TOLERANCES OF MAGNET IMPERFECTIONS FOR A STORAGE RING AT SPring-8

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ABSTRACT

Tolerances of magnet imperfections for a 8-GeV low emittance electron storage ring have been estimated with particle tracking and statistical calculations. Tight alignments of quadrupoles and small displacements of sextupoles from closed orbit are demanded for this type of ring.

INTRODUCTION

The fields of quadrupole and sextupole magnets used in a 8-GeV electron storage ring for SPring-8 are so strong that closed orbit and betatron function are very sensitive to some magnet imperfections. The distortion of linear optics can cause undesirable effects such as reduction of dynamic aperture, excitation of accidental resonances, and x-y coupling of betatron oscillation. As these effects make machine operation difficult, it is important to estimate tolerances of various magnet imperfections.

In the present study, we estimated tolerances of random misalignments and field errors for dipole, quadrupole, and sextupole magnets with particle tracking program RACETRACK.[1] The stopbands caused by accidental isolated resonances up to 3rd order were also calculated.

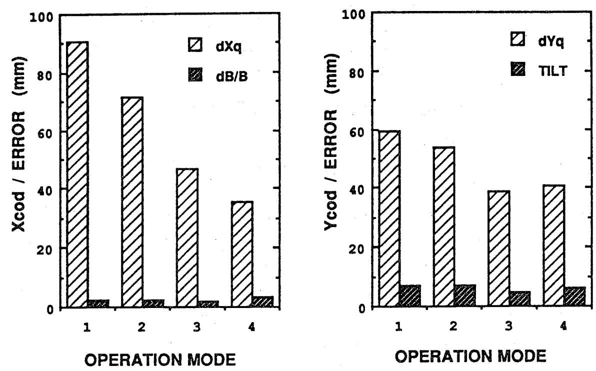
TOLERANCES

There are four operation modes for the storage ring —— hybrid, high-beta, middle-beta, and detuned modes. In the first three operation modes, strong quadrupole and sextupole fields are needed to achieve low natural emittance ($\sim 5\times10^{-9}$m). In the detuned operation mode, these fields are weakened for reducing lattice sensitivity to the magnet imperfections at the expense of emittance.[2]

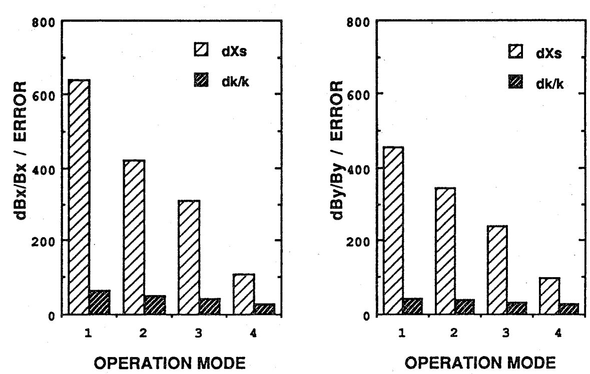
We performed statistical calculations of linear optics distortion caused by random magnet errors to see error sensitivity of these operation modes. The results of these calculations are shown in Fig. 1. The figure shows that the hybrid operation mode has largest sensitivity to the magnet errors among the operation modes. Therefore, we examine the case of hybrid operation mode hereafter.

Closed orbit is most sensitive to transverse misalignments of quadrupole magnets [see Fig. 1-(a)]. At the middle of the straight section of the ring, quadrupole rms misalignments of 0.1mm cause horizontal and vertical rms closed-orbit displacements of 9mm and 6mm, respectively. Field and tilt errors of dipole magnets also cause closed-orbit distortion. When we set these errors at 5×10^{-4} , horizontal and vertical rms closed-orbit displacements are 1mm and 4mm, respectively. The aperture of elliptical vacuum chamber is 80mm in width, and 40mm in height. As the calculated closed-orbit displacements (2.5σ) are within the aperture, we set the tolerances at 0.1mm for the quadrupole misalignments, and 5×10^{-4} for the dipole field and tilt errors.

Because of the strong nonlinearity of beam dynamics generated by sextupole magnets, magnet imperfections affect stability of the betatron oscillation in a complicated manner. We examined these effects using particle tracking program RACETRACK. Figure 2 shows the horizontal amplitude-dependent tune shifts obtained by tracking for ideal machine and five different machines with Gaussian-distributed random errors listed in Table 1. This figure shows two points: a) the amplitude dependence of tune is insensitive to the magnet errors at small amplitude: b) the horizontal and vertical betatron oscillations couple strongly, which make these tunes different from the uncoupled linear tunes significantly.



(a) closed orbit



(b) betatron function

Fig. 1 Error sensitivity of linear optics
1: hybrid mode
2: high-beta mode
3: middle-beta mode
4: detuned mode

Accidental resonances can be excited by the random distortions of betatron function by sextupole displacements from closed orbit and quadrupole gradient errors. Of these imperfections, the distortion of betatron function is more sensitive to the sextupole displacements [see Fig. 1-(b)]. To estimate the tolerances of these errors, we performed particle tracking for 10 different machines with these errors. In the tracking, we launched one particle with amplitude of 10mm and checked the stability of betatron oscillation up to 500 turns. The amplitude corresponds to the coherent amplitude of beams at injection. The results are shown in Fig. 3. From these results, the tolerances of the sextupole displacements and the quadrupole gradient errors have been set at 0.2mm and 5×10^{-4}, respectively.

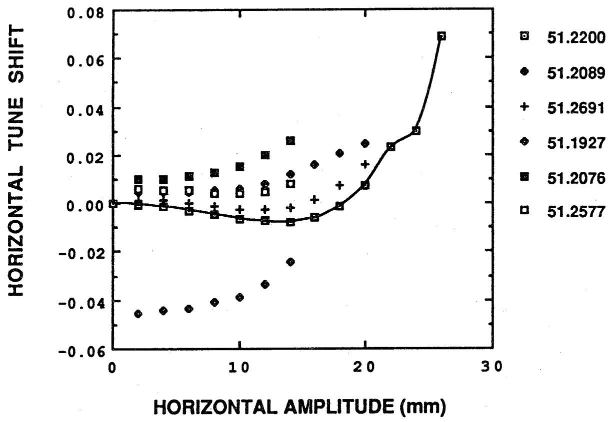


Fig. 2 Amplitude dependent tune shift
Numbers on symbols mean horizontal linear tune.

We also estimated contributions of the quadrupole and the sextupole tilt errors and the sextupole field errors to stopbands of lowest-order accidental resonances. The rms width of stopbands per unit error are listed in Table 2. The quadrupole tilt errors and the sextupole vertical displacements can cause coupling resonances of $\nu_x+\nu_y$ =integer. The quadrupole contribution is smaller than the sextupole contribution. The field errors and horizontal displacements of sextupoles can cause nonlinear resonances of $3\nu_x$=integer and $\nu_x+2\nu_y$=integer. The effect of the field errors is much smaller than that of the displacement errors. Although sextupole tilt errors can cause nonlinear resonances of $3\nu_y$ =integer and $2\nu_x+\nu_y$ =integer, stopband widths of these resonances are rather narrow. From these considerations, we have set the tolerances at 5×10^{-4} for the quadrupole and the sextupole tilt errors, and 1×10^{-3} for the sextupole field errors.

In Table 1, we listed the tolerances of magnet errors described above. Particle tracking including these magnet errors shows that all particles are stable, when horizontal amplitude are less than 10mm at the middle of the straight section.

STOPBAND

As distortion of betatron function and fluctuation of magnet fields destroy the superperiodicity of the ring, various accidental resonances may be induced. Although the analytical study of higher-order accidental resonances is difficult, lowest-order accidental resonances can be studied analytically by calculating rms excitation coefficients and stopbands. We checked validity of such calculations by comparing the anaritical results with particle tracking for accidental resonance of $3\nu_x$ =154. In the tracking, we examined the stability of betatron oscillation for 10 different machines with errors listed in Table 1. The stopband width was then obtained by tune dependence of the stability. The results are shown in Fig. 4 for horizontal oscillation amplitude of 15mm and 10mm. The rms half width of the stopband obtained by the analytical calculation is 0.012 for amplitude of 15mm, and 0.008 for amplitude of 10mm. The analytical results agree with the tracking results quite well. The stopbands of lowest-order resonances obtained analytically are shown in Fig. 5. In these calculations, we assumed the oscillation amplitude of 15mm (J_x=5.11μm) horizontally, and 5mm (J_y=1.25μm)vertically. This figure shows that the operating point is far away from the lowest order accidental resonances.

Table 1 Storage ring tolerances

Quadrupole alignment	0.1mm
Sextupole displacement	0.2mm
Quadrupole tilt	5×10^{-4}
Sextupole tilt	5×10^{-4}
Dipole tilt	5×10^{-4}
Quadrupole gradient	5×10^{-4}
Sextupole field	1×10^{-3}
Dipole field	5×10^{-4}

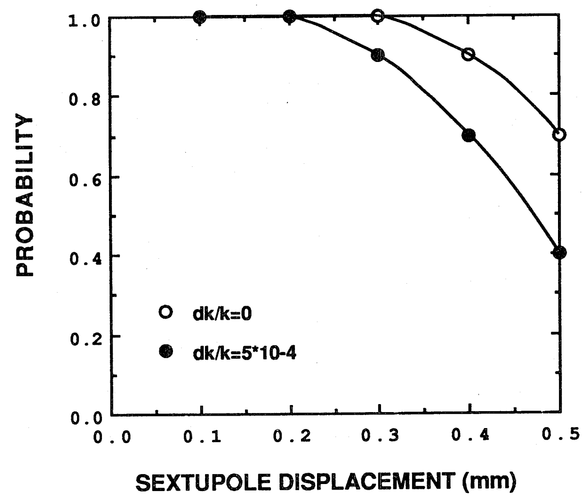


Fig. 3 Effects of sextupole displacements and quadrupole gradient errors on stability of betatron oscillation

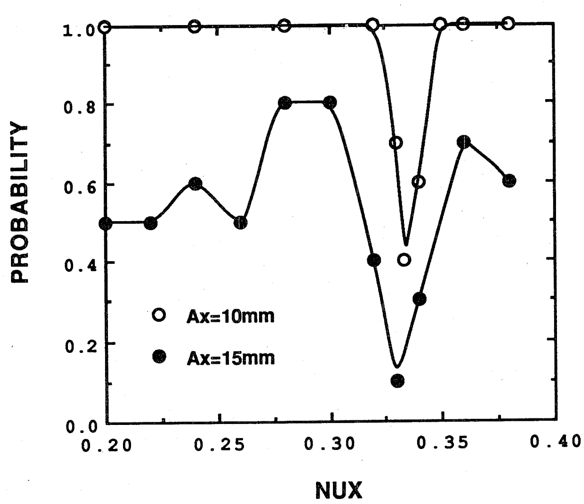


Fig. 4 Accidental resonance $3\nu_x$=154

Table 2 R.M.S stopband widths, excitation coefficients, and tune shifts per unit error

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=========================================
R.M.S. LINEAR STOPBAND WIDTH & TUNE SHIFT
(NORMALIZED VALUE)
=========================================

QUADRUPOLE TILT ERROR ( QX+QY-P )
----------------------------------
F =  0.3439E+02       BAND WIDTH =  0.6878E+02

QUADRUPOLE GRADIENT ERROR ( 2QX-P )
-----------------------------------
F =  0.2838E+02       BAND WIDTH =  0.5676E+02
                      TUNE SHIFT =  0.1419E+02

QUADRUPOLE GRADIENT ERROR ( 2QY-P )
-----------------------------------
F =  0.1572E+02       BAND WIDTH =  0.3145E+02
                      TUNE SHIFT =  0.7862E+01

SEXTUPOLE VERTICAL ALIGNMENT ERROR ( QX+QY-P )
----------------------------------------------
F =  0.2089E+03       BAND WIDTH =  0.4178E+03

SEXTUPOLE HORIZONTAL ALIGNMENT ERROR ( 2QX-P )
----------------------------------------------
F =  0.2823E+03       BAND WIDTH =  0.5646E+03
                      TUNE SHIFT =  0.1411E+03

SEXTUPOLE HORIZONTAL ALIGNMENT ERROR ( 2QY-P )
----------------------------------------------
F =  0.1732E+03       BAND WIDTH =  0.3464E+03
                      TUNE SHIFT =  0.8659E+02


============================================
R.M.S. STOPBAND WIDTH OF SEXTUPOLE RESONANCES
(NORMALIZED VALUE)
============================================

--- ACTION ---
JX =  0.5110E-05  (M)
JY =  0.1250E-05  (M)

SEXTUPOLE TILT ERROR ( 3QY-P )
------------------------------
F =  0.1931E+04       BAND WIDTH =  0.2290E+01

SEXTUPOLE TILT ERROR ( 2QX+QY-P )
---------------------------------
F =  0.2794E+04       BAND WIDTH =  0.8934E+01

SEXTUPOLE FIELD ERROR ( 3QX-P )
-------------------------------
F =  0.1307E+04       BAND WIDTH =  0.3135E+01

SEXTUPOLE FIELD ERROR ( QX+2QY-P )
----------------------------------
F =  0.7317E+03       BAND WIDTH =  0.2482E+01

SEXTUPOLE HORIZONTAL ALIGNMENT ERROR ( 3QX-P )
----------------------------------------------
P =153     F =  0.1435E+06     BAND WIDTH =  0.3441E+03
P =154     F =  0.1409E+06     BAND WIDTH =  0.3379E+03

SEXTUPOLE HORIZONTAL ALIGNMENT ERROR ( QX+2QY-P )
-------------------------------------------------
P = 89     F =  0.8619E+05     BAND WIDTH =  0.2924E+03
P = 90     F =  0.1060E+06     BAND WIDTH =  0.3597E+03

QUADRUPOLE FIELD ERROR ( 3QX-P )
--------------------------------
P =153     F =  0.1440E+05     BAND WIDTH =  0.3452E+02
P =154     F =  0.1415E+05     BAND WIDTH =  0.3393E+02

QUADRUPOLE FIELD ERROR ( QX+2QY-P )
-----------------------------------
P = 89     F =  0.8573E+04     BAND WIDTH =  0.2908E+02
P = 90     F =  0.1060E+05     BAND WIDTH =  0.3596E+02
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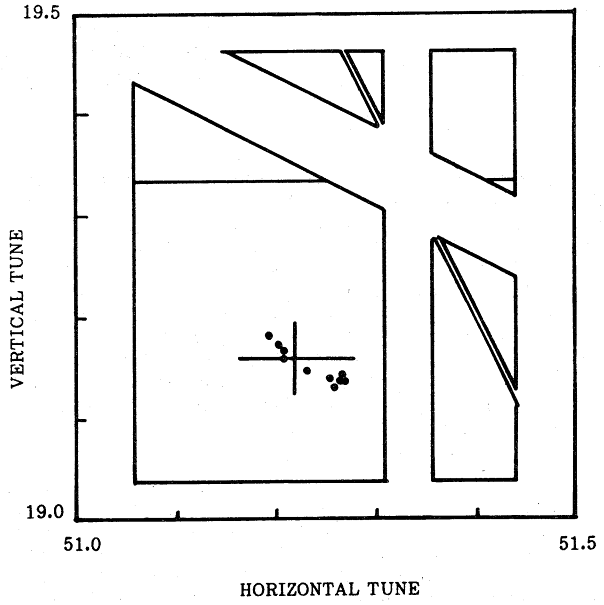

Fig. 5 Stopbands of lowest-order accidental sum resonances and tune shift (2σ)

CONCLUSION

Tolerances of random misalignments and field errors for dipole, quadrupole, and sextupole magnets have been estimated for a 8-GeV low emittance electron storage ring. The most serious magnet imperfections are the quadrupole misalignments and the sextupole displacements from closed orbit. Stopbands of lowest-order accidental resonances were calculated analytically. If the horizontal amplitude of betatron oscillation is less than 15mm, the effects of these resonances are expected to be small.

REFERENCES

1) A.Wrulich, DESY 84-026 (1984)
2) K.Tsumaki et al., presented at this symposium.