CPC(HEP & NP), 2009, **33**(5): 397—400 **Chinese Physics C** Vol. 33, No. 5, May, 2009

Design and first commissioning of a new mode with lower emittance in the SSRF storage ring*

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Abstract A new mode is designed with an emittance of 2.47 nm·rad at 3.0 GeV beam energy, lower than the nominal mode of the Shanghai Synchrotron Radiation Facility (SSRF) storage ring. Details of the linear optics design and the nonlinear optimization are presented in this paper. During Phase I commissioning of the storage ring we tested the new optics mode and some expected results were obtained. After restoring the linear optics by means of the linear optics with closed orbit technique, the main parameters of the real machine agree well with the designed values and the injection efficiency and beam lifetime are acceptable.

Key words SSRF storage ring, optics, commissioning, calibration

PACS 29.20.dk, 41.85.-p, 42.65.-k

1 Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) is a third generation light source, consisting of a 150 MeV linac, a full energy booster, a 3.5 GeV storage ring and seven primary beamlines. Its accelerator complex was installed in ten months starting from November 2006[1]. The storage ring of the SSRF is designed to provide high photo brightness by minimizing the beam sizes at the light source points. This requires low emittance and low beta functions at the source points, realized by a lattice with 20 Double Bend Achromatic (DBA) cells forming four super-periods. In the lattice, all 40 bending magnets are powered in series 200 quadrupoles with independent power supplies are grouped into ten families and allow for a large flexibility of the linear optics; 140 sextupoles in 8 families are elaborately optimized to provide ample dynamical acceptances; 80 correctors in each transverse plane and 140 Beam Position Monitors (BPMs) are used for closed orbit correction[2]. Commissioning of the storage ring for a beam energy of 3.0 GeV was started at the end of December 2007, and has achieved lots of encouraging results so far[3]. In this paper we design a new optics mode having a lower emittance (2.47 nm·rad) and lower beam sizes at 3.0 GeV beam energy than the nominal optics mode. The linear optical designed aspects are presented in Section 2, the nonlinear optimization is described in Section 3, and the first successful commissioning results are summarized in Section 4. The purpose of this work is to validate the flexibility of the linear optics of the storage ring, double check the machine correction, such as the Beam Based Alignment (BBA) and magnetic coefficient calibration, and to go for higher photo brightness.

2 Linear optics design

The tune of the storage ring is optimized to 23.324, 11.232 avoiding strong nonlinear resonances and getting stronger focusing for lower emittance. It can be expected that natural chromaticity will become large, and this can be corrected by stronger chromatic sextupoles. The corresponding nonlinearity of the sextupoles will degrade the lattice accep-

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Received 17 June 2008
* Supported by SSRF Projec

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tance more than the nominal mode, so β_x in the center of the long straight section is fitted to 12 m in order to get an ample horizontal dynamic aperture for efficient injection. The horizontal and the vertical β functions in the center of the standard section are reduced to provide additional phase advances and to obtain a smaller beam size. The main parameters of the new mode as well as the nominal designed mode are summarized in Table 1. The strengths of the quadrupoles are listed in Table 2. Fig. 1 schematically shows the linear optical functions and the magnet layout of one fold of the ring.

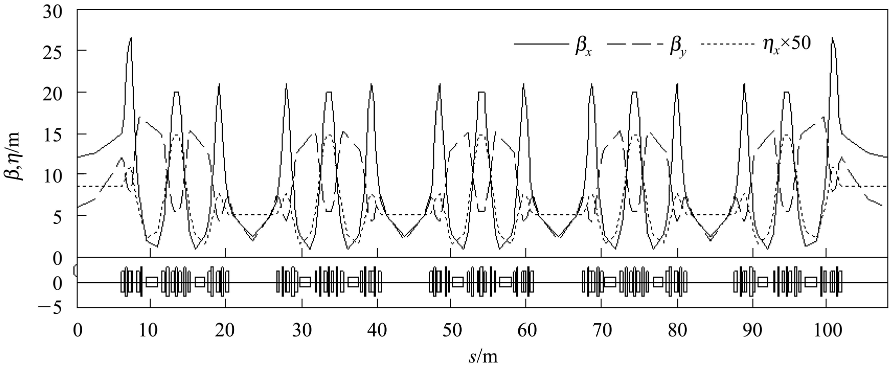

Fig. 1. The linear optical functions of the new optics in one fold of the SSRF storage ring.

Table 1. Main parameters of the new optics and the nominal optics.

parameter	the new mode	the nominal mode
tune (H,V)	23.324, 11.232	22.22, 11.29
β_x,β_y,η_x/min		
centers of straight sections	12.0, 6.0, 0.17, 2.5, 2.0, 0.10	10.0, 6.0, 0.15, 3.6, 2.5, 0.10
natural emittance/(nm·rad)	3.36 at 3.5 GeV, 2.47 at 3.0 GeV	3.92 at 3.5 GeV, 2.86 at 3.0 GeV
natural chromaticity (H,V)	−64.4, −19.9	−55.7, −17.9
momentum compaction	3.61×10^{-4}	4.27×10^{-4}
energy spread	9.84×10^{-4} at 3.5 GeV, 8.44×10^{-4} at 3.0 GeV	9.84×10^{-4} at 3.5 GeV, 8.44×10^{-4} at 3.0 GeV
radiation loss per turn/MeV	1.45 at 3.5 GeV, 0.77 at 3.0 GeV	1.45 at 3.5 GeV, 0.77 at 3.0 GeV

Table 2. Strengths of the quadrupoles and sextupoles.

magnet	strength	length/m
QL1,Q1	−0.9406, −1.5607 m^{-2}	0.335
QL2,Q2	1.3165, 1.5576 m^{-2}	0.590
QL3,Q3	−1.1639, −0.9857 m^{-2}	0.335
QL4,Q4	−1.0216, −1.2889 m^{-2}	0.276
QL5,Q5	1.3350, 1.4191 m^{-2}	0.335
S1,S3	7.3211, 14.6298 m^{-3}	0.213
S2,S4	−12.5025, −13.0509 m^{-3}	0.253
S5,SD	14.7615, −12.1047 m^{-3}	0.213
S6,SF	−16.1332, 15.1740 m^{-3}	0.253

3 Nonlinear optimizations

Because the structure of the SSRF storage ring was optimized for the nominal mode, in addition to the stronger nonlinearities, nonlinear optimization of the new mode is very difficult. We have made extensive attempts by means of several methods, such as a step-by-step chromaticity compensation[4], resonance approach[5] and Frequency Map Analysis[6], to finally get an acceptable nonlinear solution. The sextupole strengths of the solution are listed in Table 2, where the chromaticities are compensated to zero for both the transverse planes. Fig. 2 shows the dynamic apertures of on- and off-momentum particles, which were tracked for 1000 turns by means of the AT code[7]. Fig. 3 shows the dynamic aperture and frequency map for on-momentum particles. The interior of the dynamic aperture is free of nonlinear resonances, which is beneficial for injection. These results show that there are ample dynamic acceptances for long beam lifetime and efficient injection, and that

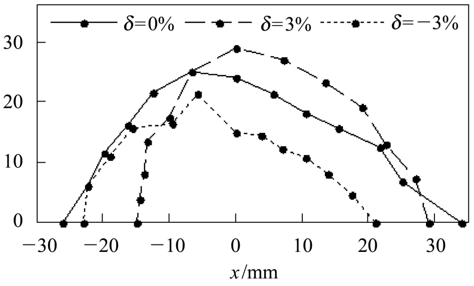

Fig. 2. Dynamic apertures of on- and off-momentum particle.

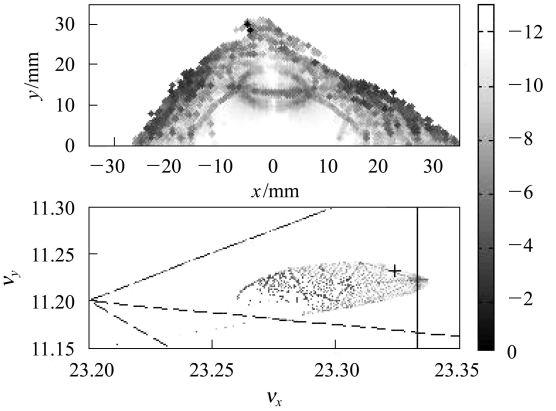

Fig. 3. Frequency map and dynamic aperture of an on-momentum particle.

operating a realistic machine under this new mode is possible.

4 First commissioning

4.1 Summary of the SSRF storage ring commissioning

Commissioning of the SSRF storage ring for a beam energy of 3.0 GeV was started at the end of December 2007. The first turn and the multi-turn were observed in BPMs, when scanning the correctors. After the sextupoles and RF cavity were switched on, beam storage was achieved by a careful balance between the RF frequency and the bending field. By means of gradually increasing the sextupole strengths, appropriate closed orbit correction, and injection optimization, the beam lifetime was improved, and the beam accumulated to 5 mA quickly. After building protect systems on closed orbit interlock and temperature interlock, a beam with 100 mA current was obtained successfully at 20:19 on January 3 2008. From then on, machine physics studies were extensively carried out.

The BPM offsets were measured precisely with the application of BBA[8]. The closed orbit deviation in both transverse planes could be corrected to 50 μm (rms) based on Single Value Decomposition (SVD)[9]. The magnetic coefficients from the magnetic field to the excited current were calibrated by Linear Optics with the Closed Orbit (LOCO) technique[10] fitting family-by-family. When the optics was switched to the new mode, similar results and correctional levels were easily reproduced. This shows that machine corrections are available, and that we can easily control the operation mode of the SSRF storage ring. When the chromaticities are corrected to +3 or so by the chromatic sextupoles, an injection rate of about 0.4 mA/s and a beam lifetime of 10—20 h (varying due to different coupling) of the 100 mA beam current could be obtained easily.

4.2 Restoration of the linear optics

The magnetic excited currents resulting from Table 2 are set in the machine. The measured tuning is about 23.39 and 11.22 for the horizontal and vertical plane, respectively. The linear optics, characterized by LOCO, is shown in the left set of drawings in Fig. 4. These results show that there is still some aberration between the designed mode and the realistic machine mode, like the nominal mode. The β beatings all over the ring are within ±15% for both transverse planes. With the LOCO fitting magnet-by-magnet, restoration of the linear optics is achieved, as shown on the right side of Fig. 4. A good period and symmetry of the optical functions is found for those having the largest β function beatings of ±1% with respect to the designed theoretic mode for both two transverse planes. The determined horizontal and vertical tuning is 23.320 and 11.227, very close to the designed values.

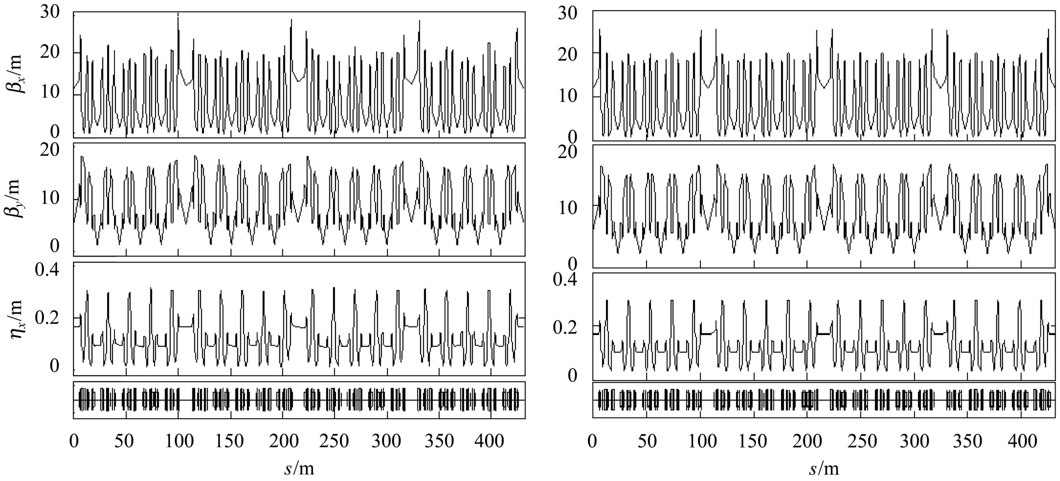

Fig. 4. Linear optical functions determined by LOCO before (left figures) and after (right figures) optics corrections.

Table 3. Parameter comparison between the designed mode, the LOCO model and direct measurements.

parameter	designed mode	LOCO model	direct measurement
tune Q_x, Q_y	23.324, 11.232	23.320,11.227	23.320, 11.229
natural chromaticity ξ_x, ξ_y	−64.4, −19.9	−64.4, −19.9	−60.2, −18.7
natural emittance/(nm·rad)	2.47	2.47	2.49
linear coupling		0.3%	0.5%

4.3 Parameter measurements

Some physics studies were done after linear optics restoration of the new mode, such as the response matrix, working point, natural chromaticity, emittance and coupling. The results, summarized in Table 3, show excellent agreement with the designed values and the model characterized by LOCO. The integer parts of the working point are recorded by the response matrix and shown in Fig. 5. The fractional parts are extracted from turn-by-turn positions of the beam in BPMs, when exciting the beam with an injection kicker and a stripline. Natural chromaticities are measured from tune shifts as a function of the bending field. The natural emittance is calculated from the beam sizes of the bending magnet. Linear betatron coupling is determined by the closest tune approach.

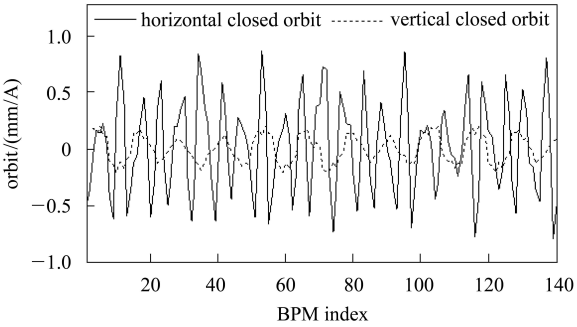

Fig. 5. A volume of the response matrix for accounting for integer parts of the tuning.

5 Conclusions

A new optics mode with lower emittance is designed and successfully commissioned in the SSRF storage ring. After optics restoration with application of the LOCO technique, the main parameters in the realistic machine, such as the working point, natural chromaticities, natural emittance, β functions and dispersion functions, are very close to the designed values. With the low emittance and beam sizes, and acceptable injection rate and beam lifetime during commissioning, the new optics mode is a good choice for operating the SSRF storage ring.

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