FIELD PROPERTIES OF THE ESR MAGNETS AND THEIR INFLUENCE ON BEAM OPTICS

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Abstract

Machine experiments at the experimental storage ring (ESR) demonstrated that the ring acceptance is strongly restricted by field errors. Higher-order field harmonics of the dipole and quadrupole magnets have been calculated and then used in particle tracking simulations in order to find out the dynamic aperture of the ESR. To benchmark the results of numerical calculations, betatron tune measurements have been performed with a uranium beam at the energy of 400 MeV/u. The results of the magnetic field simulations for the ESR magnets and a comparison between the measured and calculated tune behaviour are presented.

INTRODUCTION

The ESR at GSI is operated for accumulation and cooling of heavy ion beams in the energy range of 3-400 MeV/u [1]. A general view, schematic layout and the main parameters of the ring are shown in Fig. 1. The ring has a circumference of 108.4 m and a maximum magnetic rigidity of 10 Tm.

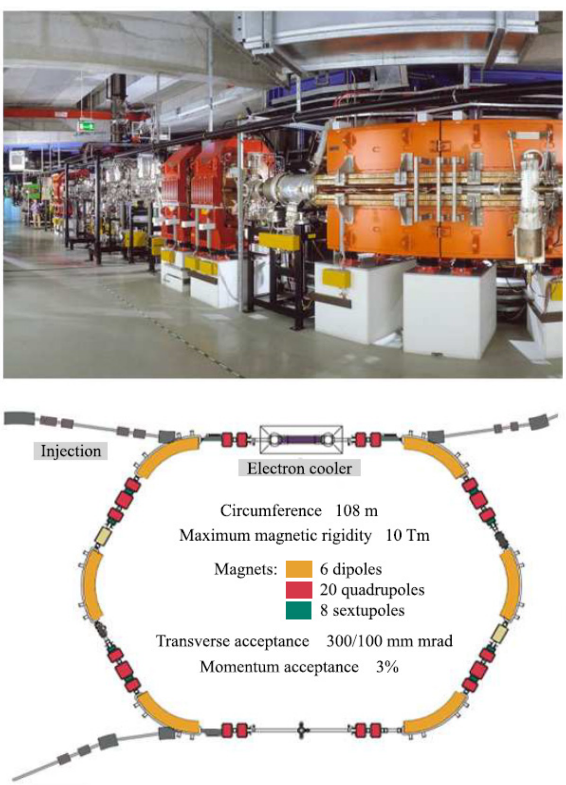

Figure 1: The Experimental Storage Ring at GSI, Darmstadt.

The design of the ESR magnets is governed by the momentum acceptance of 3 % and the horizontal/vertical acceptance of 300/100 mm mrad. The dipole and quadrupole magnets have large apertures and the magnetic field is strongly nonlinear, that gives an impact to the beam dynamics of the ring [2, 3]. The ESR is equipped with an electron cooler operated in the energy range of 3-400 MeV/u [4]. The transverse emittance can be reduced down to 0.05 mm mrad by the e-cooler. The momentum spread of the cooled beam is 0.1 - 0.001 %. Field errors of magnets do not significantly influence the particle oscillations if they have small amplitudes. Therefore, electron cooling suppresses the effects which are caused by the field nonlinearities. It is useful to estimate the impact of nonlinear field errors for a better understanding of the beam dynamics in the ESR and other large acceptance storage rings. The field properties of the ESR magnets have been studied with the OPERA code [5]. The field maps of the dipole and quadrupole magnet have been calculated and then used to evaluate the higher-order field harmonics. In order to estimate the influence of the field nonlinearities on the beam dynamics, the field harmonics have been implemented into the MAD-X code [6], where the particle tracking has been done. The experimental part of this work involved the betatron tune measurements at the ESR. The electron cooler was used to vary the beam energy (or $\Delta p/p$) and shift the beam orbit. The measured and calculated betatron tunes are compared to define properly the field harmonics of the dipole magnets.

MAGNETIC FIELD SIMULATIONS

The simulation models of the ESR magnets have been built with the MODELLER code of the OPERA package. Static field analysis has been performed with the TOSCA code, which is also included in OPERA. The calculated field characteristics are compared with measured data [7].

Dipole

The ESR bending system consists of six C-type 60° sector magnets with a maximum magnetic field of 1.6 T and a bending radius of 6.25 m (Fig. 2). The geometrical aperture of the magnet is 220 mm in horizontal and 70 mm in vertical plane. Magnetic field simulations show that the field quality in the usable aperture is 0.3% at the field level of 1.1 T. The radial field of the dipole magnet can be corrected by 23 trim coils, which are mounted on the poles over the full length of the magnet [8]. The normal field harmonics b_n have been evaluated analyzing the calculated field map.

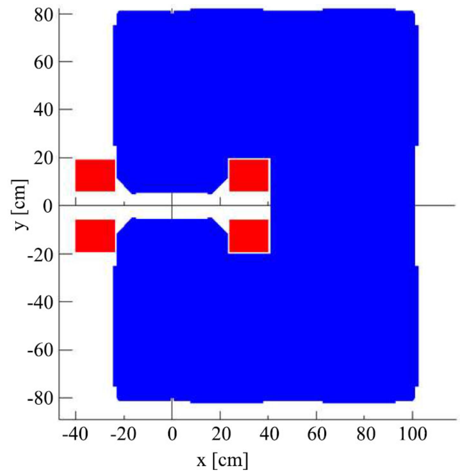

Figure 2: The cross section of the ESR dipole magnet.

Fig. 3 shows the measured integrated components b_n when the correction coils are switched on or off.

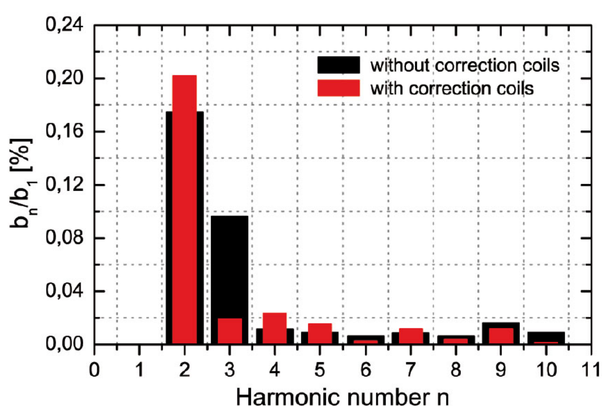

Figure 3: The integrated field harmonics b_n of the ESR dipole magnet normalized to the main dipole field. The field was analyzed at the reference radius of 5 cm. n = 1,2,3.. corresponds to the dipole, quadrupole, sextupole component etc.

Quadrupole

Focusing in the ESR is provided by 16 short (0.75 m, iron length) and 4 long (1.2 m, iron length) quadrupole magnets which have an identical cross section as shown in Fig. 4. The maximum field gradient is 6.2 T/m and the usable horizontal/vertical aperture is 300/150 mm. The bore radius of the quadrupoles is 256 mm. Due to the fringe field, the effective length is larger than the iron length. It is 0.835 m for the short quadrupole and 1.255 m for the long one at the maximum field gradient. We have performed the measurements and simulations at a gradient of 6 T/m. The calculated and measured field harmonics are shown in Fig. 5.

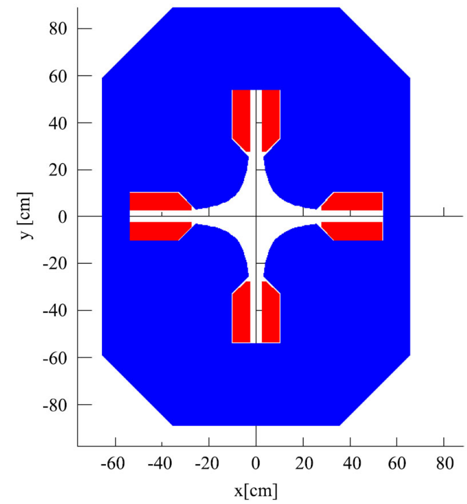

Figure 4: The cross section of the ESR quadrupole magnet.

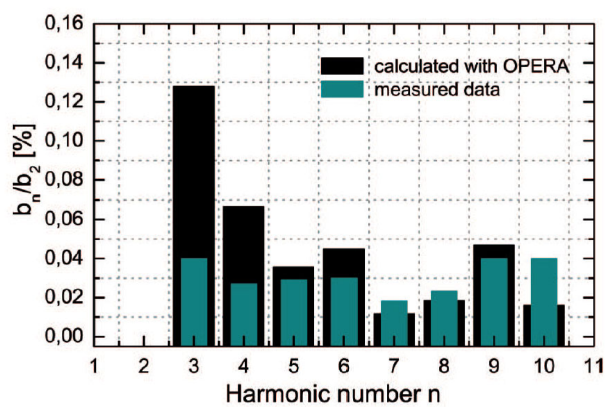

Figure 5: The integrated field harmonics b_n of the ESR quadrupole magnet normalized to the main quadrupole field. The field was analyzed at the reference radius of 12 cm.

MEASUREMENTS

The tune measurements at the ESR have been done with the $^{238}U^{86+}$ beam at an energy of 377 MeV/u. The field strength of the quadrupole magnets was adjusted to have the nominal betatron tunes $Q_x = 2.28$, $Q_y = 2.27$ on the reference orbit. Slightly changing the beam energy by the electron cooler the orbit was shifted to the corresponding $\Delta p/p$ orbit, where the nonlinear field errors are larger. After the beam was shifted, the electron cooler and the sextupole magnets were switched off and the tune measurements were performed. For the tune measurements, we used the transverse and longitudinal Schottky signals from the pick-ups. The theoretical proof of the measured results has been done by the particle tracking simulations with the MAD-X code. The single particle was tracked over 3000 turns and by applying the FFT analysis the betatron tunes were calculated. In the simulations, the field errors represented by the higher-order field harmonics given in Fig. 3 and Fig. 5 are used. In Fig. 6 we show the calculated betatron tunes, which are in good agreement with the measured ones. Systematic tracking calculations show

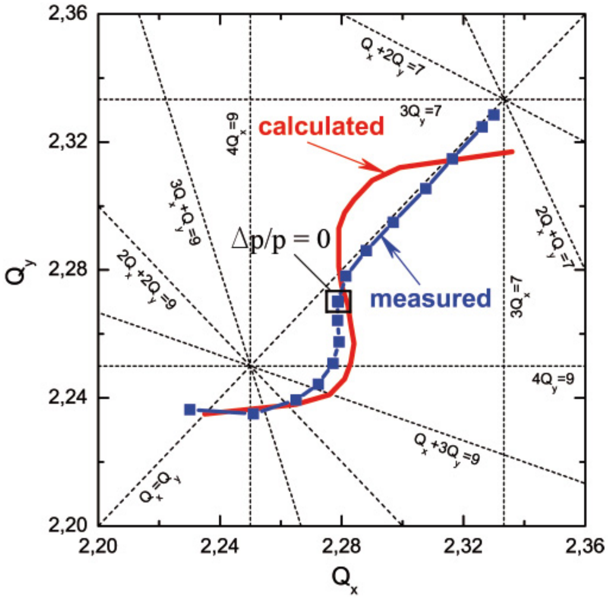

Figure 6: The betatron tunes of the ESR. Each measured point corresponds to a different beam orbit, i.e. value of $\Delta p/p$.

that the sextupole field harmonic b_3 of the dipole magnet has a dominant influence on the dynamic aperture of the ESR. In Fig. 7 the betatron tunes as a function of $\Delta p/p$ for different values of the sextupole harmonics b_3 are shown. We see that the betatron tune in the horizontal plane has a strong nonlinear behaviour over the full momentum acceptance of the ESR. In the vertical plane, the betatron tune is in good agreement with the measured one. The measured tune line is not symmetric with respect to the central orbit, i.e. the tunes are different for the inner and outer orbits. This may be caused by different focusing properties in the inner and outer part of the magnet aperture due to the C-shape configuration of the ESR dipoles.

Higher-order field harmonics of the dipole and quadrupole calculated by the OPERA code were used as field errors of the magnets. Systematic tracking calculations show that the beam chromaticity is influenced by the sextupole harmonic b_3 of the dipole magnet. According to the field calculations by the OPERA code, b_3 is 2×10^{-4}. To estimate its impact on the chromaticity, the tune line was calculated for different values of the sextupole harmonic.

CONCLUSIONS

Measurements and simulations of nonlinear beam dynamics in the ESR indicated that the beam motion is strongly influenced by the field errors of magnets. A comparison between the measured and calculated tunes allowed us to evaluate the sextupole harmonic b_3 of the dipole magnets. The estimated b_3 value is 2×10^{-4} with respect to the

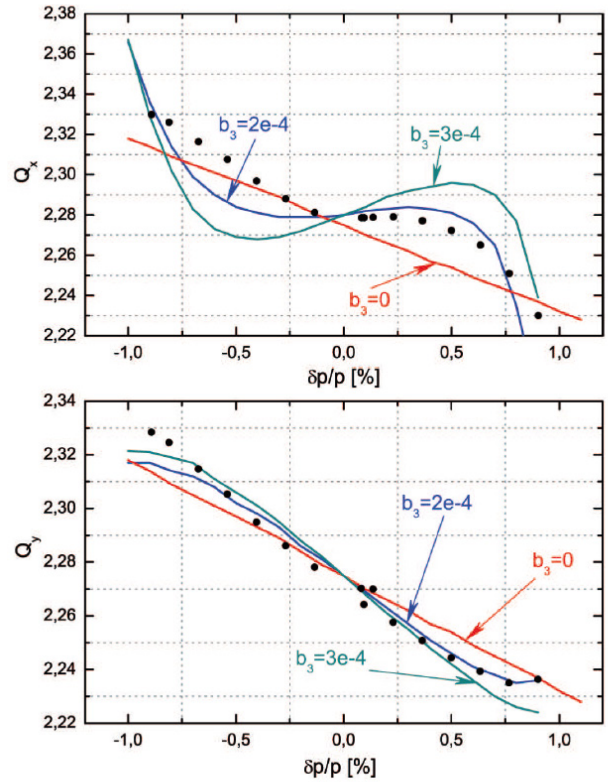

Figure 7: Measured (symbols) and calculated (curves) betatron tunes for the different sextupole harmonic b_3 of the dipole magnets.

main dipole field. The sextupole harmonic of the dipole magnets can be corrected by the trim coils, but special correction settings have to be found because of the different field nonlinearities corresponding to different beam orbits.

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