Beam dynamics of the superconducting wiggler on the SSRF storage ring*

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Abstract: In the SSRF Phase-II beamline project, a superconducting wiggler (SW) will be installed in the electron storage ring. It may greatly impact on the beam dynamics due to the very high magnetic field. The emittance growth becomes a major problem, even after correction of the beam optics. A local achromatic lattice is studied, in order to combat the emittance growth and keep the performance of the SSRF storage ring as high as possible. Other effects of the SW are also simulated and optimized, including the beta beating, the tune shift, the dynamic aperture, and the field error effects.

Keywords: SSRF storage ring, superconducting wiggler, beam dynamics, Accelerator Toolbox

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1 Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) is a third generation light source with a beam energy of 3.5 GeV[1–3]. It has been operating for user experiments since 2009. There are 20 straight sections in the storage ring of SSRF, including 4 long straight sections (LSSs) and 16 standard straight sections (SSSs). Two of the LSSs have been occupied by the injection magnets and the RF cavities respectively, and eight of the SSSs have been installed with insertion devices (IDs). The SSRF Phase-II beamline project will be implemented in the near future, and more IDs will be added, including a superconducting wiggler (SW) to generate hard X-rays. The SW has a much higher peak field than other IDs, which makes it a challenge to retain the storage ring performance. The main parameters of the existing IDs and this SW are listed in Table 1.

Since first being installed in VEPP-3 [4], SWs have been widely used in synchrotron light sources [5–12]. The magnetic field strength of SWs has gradually been raised thanks to the development of superconducting technology. A peak field as high as 7.5 T has been reached[9]. As the magnetic field strength increases, the critical energy of the photons emitted from the SW is increased, and the influence of the SW on the beam dynamics gets much stronger. Linear optics are distorted with SW, and compensation is achieved with quadrupoles in different ways, classified by local or global correction, and quadrupoles exited independently or in families. The non-linear effect is mainly in shrinking of the dynamic aperture, which will bring reduction of injection efficiency and beam lifetime. The magic finger has been used to eliminate the SW multipoles in SPEAR [5] and SOLEIL [11], and high chromaticity is abated in CLS [8]. The horizontal emittance may increase after the SW is introduced. However, it can decrease if the SW is located in a low-dispersion or achromatic section [6, 9].

Table 1. Main parameters of the IDs in SSRF.

name	type	λ/mm	L/m	B_y/T
H08U	EPU	100	4.3	0.60*
H09U58	EPU	58	4.9	0.68*
H09U148	EPU	148	4.7	0.67*
H13W	wiggler	140	1.4	1.94
H14W	wiggler	80	1.6	1.20
H15U	IVU	25	2.0	0.94
H17U	IVU	25	2.0	0.94
H18U	IVU	25	1.6	1.00
H19U1	IVU	20	1.6	0.84
H19U2	IVU	20	1.6	0.84
H03W	SW	48	1.1	4.20−4.50

*For horizontal polarization mode

The peak magnetic field of the SW proposed for SSRF is 4.2−4.5 T, and in this paper we take 4.5 T for our

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study. The SW may greatly impact on the beam dynamics of the storage ring. In order to retain the performance of the storage ring with the SW, different schemes are tested. At first, a local optics correction is made by six quadrupoles adjacent to the SW. Most of the beam parameters are restored, while the beam emittance increases by 39%, which will decrease the brightness of synchrotron radiation. Since reducing the dispersion at the SW straight section can help to depress oscillations of the electron caused by photon radiation in the SW, the beam emittance growth may be reduced. A local achromatic optics is considered then. This scheme is fulfilled with 20 quadrupoles in two cells adjacent to the SW (Fig. 1). The beam emittance growth is well suppressed. The dynamic aperture is severely degraded due to non-cancellation of the nonlinear driving terms, so re-optimization with sextupoles[13] has been implemented. These results are presented in the following sections.

Fig. 1. (color online) Layout of SW and adjacent two cells.

2 Tools and method

Simulations have been carried out with Accelerator Toolbox (AT) [14] working in MATLAB. The routines with intensive computation are written in C/C++, and compiled into MEX-files so as to be executable in MATLAB. As a result, AT can take advantage of the efficiency of interactive modelling of MATLAB without losing speed in time-consuming computation. AT is also open-ended, with continual development by people all over the world who are using and improving it [15].

An ID is considered to be a series of small dipole slices with hard edges. This model is checked with the current operation lattice, i.e. the SSRF storage ring with the IDs in operation. As long as the number of slices is sufficient, the simulation result of existing IDs with this model agrees well with the measurement. The number of slices is a key point of this model. The simulation will be more credible as the number of slices increases, but the computation time will increase a lot. To find a reasonable number of slices, the horizontal emittance is chosen as an object and plotted for increasing number of slices. The result is shown in Fig. 2, and the number of slices is chosen to be 20 per magnetic field period, which is a good trade-off between simulation accuracy and computation time.

The magnetic field is assumed to have a sinusoidal profile. The existing IDs and the SW are simulated in the SSRF storage ring with AT. The emittance and energy spread of this simulation are consistent with calculation result from the formula in Ref. [16], as shown in Table 2. The small variation between simulation and calculation is mainly from the approximation in the formula and the ID model.

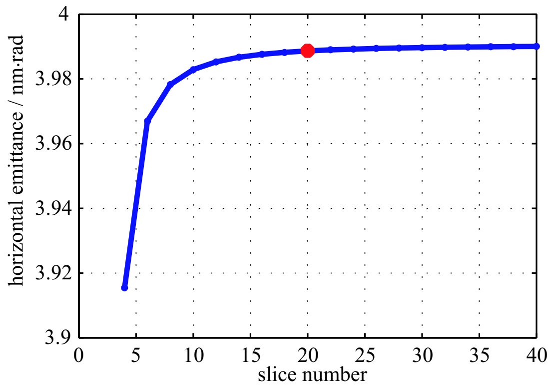

Fig. 2. (color online) Horizontal emittance as an object of slice number per magnetic field period.

Table 2. Comparison between simulation and calculation.

emittance/(nm·rad)			
lattice	bare	current	current + SW
simulation	3.91	3.99	6.18
calculation	–	4.00	5.98

energy spread/10^{-4}			
lattice	bare	current	current + SW
simulation	9.83	9.79	10.7
calculation	–	9.76	11.7

3 Optics distortion and correction

The SW significantly disturbs the linear optics of the SSRF storage ring. The vertical tune shift is 0.016, and the maximum vertical beta beating is above 10%, while the horizontal variations are not distinct. Figure 3 plots the beta beating in the whole ring, where the RMS beta beatings are 0.0013% and 7.4% in the horizontal and vertical plane, respectively. The SW distorts the beam dynamics much more in the vertical plane than the horizontal plane, because the SW, as a planar ID, has vertical magnetic field only.

In the current settings of the SSRF storage ring, the RMS beta beating of the bare lattice is around 10% without optics correction, and it can be efficiently reduced to about 1% by the individually excited quadrupoles [17]. This fact provides great confidence to compensate the distortions from the SW. In the interest of minimizing the adjustment, a local correction scheme is applied. Only six quadrupoles adjacent to the SW are used to correct the optics, and the minimum global RMS beta beatings are the objects. After correction, the RMS beta beatings are reduced to about 0.5% in the two transverse planes. However, the emittance growth is still as large as 39%, which is reduced from 55% before correction. The variation of energy spread is negligible.

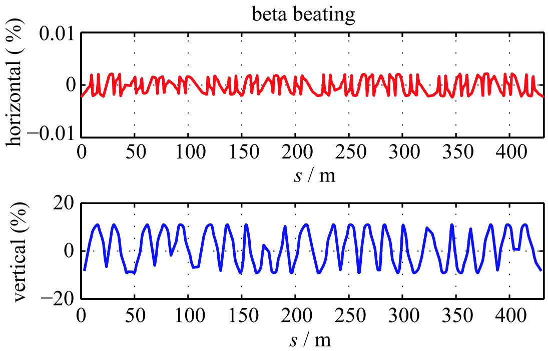

Fig. 3. (color online) Global beta beating of SW.

4 Local achromatic scheme

In order to reduce the emittance growth, a local achromatic lattice is considered, i.e. the dispersion is reduced from 0.105 m to zero in the standard straight where the SW is located, while the dispersion and the beta functions outside this section are kept the same as the current settings in order not to change the parameters of other source points. There are two constraints to achieve this scheme [18], so at least two quadrupoles before the bending magnet are needed. To match the beta function, another four quadrupoles are needed. Actually, all the quadrupoles in the adjacent two cells are involved so as to get a solution with reasonable strength.

Figure 4 plots the new achromatic optics in the two cells, comparing with the current optics. There are some variations in the two cells involved, but the optics is kept perfectly consistent apart from these two cells.

The natural emittance is reduced to 4.09 nm·rad by the stronger radiation damping of the SW in this scheme. There is only an emittance growth of about 3% from the current lattice without SW to the new local achromatic lattice with SW, which is acceptable. Table 3 summarizes the beam parameters of the new local achromatic lattice and the current lattice, where the IDs in operation are included in both lattices.

In the achromatic scheme, the major trouble of emittance increase has been solved, nevertheless the dynamic aperture degrades severely, as shown in figure 5 (blue line). Small dynamic aperture will reduce the injection efficiency or the beam lifetime. To obtain a sufficient dynamic aperture, re-optimization with sextupoles is necessary. The dynamic aperture enlarges after careful adjustment of the sextupole strength, which is shown in Fig. 5 (green line). The horizontal dynamic aperture is restored, which means undegraded injection efficiency. The vertical dynamic aperture is optimized to exceed the physical aperture.

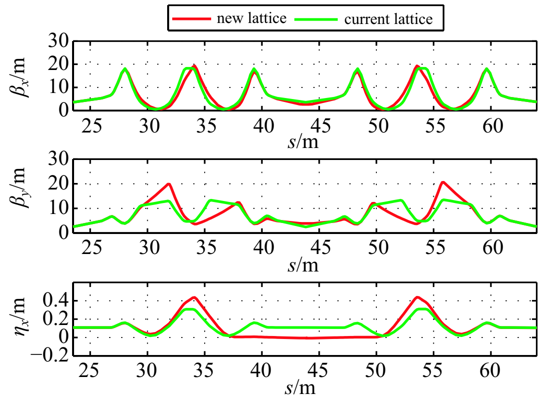

Fig. 4. (color online) Optics of the two cells adjacent to the SW.

Table 3. Beam parameters of different schemes.

	current lattice	new lattice
emittance/(nm·rad)	3.99	4.09
energy spread/10^{-4}	9.8	10.7
energy loss per turn/MeV	1.52	1.69
tune (H,V)	22.22, 11.30	22.27,11.30
natural chromaticity (H,V)	−55.7, −18.0	−55.5, −18.2
Mom. comp. factor/10^{-4}	4.3	4.5
max beta (H,V)/m	25.4,15.9	25.4,20.6
max eta/m	0.321	0.438
energy acceptance	3.75%	3.49%
bunch length/ps	12.1	13.6

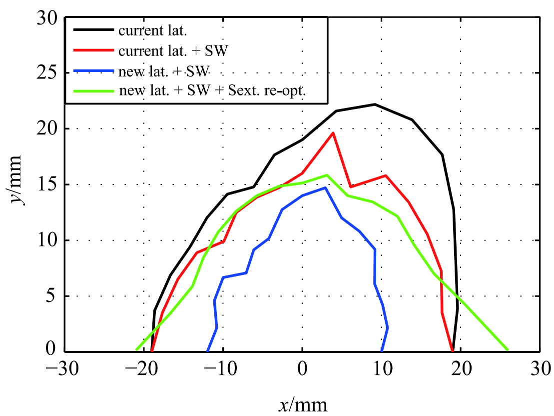

Fig. 5. (color online) Dynamic aperture of different schemes with 1000 turns tracking with AT.

5 Field error analysis

Imperfection is unavoidable in the ID manufacturing process, which will introduce errors in the magnetic field. Errors will bring variation in performance, and error analysis is essential to estimate the robustness of the lattice.

Since the ID is an array of magnet blocks, the errors will be block-dependent, so a random error array corresponding to the block array is generated. Nevertheless this array is too rough to simulate a continuous distribution. Hence we reform this array using an interpolation algorithm.

To simulate errors, we need to define their type and strength. Here we consider the errors of dipole and quadrupole, which are the main concern. The integral dipole error is investigated from 0 to ±1000 Gauss·cm, while integral quadrupole error varies from 0 to ±1000 Gauss.

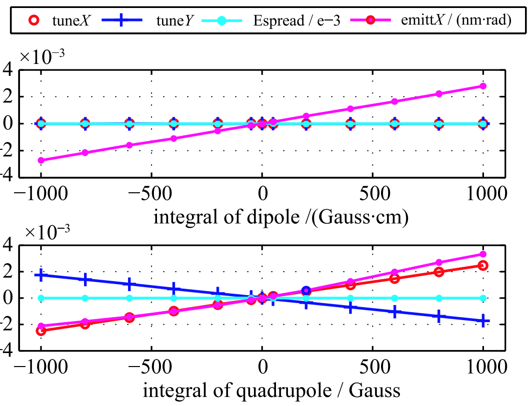

Fig. 6. (color online) The variations of main parameters with errors.

On the other hand, there are different distributions that satisfy a certain integral dipole or quadrupole error, and a different distribution will lead to a different impact on beam dynamics. In practice, 100 random distributions for each integral error are generated, and all their impacts on beam dynamics are investigated. The variations of tune, chromaticity, energy spread and horizontal emittance are observed, and the result is summarized in Fig. 6. The relationship between these parameters and errors is reasonable, and the variations of these parameters are tolerable.

6 Conclusion

The effects of a 4.5 T SW on beam dynamics in the SSRF has been studied. A significant impact on optics has been found, and the emittance increases by 55%, which will greatly reduce the brightness of synchrotron radiation. Global linear optics is restored with quadrupole correction, and the emittance growth is then 39%. For further optimization, a local achromatic lattice is considered so as to enhance the damping effect of the SW. The emittance growth is reduced to 3% without global optics distortion in this scheme, which is tolerable for the machine. However, the dynamic aperture degrades severely, which is a problem for the lifetime and injection efficiency. Optimization with sextupoles has been implemented, and the dynamic aperture is enlarged to retain the lifetime and injection efficiency. Error analysis has also been studied. The variations of main parameters are tolerable with integral dipole and quadrupole errors up to ±1000 Gauss·cm and ±1000 Gauss, respectively.

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