Simulation Study on Effects of Machine Imperfections in the KEK B-Factory

Haruyo Koiso and Yoshihiro Funakoshi
KEK, National Laboratory for High Energy Physics
1-1 Oho, Tsukuba, Ibaraki, 305 Japan

Abstract

Effects of machine imperfections in a low beta lattice with noninterleaved sextupoles are studied with computer simulations. Misalignments of quadrupoles and sextupoles significantly degrade the dynamic aperture and the vertical-to-horizontal emittance ratio. However, orbit corrections at sextupoles effectively recover both the dynamic aperture and the emittance ratio.

1. Introduction

The KEK B-factory, an 8 GeV × 3.5 GeV two-ring collider, is designed to attain a peak luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A small vertical beta function at the interaction point (IP) ($\beta_y^* = 0.01$m) is needed to realize the luminosity with reasonably small beam currents. One of the main issues in designing such a low beta lattice is how to correct a large chromaticity generated by quadrupoles in the interaction region while keeping a sufficient dynamic aperture for high injection efficiency and for a long beam lifetime. Simulations incorporating machine errors are necessary to estimate realistic values of the dynamic aperture. In this paper, we concentrate on effects of errors in the 3.5-GeV ring (LER) in which a larger dynamic aperture is required than in the 8-GeV ring.

2. Dynamic Aperture with Noninterleaved Sextupoles

In order to obtain a large dynamic aperture, we plan to adopt a chromaticity correction scheme with noninterleaved sextupole pairs. In this scheme, sextupoles are placed in pairs each of which consists of identical sextupoles connected by a $-I$ transformer both in the horizontal and the vertical planes. No other sextupoles are interleaved between paired sextupoles. Because major transverse nonlinearities of sextupoles are canceled by the $-I$ transformer within a pair[1], the dynamic aperture is expected to become large in the transverse direction.

An intensive study on the noninterleaved correction scheme has been done with computer simulations. It has been confirmed that this scheme greatly widens the transverse dynamic aperture and that the momentum aperture is also made acceptable when we place sufficient number of sextupole families in the ring [2].

In the present design of LER, forty pairs of sextupoles are distributed in arcs to correct natural chromaticities which amount to 62 and 92 in the horizontal and the vertical directions, respectively. The solutions of sextupoles strengths have been searched to minimize the deviations of the betatron tunes $\nu_{x,y}$ and those of the Twiss parameters $\beta_{x,y}^{RF}$ and $\alpha_{x,y}^{RF}$ at the center of the RF section at 12 fitting points of the momentum deviation, $\delta \equiv \Delta p/p_0 = \pm\frac{i}{6}\delta_1$ ($i = 1, 6$). The momentum bandwidth δ_1 is chosen to be about 1.5 % which is required for a long Touschek lifetime.

We estimate the dynamic aperture by particle tracking in the six-dimensional phase space $(x, p_x, y, p_y, z, \delta)$. The variable z is defined as $z = -vt$, where t is the delay from the nominal particle. In this paper, the initial conditions are chosen as $p_{x0} = p_{y0} = z_0 = 0$ and $y_0 = ax_0$, where a is a constant. We choose $y_0 = \frac{1}{3}x_0$ to check the acceptance for horizontal beam injection. The dynamic aperture is expressed by the initial values of the Courant-Snyder invariant $2J_{x,y0}$ and the momentum deviation δ_0 of particles which survive during 1000 turns without damping due to the synchrotron radiation. Although this number of turns is only 1/8 of the transverse damping time, the results of 1000-turn tracking are almost equal to or slightly smaller than those of 8000 turns with the radiation damping. All calculations concerning this study such as matching of linear optics, fitting of sextupole strengths, orbit corrections and particle tracking have been done by a computer code SAD developed at KEK [3].

3. Effects of Errors

Performance of the noninterleaved scheme has been suspected to be sensitive to machine imperfections which break the cancellation due to the $-I$ transformation. Vertical emittance growth due to errors is also harmful to maintain the required vertical-to-horizontal emittance ratio (coupling) of 1%. We discuss here effects of various types of errors to estimate their tolerances. All of random errors simulated below have Gaussian distributions with 3σ cutoff.

A)*Relative Field Strength Errors*

We introduced strength errors into quadrupoles or sextupoles. The transverse tunes were adjusted to the nominal values ($\nu_x = 40.12$ and $\nu_y = 40.19$) by varying quadrupole strengths in each case. Figure 1 shows the dynamic aperture with random relative-strength errors of 0.1%, 0.2%, and 0.3% of all quadrupoles. To express the dynamic aperture with one parameter, we introduce a parameter A which is the area of the stable region in the $2J_{x,y0}$ and

δ_0 plane. Average values of A and the coupling are also written in Fig. 1, where A_0 is the area of the dynamic aperture of an ideal lattice. The 0.2% errors are tolerable both for the dynamic aperture and for the coupling. On the other hand, strength errors of sextupoles are more tolerable and 0.5% errors do not affect the dynamic aperture significantly.

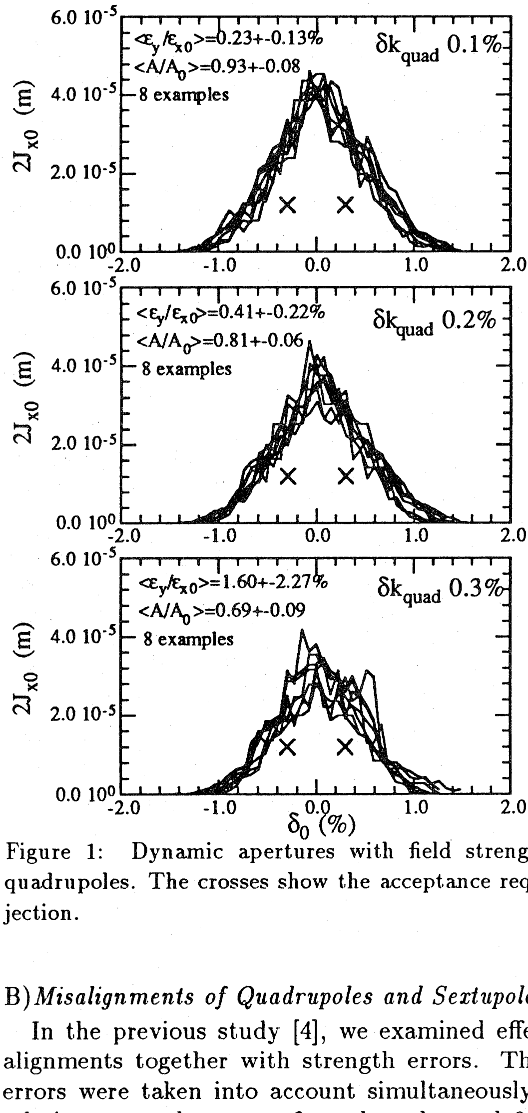

Figure 1: Dynamic apertures with field strength errors of quadrupoles. The crosses show the acceptance required for injection.

B) *Misalignments of Quadrupoles and Sextupoles*

In the previous study [4], we examined effects of misalignments together with strength errors. The following errors were taken into account simultaneously: (1) 0.1% relative strength errors of quadrupoles and 0.2% of sextupoles, (2) 0.1 mm displacements of quadrupoles and sextupoles both in the horizontal and vertical directions (3) 0.1 mrad rotation errors of all magnets and (4) 0.1 mm setting errors of position monitors. Even with these amounts of errors, the dynamic aperture remained sufficient to clear the injection condition and give a Touschek lifetime of ≥ 3 hours in all of 12 examples. Although one third of the examples brought about couplings of $\geq$ 1.5%, we easily reduced them to 1% by making only one or two vertical bumps of $\sim$ 1 mm height in the arcs. Misalignments of 0.1 mm rms may be difficult to be realized in the actual machine. Then in this study we have doubled the rms values of the errors (2), (3), and (4); 0.2 mm misalignments, 0.2 mrad rotations, and 0.2 mm monitor setting errors, while we used the same rms values of the error (1).

We examined 12 examples. In each case, the closed orbit distortion (COD) was measured with 364 position monitors equipped at the edge of quadrupoles and they were corrected with 404 steering magnets. Residual values of COD were reduced to $\sim$ 0.2 mm rms both in the horizontal and vertical directions. After the COD correction, we carried out tracking. Figure 2 shows resultant dynamic apertures and Figure 3 shows the couplings and scaled values of the dynamic aperture with open circles. As are shown in these figures, the misalignments of 0.2mm rms significantly decrease the dynamic aperture and produce the coupling much larger than 1%. In order to recover these degradations, we tried to reduce COD at sextupoles by employing additional 80 monitors at the sextupoles with 0.2 mm setting errors. In the four examples with the coupling of $\geq$ 5%, we corrected COD to $\sim$ 0.2 mm rms at monitors attached to sextupoles and quadrupoles in straight sections. After this correction, both the dynamic aperture and the coupling were fairly improved as indicated with the closed circles in Fig. 3. However, further corrections must be applied to reduce the coupling to 1%.

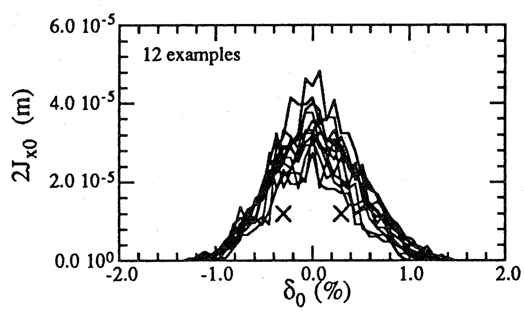

Figure 2: Dynamic apertures in the presence of misalignments.

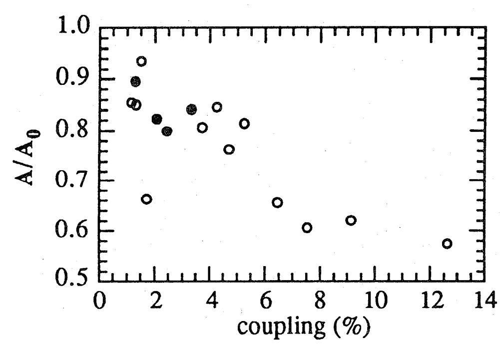

Figure 3: Couplings and normalized apertures of 12 examples.

C) *Large Misalignments of A Single Sextupole*

In the actual situation, it is likely that in addition to the small errors studied in the previous sections there exist small number of relatively large errors which are introduced by some mistakes. However, it is very time consuming work to examine every case of such errors as is easily imagined. In this paper, we studied an extreme case that one of the strongest sextupole magnets is misaligned up to 6 mm in horizontal or in vertical direction. With this study it is expected that one has some rough idea on the situation.

We gave an alignment error to a sextupole whose K2 value ($B''l/B\rho$) is -6.5975. This is the only error in the lattice and the other elements are assumed to be perfect including the partner sextupole to the misaligned one. Fig. 4(a) shows the dynamic aperture in the cases of horizontal misalignments of 0, -2, -4, and -6 mm. Here 0 mm means, of course, the perfect machine. In each case except the perfect machine, COD was measured at the position monitors at the locations of the quadrupoles and they were corrected using 404 steering magnets with a residual rms value of less than 0.13 mm. As is seen in the figure, only one misaligned sextupole can affect the dynamic aperture significantly, although the amount of error is unreasonably large. The misalignment of 6 mm can halve the horizontal acceptance. However, even in this extreme case the dynamic aperture can be almost recovered if we correct the orbit so that the beam goes through the centers of the sextupoles. This can be done by employing the position monitors attached to the sextupoles. In Fig. 4(a) the dashed line denotes the case of the 6 mm misalignment and using the monitors at the sextupoles. In the horizontal misalignment case, the coupling was not affected by the errors.

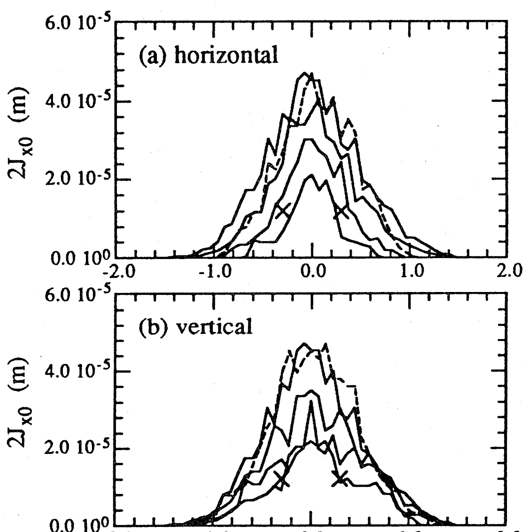

Figure 4: Dynamic apertures with large misalignments of a single sextupole.

In Fig. 4(b) effects of vertical misalignments are shown. Amounts of errors are 0, -2, -4, and -6 mm again. The horizontal apertures were decreased with the errors similarly to the horizontal cases. The aperture was recovered again by using the monitors at the sextupoles in the case of the 6 mm misalignment as is shown with a dashed line in the figure. The difference of this case from the horizontal one is that the couplings were damaged by the errors as is

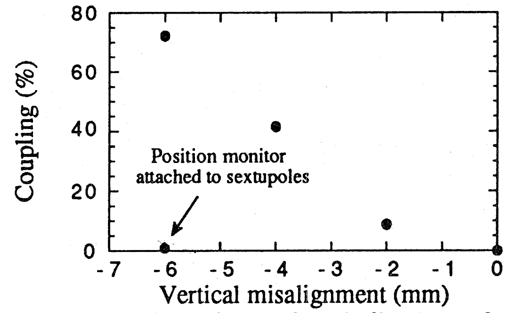

Figure 5: Couplings due to the misalignment of a sextupole.

shown in Fig. 5. However, the coupling is also recovered by centering the orbit at the sextupoles.

Through the present study, importance of centering the orbit at the sextuples has become clear. This suggests that we should install the position monitors at the sextupoles rather than at the quadrupoles in the arc section. Decreasing the setting errors of the position monitors is also important.

4. Summary

Effects of machine errors in a low beta lattice with non-interleaved sextupoles have been studied with computer simulations. This chromaticity correction scheme is not so sensitive to field strength errors of quadrupoles and sextupoles. Misalignments of 0.2mm rms and rotations of 0.2mrad rms significantly decrease the dynamic aperture and increase the vertical-to-horizontal emittance ratio. However, we can fairly recover both the dynamic aperture and the coupling when we correct orbit distortions at sextupoles. Even with a misalignment of several millimeters of a single sextupole, we can improve the dynamic aperture and the coupling by centering the orbit at the sextupole. These simulations show that orbit corrections at sextupoles are important to keep good performance of the noninterleaved scheme.

Acknowledgments

The authors wish to express their thanks to K. Oide and M. Kikuchi for many useful discussions and suggestions.

References

[1] K. L. Brown, IEEE Trans. on Nucl. Sci. NS-26, 3490(1979); K. L. Brown and R. Servranckx, AIP Conf. Proc. 127, Edited by M. Month, P. F. Dahl and M. Dienes (1983), p.62.

[2] K. Oide and H. Koiso, Phys. Rev. **E47**, 2010 (1993).

[3] K. Oide, Nucl. Instr. Meth. **A276**, 427 (1989). M. Kikuchi, Private communication.

[4] H. Koiso, To be published in Proceedings of "International Workshop on B-Factories: Accelerators and Experiments", KEK, Tsukuba, November 1992.