VERTICAL EMITTANCE REDUCTION IN THE SSRF PHASE II PROJECT

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Abstract

The Shanghai Synchrotron Radiation Facility (SSRF) Phase II beamline project (SSRF Phase II) will implement the new lattice with dual-canted insertion devices, superbends and superconducting wiggler. The emittance coupling is one of the most important parameters for the high brightness storage ring light sources. It is often less than 1% in the third-generation storage ring light sources. In this paper, the sensitivity of emittance coupling to magnetic alignment errors in the SSRF Phase II is presented. Sixty skew quadrupole magnets are utilized to correct the emittance coupling with gradient descent algorithm. The emittance coupling obtained in the SSRF Phase II lattice is below 0.3%.

INTRODUCTION

Shanghai Synchrotron Radiation Facility (SSRF) is a third-generation synchrotron light source with normal energy of 3.5 GeV. The storage ring consisting of 20 double bend achromatic (DBA) cells with four super-periods is designed with a natural emittance of 3.9 nm rad to provide high photon brightness. Each DBA cell contains two dipole magnets, ten quadrupoles, and seven sextupole magnets. The SSRF Phase II beamline project (SSRF Phase II) is under designing, the main project task is to build more than 16 beamlines which contain 4 cryogenic permanent magnet undulators (CPMU), a superconducting wiggler (4.2 Tesla) and two superbend cells. The main parameters in the SSRF Phase II project is listed in Table 1. A detailed description of the SSRF Phase II can be found in these papers [1-3].

The brightness can be increased by reducing the emittance coupling. Several storage ring light sources around the world have studied on this issue with achievements of very low emittance coupling and valuable experience [4-6]

VERTICAL EMITTANCE THEORY

The first driving contribution to vertical emittance, which is very small and intrinsic to the lattice design, is due to the opening angle of the synchrotron radiation [7]. It's only 0.14 pm rad in the SSRF Phase II lattice.

Table 1: Main Parameters in SSRF Phase II Project

Parameters	Value
Energy / GeV	3.5
Circumference / m	432
Tune	22.222/12.153
Natural emittance / nm rad	4.278
Momentum compaction factor	4.223×10^{-4}
Natural energy spread	1.113×10^{-3}
Damping partition	0.992 35/1/2.007 65

Vertical emittance in a storage ring is primarily determined by two effects: spurious vertical dispersion and betatron coupling. The dominant causes of spurious vertical dispersion and betatron coupling are magnetic alignment errors. Spurious vertical dispersion is caused by vertical bending errors from tilts of dipole $\Delta\Theta_D$, tilts of quadrupoles $\Delta\Theta_Q$, vertical alignment errors ΔY_Q on the quadrupoles and vertical alignment errors ΔY_S of the sextupoles in the dispersive region. Betatron coupling is due to quadrupole tilt errors $\Delta\Theta_Q$ and vertical misalignments ΔY_S of the sextupoles in the dispersive region.

We assume that all alignment errors are uncorrelated. Estimates of the sensitivity of a lattice to these errors can be made by analytical formulae involving the magnetic field strengths and lattice functions. The analytical formulae are [7, 8]:

$$\varepsilon_{y\_\text{dispersion}} = \frac{J_z\sigma_\delta^2}{4\sin^2\pi\nu_y}\left[\left\langle\Delta\Theta_D^2\right\rangle\sum_{\text{dipole}}\beta_y(Gl)^2+\left\langle\Delta Y_Q^2\right\rangle\sum_{\text{quads}}\beta_y(k_1l)^2+\left\langle\Delta\Theta_Q^2\right\rangle\sum_{\text{quads}}\eta_x^2\beta_y(k_1l)^2+\left\langle\Delta Y_S^2\right\rangle\sum_{\text{sexts}}\eta_x^2\beta_y(k_2l)^2\right] \tag{1}$$

$$\varepsilon_{y\_\text{coupling}} = \frac{\varepsilon_x J_x}{4J_y}\frac{1-\cos2\pi\nu_x\cos2\pi\nu_y}{\left(\cos2\pi\nu_x-\cos2\pi\nu_y\right)^2}\left[\left\langle\Delta\Theta_Q^2\right\rangle\sum_{\text{quads}}\beta_x\beta_y(k_1l)^2+\left\langle\Delta Y_S^2\right\rangle\sum_{\text{sexts}}\beta_x\beta_y(k_2l)^2\right] \tag{2}$$

Here, the angle brackets denote averaging over the Gaussian distribution of errors, $J_{x,y,z}$ represents the horizontal, vertical and longitudinal damping partition, σ_δ is the energy spread, k_1, k_2 are the normalized quadrupole, sextupole fields respectively, l is the length of corresponding magnet and υ_y is the vertical tune. Eq. (1) denotes the contribution to the vertical emittance from vertical dispersion. Eq. (2) denotes the contribution to the vertical emittance from betatron coupling. In the SSRF Phase II, the vertical emittance from vertical dispersion

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and betatron coupling from alignment errors can be calculated by putting the magnetic field strengths and lattice functions into Eq. (1-2)

$$\varepsilon_{\mathrm{y\_dispersion}} = 1.09\times10^{-2}\Delta\Theta_D^2 + 4.9\Delta Y_Q^2 + 1.21\times10^{-1}\Delta\Theta_Q^2 + 4.2\Delta Y_S^2 \quad (3)$$

$$\varepsilon_{\mathrm{y\_coupling}} = 1.15\times10^{-1}\Delta\Theta_Q^2 + 3\Delta Y_S^2 \quad (4)$$

where the units of vertical emittance, tilts of dipole, tilts of quadrupoles, quadrupole alignment errors and sextupole alignment errors are nm rad, mrad, mrad, mm, and mm respectively.

VERTICAL EMITTANCE FROM ALIGNMENT ERRORS IN SSRF PHASE II

We set tilt errors as 0.2 mrad in dipole and quadrupole magnets, vertical misalignments as 0.15mm in quadrupoles and sextupoles. All these errors are root mean square (RMS) misalignments and generated with Gaussian distribution truncated at 2.5σ.

Fig. 1 shows the RMS of vertical COD resulting from four families of alignment errors. The blue circles are simulated by accelerator toolbox (AT) [9]. The slope of each image is 5.09×10^{-4} mm/mrad, 3.39×10^{-3} mm/mrad, 40.28 and 1.63×10^{-2}, respectively. The vertical COD from quadrupole vertical misalignments is some orders of magnitude greater than the contribution of other misalignments. The ratio between the RMS of COD and the RMS of magnetic misalignments is known as the orbit amplification factor. It can be calculated in the approximate formula [8].

$$\left\langle \frac{y_{\mathrm{COD}}}{\Delta Y_Q} \right\rangle = \sqrt{\frac{\beta_y(s)}{8\sin^2 \pi\nu_y} \sum_{\mathrm{quads}} \beta_y (k_1 l)^2} \quad (5)$$

In the SSRF Phase II, the orbit amplification factor can be calculated by Eq. (5), and 42.70 is obtained. The orbit amplification factor is about 40.28 by simulation (Fig. 1c).

The vertical COD, which is generated by vertical misalignments on the quadrupoles, results in vertical beam offset in the sextupoles with the same consequences of vertical misalignments of the sextupoles. Therefore, the effect of the vertical misalignments on quadrupole magnets on vertical emittance wouldn't be discussed in this session separately and it would be included in the next session. The effect of each family of alignment errors on the vertical emittance was simulated with 1000 random machine seeds. The result of simulation is shown in Fig. 2.

The mean of the vertical emittance from tilts of dipole, tilts of quadrupoles, and vertical misalignments of sextupoles is 4.0×10^{-4} nm rad, 1.1×10^{-2} nm rad, and 0.18 nm rad respectively. According to Eq. (3-4), yielding the results

$$\varepsilon_{\mathrm{y\_dipole}} = 1.09\times10^{-2}\Delta\Theta_D^2 = 4.4\times10^{-4}\,\mathrm{nm\ rad} \quad (6)$$

$$\varepsilon_{\mathrm{y\_quads}} = 0.24\Delta\Theta_Q^2 = 9.6\times10^{-3}\,\mathrm{nm\ rad} \quad (7)$$

$$\varepsilon_{\mathrm{y\_sexts}} = 7.2\Delta Y_S^2 = 0.16\,\mathrm{nm\ rad} \quad (8)$$

It is found that the approximate formula agrees well with the simulation.

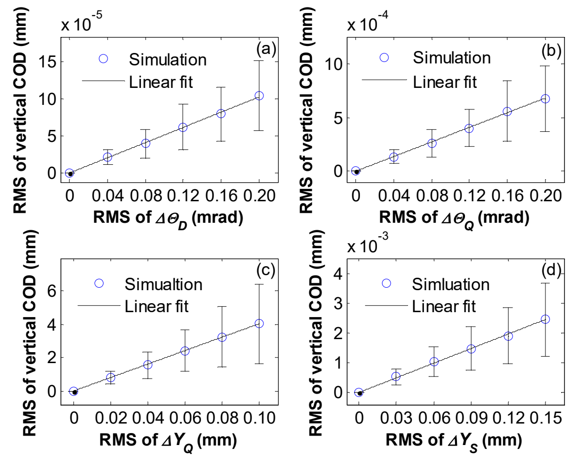

Figure 1: RMS of vertical COD resulting from (a) tilts of dipole, (b) tilts of quadrupoles, (c) vertical misalignments on quadrupole magnets and (d) vertical misalignments of the sextupole magnets.

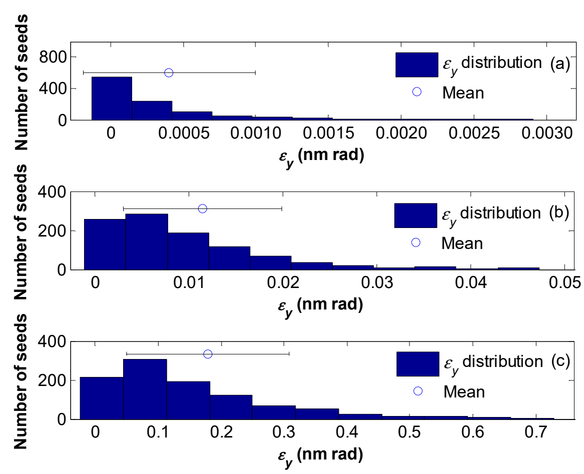

Figure 2: Distribution of vertical emittance from (a) tilts of dipole, (b) tilts of quadrupoles, (c) vertical misalignments of sextupole magnets for random seeds.

CORRECTION OF EMITTANCE COUPLING FOR THE SSRF PHASE II

The major contribution to vertical emittance is the vertical misalignments of the sextupole magnets based on the above simulation. In order to make the simulation more real, alignment errors in all magnets should be taken into account. Two hundred seeds were used to ascertain the validity of simulation.

We should correct the vertical COD by singular values decomposition (SVD) before correcting the emittance coupling. We used 140 beam position monitors (BPM) and 80 corrector magnets (CM) to correct the vertical COD. An approximate mean of 0.06 mm vertical COD was obtained after orbit correction (Fig. 3b). The comparison of the RMS of vertical COD is shown in Fig. 3.

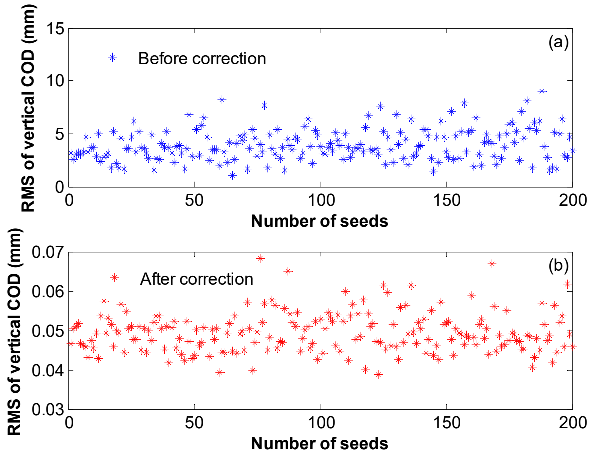

Figure 3: RMS of the vertical COD of 200 (a) uncorrected and (b) corrected random machine seeds.

We can use 60 skew quadrupole magnets as effective knobs to correct the emittance coupling. Sixty skew quadrupole magnets are auxiliaries winded on the sextupole magnets, fed by power supplies independent of the main magnet supply. The gradient descent algorithm was employed in the correction. Our objective is to bring the emittance coupling below 0.3%. The comparison of the emittance coupling is shown in Fig. 4. The emittance coupling of each seed can be corrected below 0.3% using 60 skew quadrupole magnets (Fig. 4b). The vertical dispersion before and after coupling correction is shown in Fig. 5. Almost all of the vertical dispersion of the 200 machine seeds were decreased. There were approximately 3mm RMS vertical dispersion after corrected the emittance coupling. The strengths of these skew quadrupoles can be provided by the power supplies of SSRF storage ring.

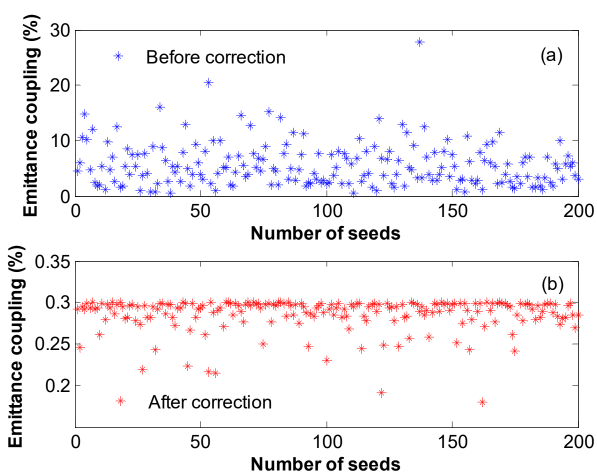

Figure 4: Emittance coupling of 200 (a) uncorrected and (b) corrected random machine seeds.

CONCLUSION

The sensitivity of emittance coupling to various kinds of alignment errors in the SSRF Phase II lattice has been discussed in this paper. With 60 skew quadrupole magnets and gradient descent algorithm, we can correct the emittance coupling and keep it below 0.3% for the magnetic alignment errors.

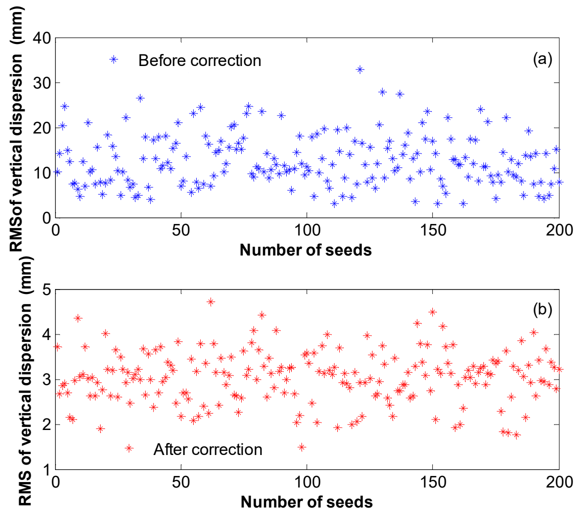

Figure 5: RMS of the vertical dispersion of 200 (a) uncorrected and (b) corrected random machine seeds.

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