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Studies of closed orbit correction and slow orbit feedback for the SSRF storage ring*

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Abstract Details of the active ways to suppress Closed Orbit Distortion (COD), including bending magnet sorting and survey and alignment of the magnets, are discussed based on the studies of affections to the COD by the bending magnet field error and the misalignment of quadrupoles. The closed orbit correction and the Slow Orbit Feed Back (SOFB) system for the SSRF storage ring are presented in this paper. With these available methods, better results were obtained during the commissioning period with 3 GeV beam energy.

Key words SSRF, closed orbit distortion, slow orbit feedback, sorting, alignment, SOFB

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1 Introduction

The accelerators of the SSRF project were installed in ten months from November 2006. The commissioning of the Shanghai Synchrotron Radiation Facility (SSRF) storage ring was started on Dec. 21, 2007 with the beam energy of 3 GeV and the first turn signal was achieved on the same day. Accumulation of the beam came true on Dec. 24, and the beam of 100mA was obtained on Jan. 3, 2008[1]. The storage ring is designed with a very low beam emittance to produce synchrotron radiation with very high brilliance in X-ray regions with energy 0.1—40 keV[2, 3]. This requires rather strong focusing quadrupole and sextupole magnets. Errors of these magnets, such as manufacture error and misalignment, will therefore introduce large COD. It will generate a lot of negative effects, such as reducing the dynamic aperture, shifting working point, and thus reaching a low injection efficiency and short beam lifetime. Sometimes, it is even difficult to attain the closed orbit or a stable linear optics without elaborately considering these magnetic errors[4—6]. For the users, it will change the position of synchrotron light at the front-end of beam line, which will reduce the brightness at experiment station.

So it is necessary to reduce the large COD from active and passive aspects. As an active way to decrease the horizontal COD caused by the dipole field errors, bending magnets are sorted based on the local-cancellation-like method. It can reduce the horizontal COD by a factor of 4—5[7]. Details of bending magnet sorting are discussed in this paper. As another active way, survey and alignment of the magnets are very important to make the misalignment of magnets as small as possible[8]. The survey and alignment result of the SSRF storage ring which is perfectly and accordant with the simulation is also introduced in this paper.

Once the magnets are installed and aligned, it is necessary to develop an efficient closed orbit correction system including the reasonable installing of an appropriate number of Beam Position Monitors (BPM) and dipolar correctors[9] as a passive way. After the closed orbit correction on which the Beam Based Alignment (BBA)[10—13] is performed elaborately, the residual orbits with a sigma of about 50 μm in both planes are obtained during the commissioning with 3 GeV beam energy in the SSRF storage ring.

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Maintaining the proper beam orbit stable is an important operational issue for all light sources. The most commonly used figure-of-merit for stability is that the beam should be stable to one-tenth of the beam size. This implies a very tight tolerance for orbit movement at the SSRF as shown in Table 1[14] (assuming 1% coupling). The SOFB system was developed first for slow orbit drift control in the 1st commissioning stage. The design and test results of the SOFB are presented in this paper.

Table 1. Beam stability requirements.

beam location	horizontal/μm	vertical/μm
long straights	< 23	< 1.3
normal straights	< 16	< 0.9
bending magnets	< 4	< 2

Singular Value Decomposition (SVD) algorithm is used for both COD correction and SOFB based on the MML toolbox in Matlab[15]. The interface programs are also developed for easy control.

2 COD due to errors

The COD arising from the magnetic imperfections and misalignment of magnets can be written as[3]

$$z(s)=\frac{\sqrt{\beta_s}}{2\sin\pi\nu}\sqrt{\beta_{s_0}}\theta\cos(\pi\nu-|\psi_s-\psi_{s_0}|)\ , \qquad (1)$$

where $z(s)$ is the COD at the observation point, β_s and β_{s_0} are the β function at the observation point and error source point separately, $\psi_s-\psi_{s_0}$ is the phase advance from s_0 to s, $\theta=\dfrac{\Delta B(s_0)}{B\rho}\mathrm{d}s_0$ is the dipole kick which is mainly generated from the misalignment of quadrupole magnets, the roll error of bending magnets and the bending magnetic field errors.

The rms COD at location s generated by a random distribution of the $\theta_{\rm rms}$ is given by[4, 16]:

$$z(s)_{\rm rms}=\begin{cases}\dfrac{\sqrt{\beta(s)}}{2\sqrt{2}|\sin\pi\nu|}\Delta z_{\rm Q,rms}\sqrt{\sum\beta(KL_{\rm Q})^2},\\[2ex] \dfrac{\sqrt{\beta(s)}}{2\sqrt{2}|\sin\pi\nu|}(\Delta B/B)_{\rm B,rms}\sqrt{\sum\beta(L_{\rm B}/\rho)^2},\end{cases} \qquad (2)$$

where $\Delta z_{\rm Q,rms}$ is the rms misalignment of quadrupole, and $(\Delta B/B)_{\rm B,rms}$ is the rms bending magnet field errors. The amplification factor of rms COD at all BPM locations, i.e. $\langle\Delta z(s)|_{\rm BPM}\rangle$ caused by rms misalignment of quadrupole is defined as

$$A=\frac{\langle\Delta z(s)|_{\rm BPM}\rangle}{\Delta z_{\rm Q,rms}}\ . \qquad (3)$$

The simulation results reveal how much the COD is affected by the misalignment of quadrupole in the SSRF storage ring. The amplification factors of misalignment of quadrupole in horizontal and vertical planes are 38.437 and 22.455 separately.

In the 3rd generation light sources whose magnets are designed with strong focusing strengths in order to obtain low emittance, the amplification factors are usually big. And the factors increase with the square root of the number of magnets, which means the sensitivity increases with the size of the accelerator. The tolerance for the misalignment is usually as small as a few hundred microns, which demands more precise survey and alignment, if the required rms closed orbit is a few mm. Based on the amplification factors obtained from the simulation for the SSRF storage ring, the tolerance for misalignment of quadrupole magnets in design are within 0.2 mm in rms[14].

The affections to COD by the bending magnet field errors are also studied. The simulated result is given as

$$\langle\Delta z(s)|_{\rm BPM}\rangle=1171\times\langle\Delta B/B\rangle+0.01597\ . \qquad (4)$$

The tolerance for the bending magnet field errors in design for the SSRF storage ring is within 0.1% in rms.

The COD introduced by magnetic imperfections and misalignment of magnets needs to be corrected. From the active aspects, the bending magnets can be sorted by their field errors to suppress the horizontal COD before installation. And the misalignment of magnets is hoped to be as small as possible by improving the survey and alignment precision standard before commissioning. Once the magnets are installed and aligned, the COD can be corrected by using the correctors as a passive way.

3 Active ways to suppress COD

3.1 Sorting of the bending magnet field errors

The 432 m long storage ring contains 40 bending magnets with 1.44 m effective length which are powered in series by two power supplies. The specification for the bending magnet field errors is within 0.1% in rms. Based on the measurements, the rms field error is 0.02%, with the measurement resolution 0.005% in rms which is 1/4 of the rms measured value, meets the requirement of magnet manufacture.

Bending magnets are sorted by carefully phase advance choosing based on the local-cancellation-like method for beam operation at 3.5 GeV. As the rms measured field error is only 1/5 of the value in design, the horizontal COD caused by the field errors is usually within 0.3—0.4 mm in rms. After sorting, the rms horizontal COD is usually reduced to 0.08 mm. Typical horizontal COD after sorting and affections by the measurement resolution is shown as Fig. 1.

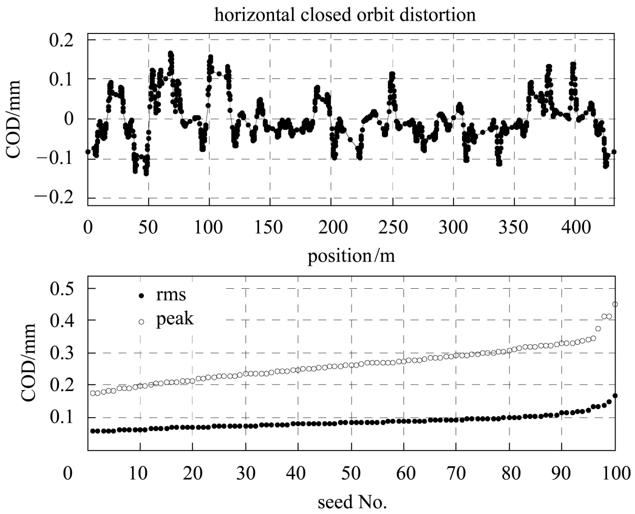

Fig. 1. Typical horizontal COD after sorting and affections by the measurement resolution.

Sorting of the bending magnetic field errors, which can reduce the horizontal COD by a factor of 4—5, is successfully applied in the SSRF storage ring.

3.2 Survey and alignment of SSRF

Survey and alignment is very important to keep the magnet misalignment within the specifications. By the five curial steps for the installation and alignment process including control network, fiducialization, pre-alignment, installation on site and smoothing, great goals are achieved based on a mass of time-consuming work by the mechanical group. The measured horizontal and vertical misalignments Δz of quadrupoles in rms after installation are 0.02 mm and 0.01 mm separately within the same girder, and 0.06 mm and 0.04 mm separately between different girders in the same control-net as shown in Fig. 2. The misalignment of quadrupoles of the whole ring will increase a little because of the error between different control-nets. As the designed goals of misalignment of quadrupoles are within 0.08 mm and 0.15 mm in rms separately within the same girder and between different girders, the final measured results meet the requirement perfectly.

As the rms horizontal and vertical CODs, measured in the commissioning without any correctors at 22.22/11.29, are 3 mm and 1.75 mm separately, we can deduce that the rms horizontal and vertical misalignments of quadrupoles are both 0.078 mm from the formula (3) by the simulated amplification factors. This result accords well with the measured value.

After suppressing COD effectively by the two active ways discussed above, the real COD which is within ±7 mm and ±5 mm in the horizontal and vertical respectively needs to be corrected by using the 80 static corrector families well distributed around the ring.

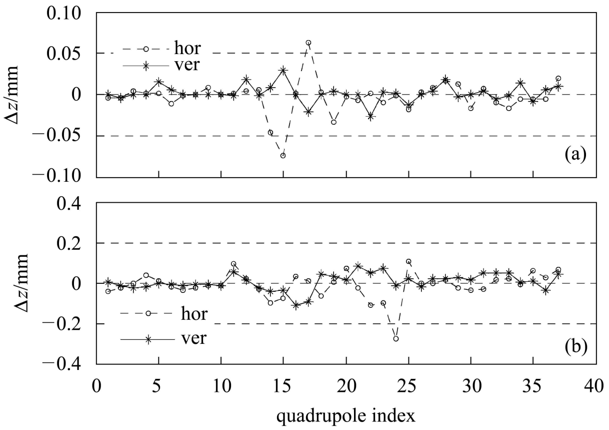

Fig. 2. Measured misalignments of quadrupoles. (a) Within the same girder; (b) between different girders.

4 Closed orbit correction

4.1 COD correction system

The COD correction system includes BPMs and correctors. The numbers and locations of BPMs and correctors are well determined around the ring as follows.

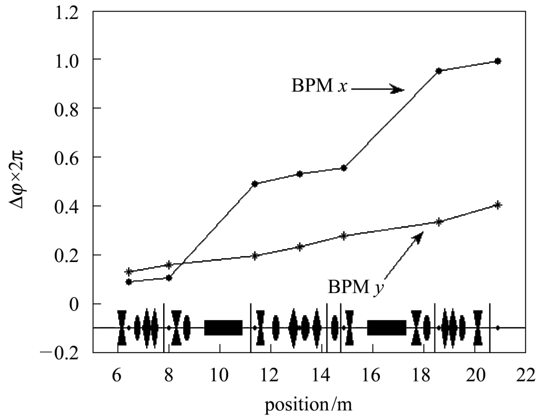

Fig. 3. Layout and phase advance of BPMs in Cell 1.

The BPMs must be placed at the crucial points as close as possible to the quadrupoles or sextupoles where misalignments are the sources of orbit distortion and dynamic aperture reduction, and at the end of each insertion straight section in order to provide local orbit correction[6]. The set of 7 BPMs per cell solution has been adopted for the SSRF storage ring: 2 BPMs are directly fixed on the highly stable girder at the two ends of each cell; the other 5 BPMs are fixed on the aluminium vacuum chamber adjacent to certain quadrupole or sextupole. Fig. 3 shows the layout and phase advance of the BPMs in the first cell. The total number of BPMs used for COD correction is 140.

The correctors are placed mostly at the locations with large β-functions to generate large orbit deviation as shown in Fig. 4. The layout and phase advance of the correctors are shown in Fig. 4. Totally 80 correctors in each plane have been installed for efficient correction.

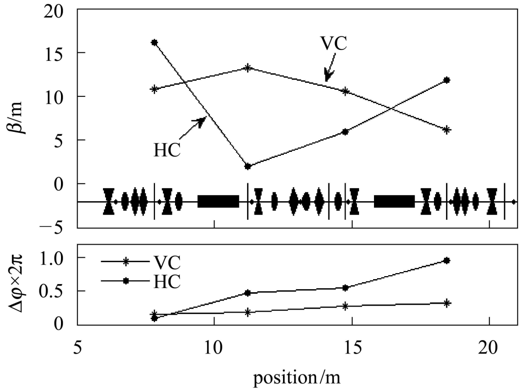

Fig. 4. Layout and twiss-parameter of correctors in Cell 1.

The COD correction is simulated based on AT[17] toolbox in Matlab using SVD algorithm to test the correction system. Totally 100 random samples are generated by the following errors, expressed with rms values: (1) misalignments of dipoles, quadrupoles and sextupoles are the same as $\langle x\rangle = \langle y\rangle = 0.2$ mm, (2) axial rolls of dipoles, quadrupole and sextupoles are the same as $\langle\theta\rangle = 0.2$ mrad, and (3) dipole field error $\langle Bl\rangle/Bl_0 = 0.1\%$. The rms CODs before correction in the horizontal and vertical planes are usually 7.5 mm and 3.5 mm separately. After correction, the COD can be reduced below 0.1 mm by using correctors with a sigma of 0.1 mrad in strength in both planes. The dynamic apertures at the middle point of long straight section of five random samples after correction are tracked that the horizontal values are near 30 mm and the vertical values are near 20 mm. Simulation work reveals that the system can effectively reduce the COD by using appropriate correctors below the max designed strength.

4.2 Beam based alignment

The desirable closed orbit should go through the centers of quadrupoles. The real orbit information can only be acquired by the BPMs and the orbits at the quadrupole locations are approximately marked by the adjacent BPMs. As a displacement, the so-called BPM-to-quadrupole offset(offset for short), between the magnetic center of the quadrupole and the electronic center of the adjacent BPM always exists, the beam usually dose not go through the magnetic center of quadrupoles while the orbits at the BPM locations are selected as the object to be corrected. But the offset can be determined using the beam based alignment (BBA) techniques. By changing the power supply of each individual quadrupole and analyzing the result of closed orbit perturbations, the corresponding offset is figured out and the magnetic center of the quadrupole is found.

Because most of the BPMs are directly fixed on the aluminium vacuum chamber and are not aligned precisely as the quadrupoles which are fixed on the girders, the initial offsets in the SSRF storage ring are large and even reach 2—3 mm somewhere which will certainly increase the COD. After 3 rounds of careful BBA measurements, the total offsets were found with a sigma of 0.803 mm and 0.587 mm in the horizontal and vertical plane separately as shown in Fig. 5.

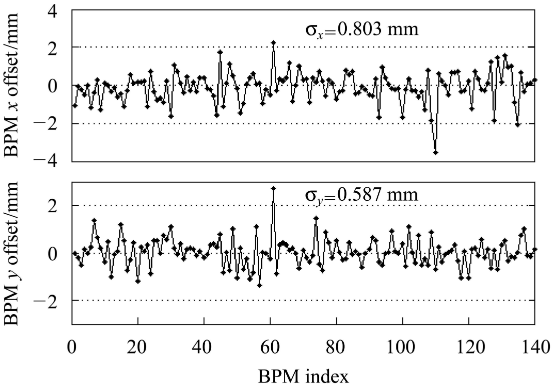

Fig. 5. Offsets found by BBA measurements.

Once the offset is determined, the COD can be reduced effectively to go though the center of quadrupoles. And the remaining offset will decrease with the correction. By executing the BBA measurements and the COD correction alternately after several rounds, a few ten microns COD can be obtained with few ten microns offset.

4.3 Closed orbit correction

Like many high level controls for the SSRF storage ring[18], the global orbit correction software was modified and developed on the ORBITGUI, which supports the interface operation for easy control based on MML toolbox in Matlab. The correction algorithm is the SVD.

The response matrix is measured by monitoring the orbit deviations while changing the current of corrector one by one. The corrector current change should be well determined. If the current change is large, the measured response matrix will be better, i.e. higher signal-to-noise ratio from the BPMs. Too large current change will generate large orbit deviation in the sextupoles which will introduce the nonlinear effect and make the measured response matrix inaccurate. The corrector current change is determined as 0.5 A each step in the measurement. The BPM acquisition data, with a frequency of 10 Hz for closed orbit information, have a high measurement precision of typically better than 0.2 μm in the vertical and 0.4 μm in the horizontal plane. As 0.5 A change of corrector will usually generate 0.35 mm and 0.15 mm orbit deviation in rms in the horizontal and vertical planes, the precision of measured response matrix is nearly 0.1% in both planes. The measured response matrix is very close to the model one.

With the reasonably measured response matrix, the correction algorithm settles down in 2 to 3 iterations using 60 singular values. After the correction, the residual orbit has a sigma of about 50 μm in both planes during the first commissioning stage with the beam of 100 mA at 3 GeV at which the BBA is performed. The rms currents of correctors in the horizontal and vertical plane are 0.4 A and 1.2 A separately, 0.06 mrad and 0.10 mrad transferred to the deflection angle.

5 Slow orbit feedback

The electron beam stability is important over a huge frequency range in time scale of milliseconds to days. This paper focuses on the slow orbit motion.

The orbit drift can reach 500 μm in the horizontal plane at the locations with large dispersion functions and few ten μm in the vertical plane during 8 hours without feedback. The SOFB system is added for the standard operation of the SSRF storage ring.

5.1 SOFB system

The hardware system of SOFB is the same as the closed orbit correction system as discussed above, and the correction algorithm is also SVD. The SOFB software is developed on the SOFBGUI, which also supports the interface operation for easy control based on MML toolbox in Matlab.

The SOFB frequency can reach few Hz depending on the BPM data acquisition frequency and the processing time cost including applying the correction by changing the currents of correctors. As the largest orbit drifts from the BPMs in one hour typically are 25 μm and 5 μm in horizontal and vertical planes separately, the loop time of SOFB is 100 seconds now for suppressing the slow orbit drift. And an average of 20 BPM acquisition data in 2 seconds is taken into account as the closed orbit information to suppress the disturbed effects by the kicker action when injection.

The applied current change factor of corrector is carefully determined as 0.75 to insure that it will not make excessive orbit change but have certain fast feedback speed at the same time. 32 singular values in both planes are used now for SOFB.

The SOFB system can correct the small orbit perturbations about 20 μm in rms caused by the single corrector change to a residual orbit with a sigma of 1.5 μm in the horizontal plane, and can reduce that from 10 μm to 1.5 μm in rms for the vertical plane. Thus the SOFB can now maintain the orbit within 1.5 μm in rms, while within ±5 μm in peak.

5.2 RF frequency feedback

The change of circumference due to thermal expansion or tidal effect can generate the dispersion-like orbit in order to keep the single-turn electron trajectory constant and thus the electron energy is changed if the RF frequency remains the same. This off-momentum electron orbit can be corrected by changing the RF master-clock frequency as

$$\frac{\Delta f_{\mathrm{rf}}}{f_{\mathrm{rf}}}=-\alpha_{\mathrm{c}}\frac{\Delta x}{D_x}\ . \tag{5}$$

where D_x is the dispersion function, and α_{c} is the momentum compaction factor.

The off-momentum orbit correction procedure can be automated in machine operations. As the slow orbit change is mainly caused by various thermal effects, the RF frequency feedback is also included in the SOFB system.

Figure 6 shows the measured dispersion function η by tuning the RF frequency from 499673058 Hz to 499673258 Hz compared with the model one, where

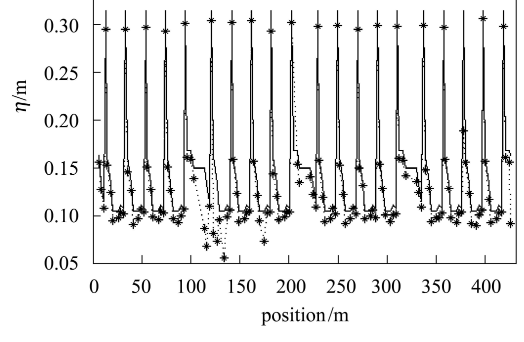

Fig. 6. The measured and model dispersion functions.

α_c is calculated by the model as 4.2703×10^{-4}. The measured dispersion function accords with the model one in most BPM locations.

5.3 SOFB results

Before the insertion devices installation, the SOFB was tested for suppressing the tidal orbit drift during 2 weeks. The SOFB worked so well that the orbit drift could be mostly retrained within ±5 μm in both planes during 8 hours on which the orbit drifted most severely. Fig. 7 and Fig. 8 show the orbit drift at the BPM [7, 7], [9, 7], [13, 7], after which are the straights to install the insertion devices, selected in the same 8 hours from 8 a.m to 16 p.m of March 10th and 28th with and without SOFB operation separately. The orbit stability requirements for slow orbit drift were basically achieved during the SOFB operation.

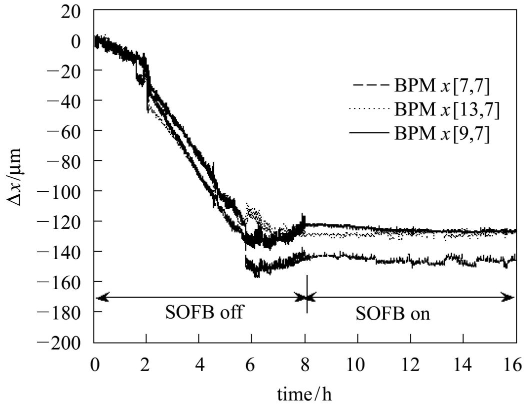

Fig. 7. The horizontal orbit drift.

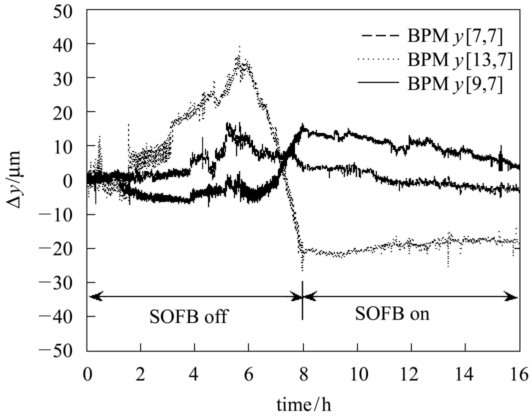

Fig. 8. The vertical orbit drift.

6 Conclusions

Based on the bending magnet sorting and excellent survey and alignment job, a small real COD of the storage ring is guaranteed. The quad centers have been accurately determined using the BBA technique. This work has paved the way for the development of a global orbit correction scheme using SVD. The COD can be reduced to a sigma about 50 μm in both planes by closed orbit correction in the first SSRF commissioning stage. Integrated with operation, the closed orbit correction system has significantly improved the overall storage ring operation.

The SOFB system is being tested to maintain long-term stability. This system will simplify the light source operation and further improve the light source performance. Further work for the insertion device gap change feedback and eventually noise caused by the environment needs to be studied. And the injection system needs to be optimized to suppress the orbit perturbation caused by the kicker action when operated with Top-Up injection.

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