: Calculated peak-to-peak CO deviations for the antiproton (top) and rare isotope (bottom) optics.

The corrector strength distribution and the distribution of the maximum values of corrector strengths for the antiproton and ion optics are shown in Fig. 8. The maximum required kick strength is below 0.75 mrad.

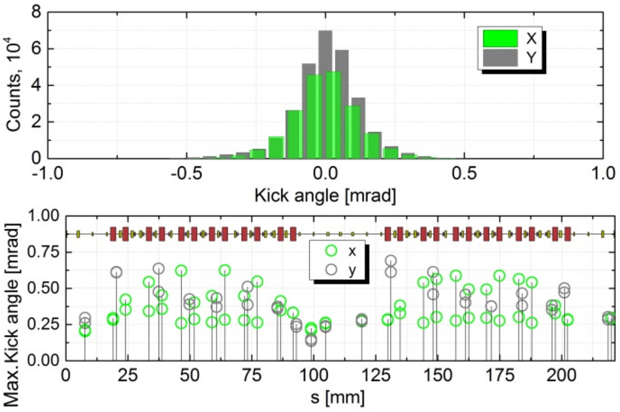

Figure 8: Histogram of the required corrector strengths (top) and the distribution of maximum values for correctors over the ring (bottom) for the antiproton and ion optics.

## REFERENCES

[1] The MAD-X code, `http://www.cern.ch/madx`
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