EFFECTS OF FIELD IMPERFECTIONS IN THE ISOCHRONOUS MODE OF THE CR STORAGE RING AT FAIR

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Abstract

Today the challenge is to measure masses of exotic nuclei up to the limits of nuclear existence which are characterized by low production cross-sections and short half-lives. The large acceptance Collector Ring (CR) [1] at FAIR [2] tuned in the isochronous ion-optical mode offers unique possibilities for such measurements. Nonlinear field errors as well as fringe fields of the wide aperture quadrupoles and dipoles strongly excite the high-order aberrations which negatively affect the time resolution of the isochronous ring. Their influence is investigated here and a possible correction scheme is shown.

INTRODUCTION

The CR is a symmetric, achromatic ring with two arcs, two straight sections and a total circumference of 221.5 m. It is designed for operation at a maximum magnetic rigidity of $B\rho = 13$ Tm [3]. The purpose of the CR is fast pre-cooling of antiprotons and radioactive ion beams [4]. In addition the CR will be operated in the isochronous ion-optical mode as a Time-of-Flight (ToF) spectrometer for the mass measurement of exotic very short-lived nuclei ($T_{1/2} > 20\mu s$) produced and selected in flight with the Super-FRS fragment separator [5].

The isochronous mode has been calculated for three different values of the transition energy γ_t [6]. In our calculations we always used the setting of $\gamma_t = 1.67$ which allows to measure masses up to $m/q = 3.1$. In this case the momentum acceptance is about $\Delta p/p = \pm 0.45\%$ while the transverse acceptance is 100 mm mrad in both planes.

The basic condition for isochronicity is the equation which describes the relative change of revolution time (T) depending on mass-to-charge ratio (m/q) and velocity (v) of the stored ions circulating in the ring:

$$\frac{\Delta T}{T} = \frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{(m/q)} + \left(\frac{\gamma^2}{\gamma_t^2} - 1\right)\frac{\Delta v}{v} - \frac{dT}{T}, \quad (1)$$

where γ is the relativistic Lorentz factor. The isochronous condition is reached when $\gamma = \gamma_t$. This means, the second term in Eq. (1) vanishes and $\Delta(m/q)$ can be determined from the observed ΔT. The resolution depends on the time spread (dT) given by additional aberrations of the time-of-flight.

The main and strongest contribution to dT is due to the second-order pure chromatic time aberration (second-order isochronicity), which, however can be easily corrected with one family of the sextupole magnets installed in the dispersive part of the ring. The influence with second most importance comes from the transverse motion. In Ref. [7] it has been derived, that the time resolution is inversely proportional to the transverse emittance and, in order to reach the necessary mass resolution of 10^{-6} the transverse acceptance of the CR would be limited to 10 mm mrad in both planes, which would crucially restrict the transmission of the exotic nuclei into the ring. However, the negative effect of the transverse emittance can be compensated by correcting the natural chromaticity with two families of sextupole magnets (each family is for each transverse direction) [8]. Moreover, correcting the third-order time aberrations with the octupole magnets, one can further improve the time resolution [8].

Nonlinear field errors and fringe fields of magnets excite the high-order aberrations which contribute strongly to dT [7]. In this case the octupole correction becomes especially important.

NONLINEAR DIPOLE FIELD

The CR dipole field homogeneity is crucial for the time resolution. It can be written in terms of normal multipole coefficients (b_n) as:

$$\frac{\Delta B}{B_0} = \sum_{n=1}^{5} b_n \cdot \left(\frac{x}{r_0}\right)^n, \quad (2)$$

where r_0 is a reference radius for the multipole expansion. The calculated b_n are listed in Table 1:

Table 1: The calculated b_n of the CR dipole normalized with respect to the b_0 component. The values are expressed in units of 10^{-4} at the reference radius of 190 mm

b_1	b_2	b_3	b_4	b_5
0	6.3	0.03	1.7	0.0088

These values are calculated at the maximum field strength of $B = 1.6$ T. One can see the CR magnet design implies high-order components which negatively act on dT. The influence of sextupole (b_2) and octupole (b_3) components can be completely compensated using the sextupole and octupole magnets. The decapole component (b_4) is the largest. Within its influence on dT the goal of 10^{-6} of mass resolution over the full momentum acceptance is unachievable. It can be reached only for $dp/p = \pm 0.2\%$ (black curve in Fig. 1). Alternatively, one can compensate this crucial effect and get $\Delta m/m$ of about $5 \cdot 10^{-7}$ using one family of the decapole magnet installed in the dispersive part of the ring (red curve in Fig. 1).

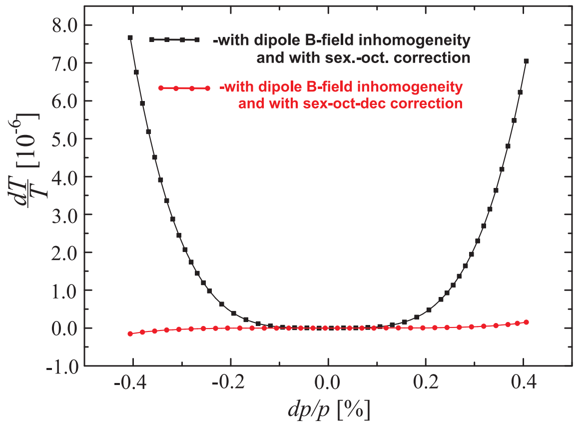

Figure 1: Relative time difference as a function of the momentum deviation in the CR with inhomogeneous dipoles. Only pure chromatic dependence on the revolution time is included. Black curve: After sextupole-octupole correction mainly decapole component contributes to dT. Red curve: After additional correction with one decapole, only the small remaining effect of the b_5 component of the dipole remains.

FRINGE FIELDS

The influence of the fringe fields on the revolution time was studied. The analysis is based on the fringe field distribution, which was calculated for the CR dipole and quadrupole magnets [9]. They were approximated by the Enge function and the corresponding transfer matrices were calculated [10]. These matrices were implemented into the GICOSY code [11, 12] which was used for the calculations.

Taking the quadrupole fringe fields into the ion-optics simulation results in a matched beam with slightly altered beam parameters and small dispersion mismatch. The first-order isochronous condition, betatron tunes and the natural chromaticity are changed slightly. However, the third-order aberrations of the quadrupole fringe fields make a significant influence on dT, which is next to importance after all effects discussed above.

The CR dipole magnets have no edge focusing. The fringe fields provide an additional first-order focusing in the vertical plane [13]. Its magnitude is smaller than in the fringe fields of quadrupoles. The change of the vertical focusing leads to the change of the betatron vertical tune and correspondingly of the vertical chromaticity. The influence of the dipole fringe fields on dT is less than due to the quadrupole fringe fields but still noticeable and has to be considered.

Therefore, considering the nonlinear field errors and fringe fields of magnets requires a recalculation of the quadrupole, sextupole and octupole settings to adjust isochronicity and chromaticity. The higher-order effects from different types of imperfections has been studied numerically and the results are presented below.

NUMERICAL SIMULATIONS

Numerical simulations were done by tracking ions about 100 turns in the ring with the GICOSY program. The fifth-order transfer matrices for each optical element have been used in the simulations. In the simulations the transverse emittance of 100 mm mrad in each plane and the momentum spread of $\pm 0.5\%$ were assumed.

In order to reveal the influence to dT from different field imperfections we have performed a series of numerical calculations for each of them. In calculations the sextupole, octupole and decapole correction has been performed, which means that only high-order time aberrations coupling the longitudinal and transverse motion showed up. The results of simulations are illustrated in Fig. 2. One can see, that the quadrupole fringe fields represent a major contribution to the limit of the time resolution.

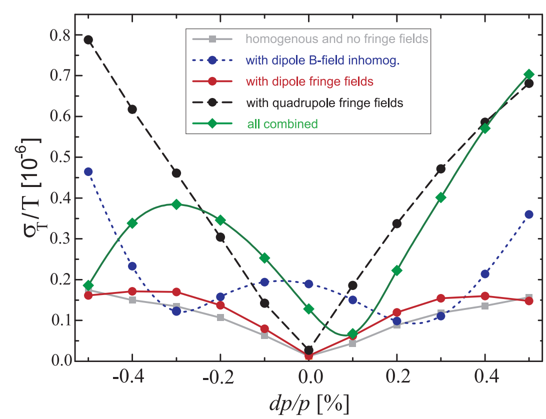

Figure 2: Relative standard time deviation after 100 turns in the ring for the full accepted transverse phase space as function of momentum deviation. Different curves correspond to the influence of different magnets imperfections. The green curve shows all effects combined. The grey curve shows the ideal case without any errors.

Considering all effects the time resolution depending on number of turns in the ring has been simulated. The result is shown in Fig. 3. Correcting only the isochronicity with 1 sextupole, 1 octupole and 1 decapole families the effect of the transverse emittance still limits the time resolution (blue curve in Fig.3). The chromaticity correction with additional 2 sextupole families improves the time resolution by almost a factor of ten (black curve in Fig.3).

Correcting significant third-order time aberrations with additional 3 octupole families the time resolution is improved a bit (orange curve in Fig. 3). The effect of quadrupole fringe fields is more difficult to compensate. Contrary to the dipole inhomogeneity it does not correspond to a simple multipole component which can be compensated with an opposite field nearby. Finally, one can reach a resolution of up to $dT/T \approx 3.0 \cdot 10^{-7}$, which corresponds to the mass resolution of $\Delta m/m = 10^{-6}$.

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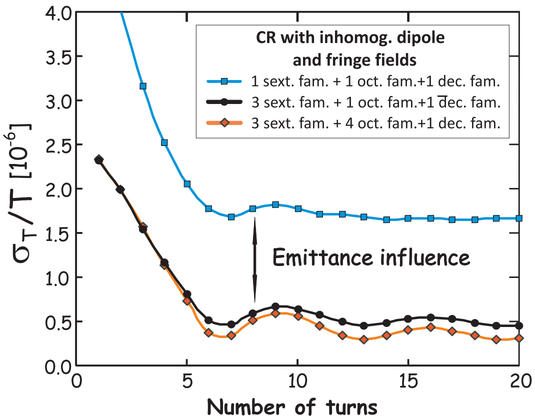

Figure 3: Monte-Carlo simulation of the relative standard time deviation as a function of turns. Dipole inhomogeneities and fringe fields of magnets are included.

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