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Calibration of the linear optics in the SSRF storage ring

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Abstract Phase I commissioning of the SSRF storage ring at 3.0 GeV was ended with encouraging results. Distortions and calibrations of the linear optics during the storage ring commissioning are discussed in this paper. The calibration procedure has reduced sextupole-additional focusing effects by minimizing closed orbit deviation and corrected quadrupole magnetic coefficients with the linear optics from closed orbit (LOCO) technique. After fitting the closed orbit response matrix, linear optics of the storage ring is substantially corrected, and the measured parameters agree well with the design. Four optics modes were commissioned, and relevant machine physics studies were carried out. Their results are summarized.

Key words SSRF storage ring, Linear optics, Commissioning, Calibration

CLC number TL5

1 Introduction

The Shanghai Synchrotron Radiation Facility (SSRF), with a 3.5-GeV electron storage ring, a full energy booster, a 150-MeV linac and seven beamlines in its Phase I construction, is an intermediate energy third generation light source[1]. The storage ring, with a structure of 20 double bend achromatic cells forming four super-periods[2], is designed to achieve very low natural emittance to produce X-rays of high brightness or flux for users. Each super-period contains three standard cells and two matching cells, so as to ensure good performance of SSRF and to meet requirements on the X-rays by the users. Total length of the straight sections accounts for about 35% of the ring circumference, enabling placement of over 20 insertion devices. All the 40 bending magnets are powered in series. The 200 quadrupoles with independent power supplies are grouped into ten families. These allow large flexibility for the linear optics. The storage ring has 140 sextupoles in eight families that are elaborately optimized to provide sufficient dynamic acceptances. The 80 correctors in each plane and 140 beam position monitors (BPMs) are used for closed orbit correction.

Commissioning of the storage ring began ahead of schedule on December 21, 2007. Because the super-conductive RF cavities to compensate energy loss at 3.5 GeV were not available yet, Phase I of the commissioning was carried out at 3.0 GeV with three room temperature RF cavities[3,4]. The first turn and the multi-turn beam signals were observed in the BPMs, as we were scanning the correctors one by one, without switching on the sextupoles and the RF cavity. By switching them on, beam storage was achieved by carefully balancing RF frequencies and bending fields. By optimizing the sextupole strengths, closed orbit correction and beam injection, the beam lifetime was improved, achieving 5 mA beam storage on December 24, 2007. After building protection systems on the closed orbit interlock and the temperature interlock, beam storage of 100 mA was successfully achieved on January 3, 2008.

It was found in commissioning the storage ring, however, that the linear optics had serious aberration

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with respect to the theoretical expectation due to inevitable errors in the effective quadrupole integral strengths distributing along the ring. Breaking periodicity or symmetry of the linear optics cannot provide an expected beam size for users. Also, this will excite stronger nonlinear resonances, giving rise to dramatic reduction of the dynamic acceptances[5]. To ensure high injection efficiency and long beam lifetime, we had to find ways for restoration of periodicity and symmetry of the linear optics[6].

The effective quadrupole integral strength errors usually have two origins in the bare lattice of the SSRF storage ring. The first one is the additional quadrupole field in the sextupole due to the large closed orbit deviation, and the second one is the effective integral strength error in the quadrupole introduced by effective length errors, excited current shifts, or beam energy deviation. During the commissioning, the BPM offsets with respect to the nearest quadrupoles were precisely measured with several rounds of beam based alignment (BBA)[7]. After setting all the offsets in BPMs, the closed orbit deviation could be substantially corrected based on the singular value decomposition (SVD) with the precisely measured orbit response matrix[8]. Effects of additional focusing of the sextupoles, which cannot be completely ignored because of unavoidable misalignment of the sextupoles, can be improved by minimizing the closed orbit deviation. It is true that beam energy deviation and errors in quadrupole effective length distort the linear optics, but as a feasible tradeoff, one may perform step-by-step corrections of just the quadrupole magnetic coefficients to compensate the total error effects, and to restore periodicity and symmetry of the linear optics as much as possible. A well-known technique, the linear optics form closed orbit (LOCO)[9] was applied to correct the quadrupole magnetic coefficients by fitting the orbit response matrix family by family, and restore the linear optical functions by magnet-by-magnet fitting. LOCO has been used in third generation light sources of DIAMOND[10], SOLEIL[11] and ASP[12], and its powerful capabilities have been demonstrated.

In this paper, we report the linear optics design, the nonlinear optimization, the detailed linear optics calibration processes, and the physics study results for the SSRF storage ring.

2 Linear optics design and nonlinear optimization

Main parameters of the four linear optics modes, which were successfully commissioned in the SSRF storage ring, are summarized in Table 1. Theoretical linear optical functions in one fold of the lattice are plotted in Fig.1. Mode I is the nominal mode that distributes a little dispersion in the straight sections for further reducing the natural emittance. Mode II is the nominal dispersion-free mode. The vertical tunes (Q_y) of the two modes are reduced to 11.29 from 11.32 in order to avoid a structural resonance ($3Q_x-2Q_y=44$) and a serious resonant node. The β functions are set to large values in the long straight sections in order to obtain ample dynamic aperture for efficient injection, but small values in the standard straight sections in order to provide low beam sizes. An exception is Mode IV, which has large beta functions in the standard straight sections in order to release phase advances for low tunes. The linear optics is perfectly four-super-periodic and symmetric. At 3.0 GeV beam energy, the resulting lattice provides a natural emittance of 2.86 nm·rad for Mode I, 8.4 nm·rad for Mode II, 2.47 nm·rad for Mode III, and 3.98 nm·rad for Mode IV.

Because strong nonlinearity, corresponding to the sextupoles for compensating large natural chromaticities, degrades drastically the dynamic acceptances of the lattice, the nonlinear optimization is difficult. Several methods were used to optimize the harmonic sextupoles (details can be found in Refs.[13,14]). By elaborate nonlinear optimizations, all the four modes could provide sufficient dynamic acceptances to satisfy specifications on the injection efficiency and beam lifetime. Fig.2 shows on-momentum dynamic apertures of the four modes. The plots are from a 1000-turn tracking with AT code[15], and are normalized by the β functions.

Table 1 Main parameters of the four commissioned modes

Parameters		Mode I	Mode II	Mode III	Mode IV
Tune Q_x, Q_y		22.22, 11.29	22.22, 11.29	23.324, 11.232	19.22, 7.32
β_x, β_y, η_x in center of the straight sections / m		10, 6.0, 0.15 3.6, 2.5, 0.10	10, 6.0, 0 3.6, 2.5, 0.006	12.0, 6.0, 0.17 2.5, 2.0, 0.10	15.0, 8.0, 0.15 13.4, 4.6, 0.14
Natural emittance / nm.rad	3.5 GeV	3.92	11.4	3.36	5.42
	3.0 GeV	2.86	8.4	2.47	3.98
Natural chromaticity ξ_x, ξ_y		–55.7, –17.9	–55.6, –18.1	–64.4, –19.9	–45.8, –21.8
Momentum compactor		4.27×10^{-4}	5.42×10^{-4}	3.61×10^{-4}	5.89×10^{-4}
Natural energy spread	3.5 GeV	9.84×10^{-4}	9.84×10^{-4}	9.84×10^{-4}	9.84×10^{-4}
(root mean square)	3.0 GeV	8.44×10^{-4}	8.44×10^{-4}	8.44×10^{-4}	8.44×10^{-4}

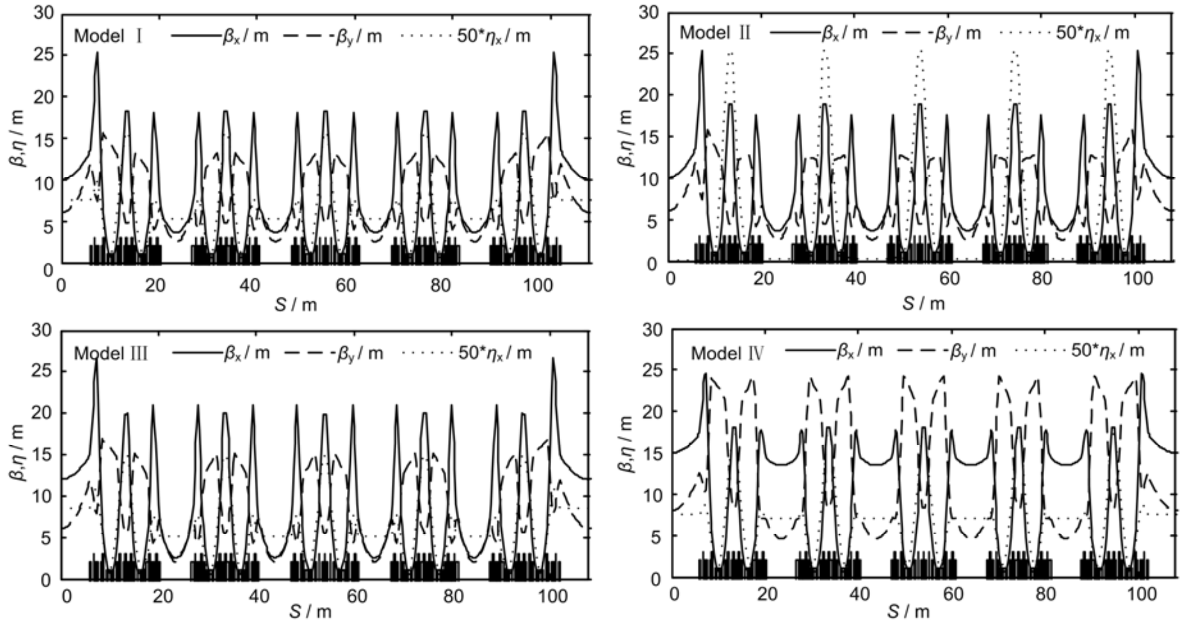

Fig.1 Linear optical functions and magnet layout of one fold of the storage ring.

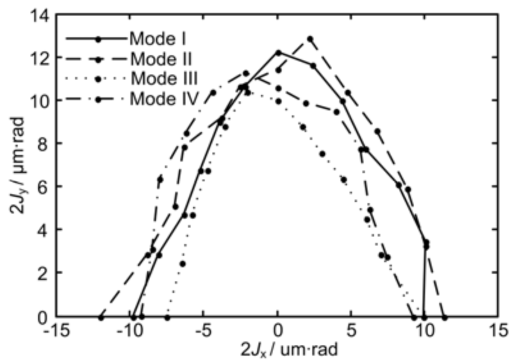

Fig.2 On-momentum dynamic apertures normalized by β functions for the four optics modes.

3 Aberrations of the first commissioned model

We started the SSRF storage ring commissioning with Mode II. To achieve its beam accumulation, exciting currents of the quadrupoles were carefully adjusted. However, the results differ greatly from those obtained with a theoretical model, in which the quadruple gradients were transformed from the exciting currents, such as the tunes with about 1.5 and 0.4 deviations in the horizontal and the vertical plane, respectively. Origins and solutions of the problem are described in above paragraphs. Because it is difficult to steer the beam centering the sextupoles, the sextupole-additional focusing effects were suppressed just by minimizing the closed orbit deviation after BBA for pinpointing the magnetic centers of the quadrupoles. The effective length errors and the effective gradient errors of the quadrupoles have the same effects on the linear optics distortion. Although it is difficult to distinguish their contributions, we were able to correct the gradient errors (calibrate the magnetic coefficients for systematic errors and adjust the gradient of individual quadrupole for random errors along the ring) to compensate the total effective integral strength errors. And errors caused by the beam energy deviation could be corrected in this way, too.

4 Procedure of the linear optics calibration

The linear optics calibration in the SSRF storage ring was completed and periodicity and symmetry of the linear optics were restored on March 17, 2008. Since then, we could accurately operate the SSRF with a designed mode, and many machine physics studies were carried out.

4.1 Suppression of COD effects and simple scaling for quadrupole magnet coefficients

After about one month for cleaning the vacuum chamber, lifetime of 100 mA beam increased to 10-20 h, and the high beam current seems of help to obtain a better resolution of beam position in the BPM. After two rounds of BBA for setting the BPM offsets with respect to the closest quadrupoles, the closed orbit deviation (root mean square, RMS) could be 80 and 90 μm in the horizontal and vertical plane, respectively. With a simple relative scaling for all the quadrupole magnetic coefficients (decreasing by 1.6% for Q4 and Q4L, and 2.6% for others), the new optics of the machine recovered the tunes to 22.196 (H) and 11.214 (V), which were measured by exciting the beam. The natural chromaticities were –58 (H) and –18 (V), measured by recording tune shifts as a function of the bending field. When we built an AT model with the quadurpole gradients transformed from the exciting currents by using the temporal magnetic coefficients, the one-turn-map tracking resulted in a tune of 22.075 and 11.189, and a natural chromaticity of –78 and –18. The average β functions at the quadrupoles in one fold of the ring were measured by recording the tune shifts as a function of the quadrupole field (Fig.3). But still, the results revealed large difference between the machine and the model, especially in the horizontal plane. In other words, the AT model resulting from the temporal *B-I* transformation of the quadrupole could not characterize the real machine, and the linear optics could not be corrected. So, the quadrupole magnetic coefficients had to be calibrated.

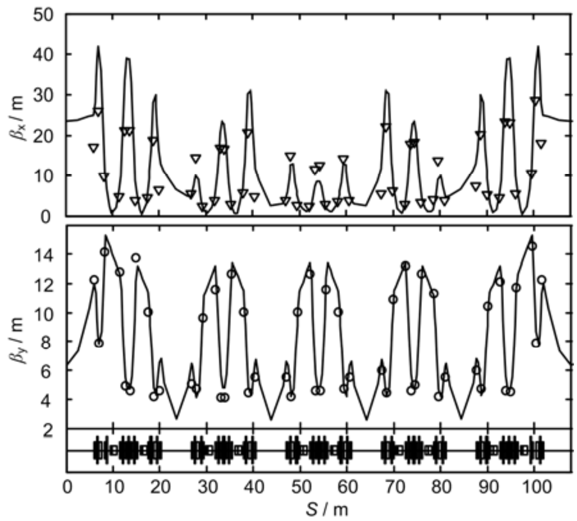

Fig.3 Results of the β function measurements.
▽Measured horizontal β function
○ Measured vertical β function
—Tracking result of AT model

4.2 Corrections for the quadrupole magnetic coefficients with LOCO

Since the orbit response matrix contains information of the quadrupoles, the gradient error can be extracted by fitting the orbit response matrix family by family or magnet by magnet. Mode I was used in the commission. The gradient deviation of each family between the machine and the designed mode was extracted by LOCO, and the quadrupole magnetic coefficients were scaled for individual family so that the machine has the same effective integral strengths as the designed mode. The results will be summarized in Section 5.2. When the closed orbit deviations (RMS) were corrected to 70 μm (H) and 80 μm (V), the tunes were measured to be 22.26 (H) and 11.28 (V). These are close to the designed values. The β functions were determined with LOCO (Fig.4). One finds little distortion within the four folds of the ring. Therefore, the *B-I* transformation systematic error in each family was corrected. The β beatings (RMS) of the machine with respect to the designed mode are about 4% (H) and 6% (V). Restorations for the symmetry and the period of the linear optics should be achieved by LOCO fitting magnet by magnet.

Fig.5 shows the measurement results (the dots) of β beatings (RMS) of the machine to be about 20% (H) and 10% (V), which are larger than the LOCO results, because of measurement errors of the tune. Fig.5 shows also a graphic user interface (GUI) for automatic β function measurement, which was developed during the storage ring commissioning. The figure can be zoomed with the bottom handles, and the current variation of the individual quadrupole can be set with the right handles. The tool provides much convenience for checking results of the linear optics calibration.

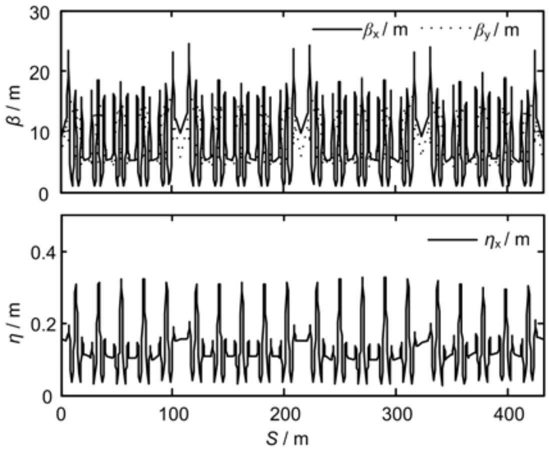

Fig.4 Linear optical functions along the ring determined by LOCO technique.

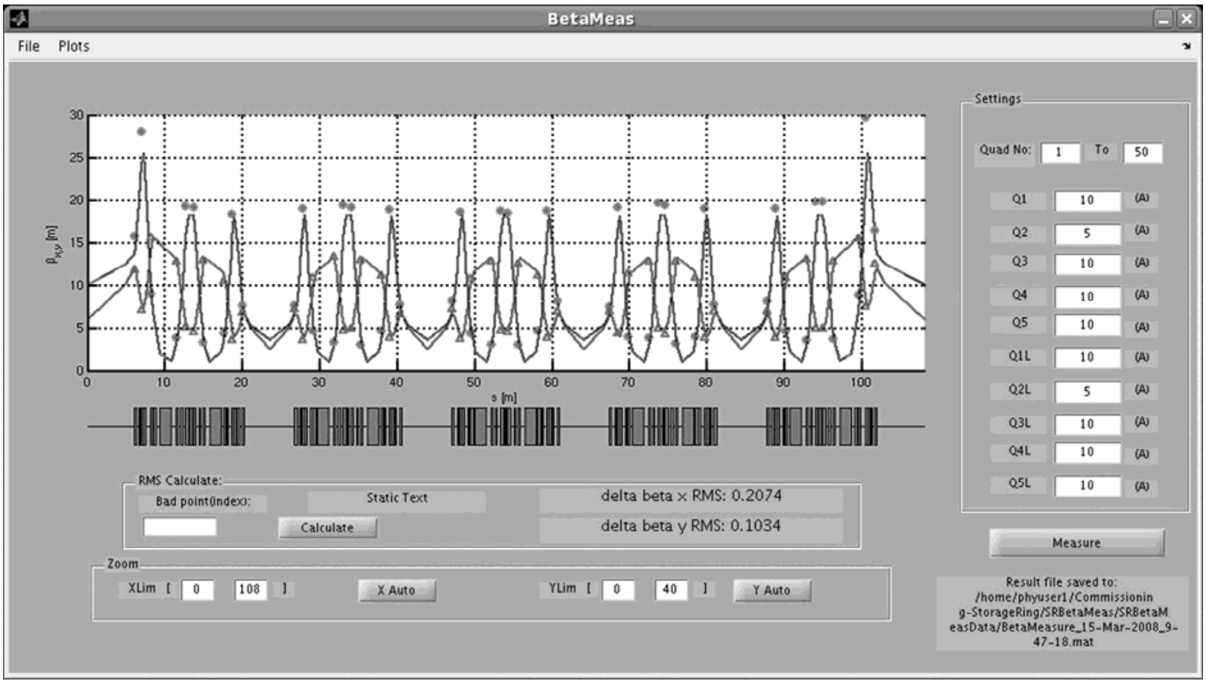

Fig.5 A GUI for automatic beta function measurements.

4.3 Periodicity and symmetry restorations for linear optics

After the above calibrations, symmetry and periodicity of the linear optics were improved, and the β beatings along the ring were corrected within ±10%. Residual distortion of the linear optics could be minimized with the LOCO fitting magnet by magnet. After two rounds of LOCO corrections, random errors of the quadrupole gradients were measured at ±1% or less. The restored linear optical functions characterized by LOCO are showed in Fig.6, with the tunes of 22.223 (H) and 11.292 (V). The β beatings (RMS) were 0.5%, well within ±1.5%, for both transverse planes (Fig.7). These facts show an excellent agreement between the storage ring and its designed mode.

The measured parameters of the storage ring agree well with the designed mode and LOCO determination, such as the tune, the natural chromaticity, the natural emittance, etc. The results are summarized in Table 2. These results illustrate that the machine can be operated accurately with a designed mode. When switching the storage ring to other modes, or operating it at different beam energy, the linear optics can be easily calibrated close to the ideal condition with several rounds of the LOCO corrections.

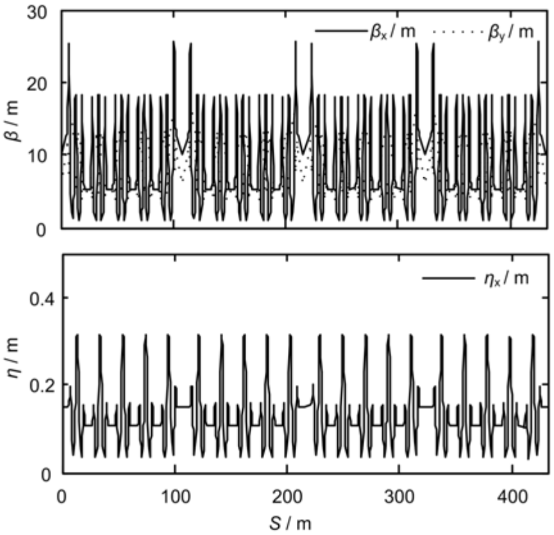

Fig.6 Restored linear optical functions along the ring determined by LOCO.

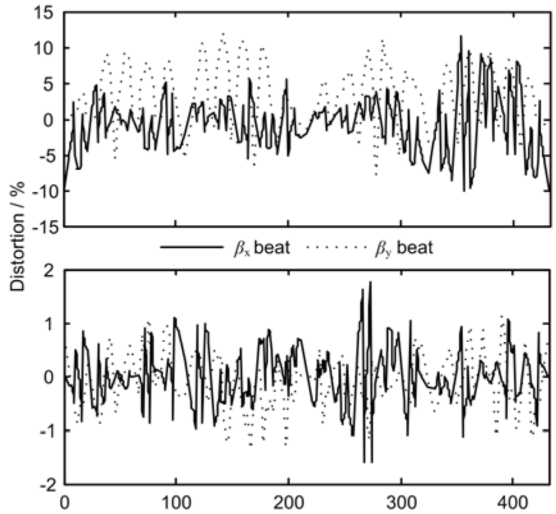

Fig.7 Beta beatings of the real machine with respect to the designed mode before (top) and after (bottom) LOCO correction.

Table 2 Parameter comparisons of Mode I

Parameters	Designed value	LOCO determination	Measured value
Tune Q_x, Q_y	22.22, 11.29	22.223, 11.292	22.2213, 11.2905
Natural chromaticity ξ_x, ξ_y	–55.7, –17.9	–55.68, –17.93	–50, –17
Natural emittance / nm·rad	2.86	2.857	2.83
RF frequency / MHz	499.654000	499.674660	499.674640

5 Summary of the linear optics calibrations

The designed mode of linear optics was realized step by step in its calibration. Meanwhile, physics studies, such as BBA, closed orbit correction, and *B-I* transformation correction, were conducted in the calibration. Some results, and commissioning results of the other three modes, are presented in this section.

5.1 Beam based alignment and closed orbit correction

BBA is a reliable technique to check whether a BPM electrical center is identical to the quadrupole magnetic center by varying the quadrupole gradient and observing the orbit. After several rounds of BBA, the BPM offsets of the storage ring are precisely measured (Fig.8). It can be seen that most of the offsets are within ±2 mm. After setting the BPM offsets, the RMS closed orbit deviations can be corrected down to less than 50 μm in both transverse planes based on the SVD technique. Fig.9 plots typical deviations of the closed orbit along the ring, together with the RMS data.

By changing exciting current of the sextupoles, the tune shifts and the closed orbit shifts are observed. This indicates that the beam did not center the sextupoles, and the sextupole-additional effect on the linear optics was not eliminated. In the LOCO calibration, this effect is compensated by correcting individual quadrupole strength. Because the sextupoles are powered in series for each family, one cannot measure the BPM offsets with respect to the closest sextupoles by varying individual sextupole strength and observing the tune effects.

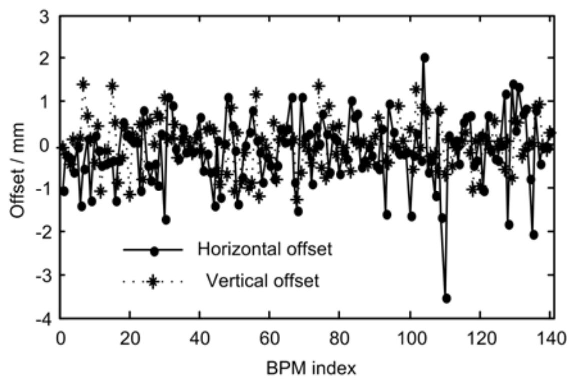

Fig.8 BPM offsets.

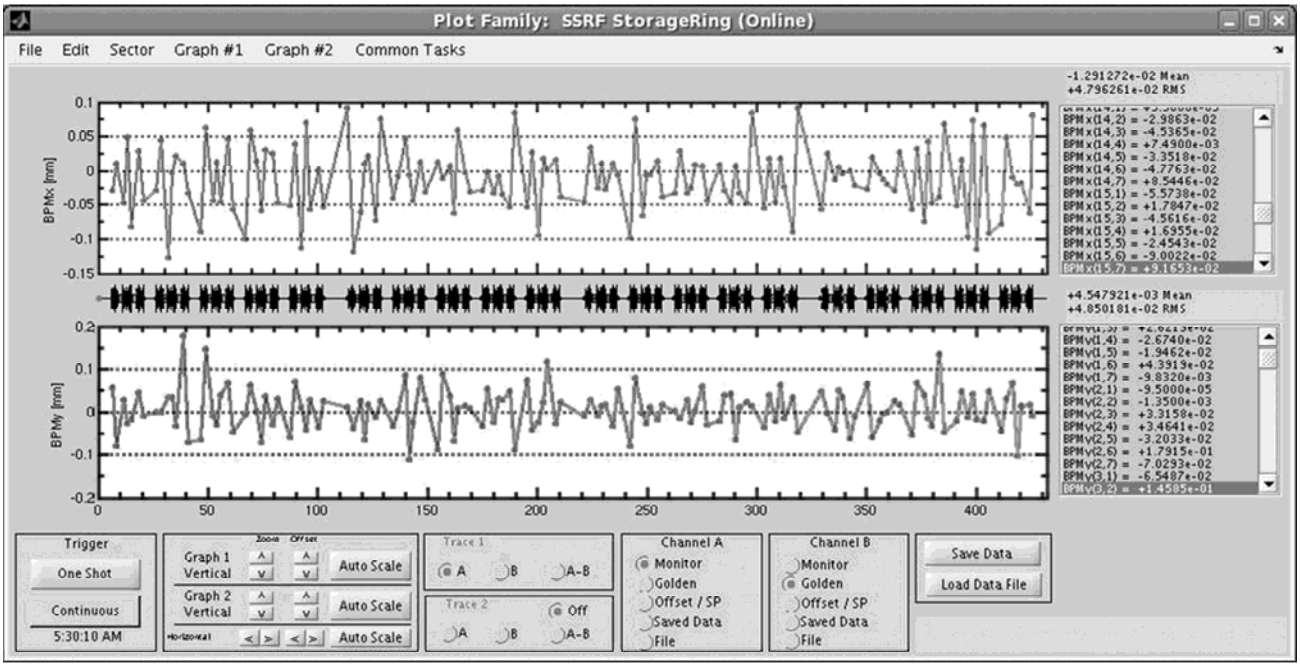

Fig.9 Typical closed orbit deviation along the ring.

5.2 Calibration of the quadrupole magnetic coefficients

B-I curves of the quadrupoles are approximated by measuring the integral strengths as a function of the exciting current. Due to the very fast convergence of the coefficients, the approximation is limited to the third order. The average gradients of the quadrupoles can be expressed as

$$\overline{G}(I) = P_0 + P_1 I + P_2 I^2 + P_3 I^3 \qquad (1)$$

where I is the exciting current, and P_i (i=1, 2, 3) are magnetic coefficients of different orders (see Table 3). As described above, linear optics of the storage ring, in which the quadrupole exciting currents were set according to these coefficients, had a large distortion with respect to the theoretical mode. Although the distortion may be caused by the effective length errors, the magnetic coefficient errors, and the beam energy deviation, it can be compensated by correcting just the magnetic coefficients. The correction was carried out in two steps: 1) scaling all the quadrupole magnetic coefficients to correct the tunes, and 2) scaling individual quadrupole family by using LOCO technique, to bring the machine close to the designed mode. As shown in Table 4, all the coefficients decreased by 2%~3%. We could not decide on a real or major causer of the distortion, but the commissioning results of the different mode or on different beam energy show the feasibility of the *B-I* curve correction.

Table 3 Magnetic coefficients and effective lengths of the quadrupoles

Quadrupole type	Effective length / m	P_0	P_1	P_2	P_3
Q260	0.276	6.6622×10^{-1}	6.5964×10^{-2}	1.8916×10^{-4}	-5.4336×10^{-7}
Q320	0.335	5.9678×10^{-1}	6.8714×10^{-2}	1.6681×10^{-4}	-4.7394×10^{-7}
Q580	0.590	4.4751×10^{-1}	7.3481×10^{-2}	1.2352×10^{-4}	-3.4608×10^{-7}

Table 4 Magnetic coefficient scaling for the quadupoles

Quadrupole family	Type	Coefficient scaling
Q1	Q320	97.30%
Q1L	Q320	97.30%
Q2	Q580	97.50%
Q2L	Q580	97.60%
Q3	Q320	97.21%
Q3L	Q320	97.40%
Q4	Q260	98.01%
Q4L	Q260	98.01%
Q5	Q320	97.40%
Q5L	Q320	97.50%

5.3 Linear optics calibrations for the other three modes

On March 22～30, 2008, the other three modes were commissioned in the storage ring at 3.0 GeV. By setting quadrupole exciting currents according to the corrected magnetic coefficients, linear optics of the storage ring had just a few distortions. After two or three rounds of LOCO corrections, periodicity and symmetry of the linear optics were restored. The quadrupole gradient errors were within ±1.5%, and the β beatings were within ±2% approximately. The results, including the tunes, the natural emittance and the natural chromaticities, were in good agreement with the design. The β beatings (RMS) of the four commissioned modes are given in Table 5, with the results before and after LOCO correction. The correction results are good enough to validate the magnetic coefficients for the quadrupoles.

Commissioning of Mode I in the storage ring at 1.5 GeV, 2.0 GeV and 2.75 GeV were carried out, too, and after restoration of the linear optics, the measured parameters were close to the design.

Table 5 **C**alibration results (RMS) of the four designed modes

Items	Model I	Model II	Model III	Model IV
Horizontal and vertical β beating before LOCO	3.91%, 5.78%	7.83%, 4.08%	6.08%, 4.08%	4.37%, 4.85%
Horizontal and vertical β beating after LOCO	0.50%, 0.52%	0.52%, 0.87%	0.48%, 0.71%	0.81%, 0.36%
Quadrupole field deviation between model and machine	0.29%	0.43%	0.33%	0.23%

6 Conclusions

During Phase I commissioning of the SSRF storage ring, machine physics studies were carried out with encouraging results. After several rounds of BBA, the BPM offsets with respect to the quadrupoles were precisely measured, and closed orbit deviation (RMS) of the storage ring could be corrected to less than 50 μm for both transverse planes. The sextupole-additional effects on the linear optics were reduced, but distortions due to misalignment of the sextupoles could not be ignored. The effective integral strength errors in the quadrupoles were compensated by calibrating the magnetic coefficients, and linear optics of the storage ring could be very close to the design by using the LOCO technique. The symmetry and periodicity restorations for the linear optics of different modes at different beam energies were fulfilled, and the measured parameters agreed well with the design. The progresses proved the feasibility of our calibration procedure, and set a stage for Phase II commissioning of the storage ring at 3.5 GeV.

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