Design of the SSRF storage ring magnet lattice

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Abstract The Shanghai Synchrotron Radiation Facility (SSRF) is a proposed 3rd generation light source with 3.5 GeV in energy. It is composed of 20 DBA cells resulting in a ring that is about 10 nm·rad in emittance and 396 m in circumference, and provides 10 straight sections of 7.24 m and other 10 straight sections of 5.0 m for the inclusion of insertion devices, injection components and RF cavities. The lattice has high flexibility, and the tunes and beta functions can be easily adjusted within a wide range to meet the requirements for different operation modes, including high beta mode and hybrid beta mode with and/or without dispersion in straight sections. In this paper, the results of linear optics design and dynamic aperture study are presented.

Keywords Synchrotron radiation light source, Electron storage ring, Magnet lattice

CLC numbers TL503, TL594

1 Introduction

The SSRF was proposed by the Chinese Academy of Sciences and the Shanghai Municipal Government in 1995, and is under design and R&D.[1] According to the user's requirements, it should be able to provide high brightness and high flux X-ray photon beams in energy from 0.1 to 40 keV. To meet this goal, the energy of SSRF has been chosen to be 3.5 GeV. The SSRF accelerator complex consists of a 300 MeV linac, a 3.5 GeV booster and a 3.5 GeV storage ring.

The 3.5 GeV storage ring is the principal component of the SSRF. Its design should be optimised to satisfy the following conditions:

1) Circumference is less than 400 m,
2) Emittance is around 10 nm·rad,
3) Beam current is 200~300 mA for multi-bunch mode and 5 mA for single-bunch mode,
4) Beam lifetime is longer than 20 h,
5) Beam position stability is about 10% beam size at photon source points.

In the following, design of the linear optics and studies of the dynamic aperture are reviewed.

2 Linear optics design

The performance of a light source, such as the SSRF, is determined primarily by the design of the storage ring magnet lattice.[2] To meet the design goals, extensive studies have been carried out. Several possible lattices, such as the Double-Bend-Achromatic (DBA) structure[3] and the Triple-Bend-Achromatic (TBA) structure,[4] have been studied. As it can achieve the design goals and has a large number of straight sections for the inclusion of insertion devices, a DBA lattice has been chosen to be the basic structure of the SSRF storage ring. The storage ring consists of 20 DBA cells. Each DBA cell contains 2 dipoles, 10 quadrupoles and 7 sextupoles.

The initial design[1,2] of DBA lattice was referred to the high- beta lattice type, with high β_x(15 m) in the middle of all straight sections and the circumference of the storage ring being 384 m. To obtain high flux density, low β_x in some of the straight sections is required. Therefore the storage ring magnet lattice has been adjusted to be able to operate both in high-beta mode with high β_x in all straight sections and in hybrid-beta mode with high β_x in 10 straight sections and low β_x in other 10 straight sections. To match the hybrid-beta mode, the focusing quadrupole in the quadrupole triplet at both ends of the straight sections should be lengthened. And then, the circumference of the storage ring has been increased to 396 m. The present DBA lattice provides 10 straight sections of 7.24 m and other 10 straight sections of 5.0 m for the

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inclusion of insertion devices, injection components and RF cavities. Fig.1 shows the layout of one DBA cell, and Table 1 lists the major parameters of the storage ring.

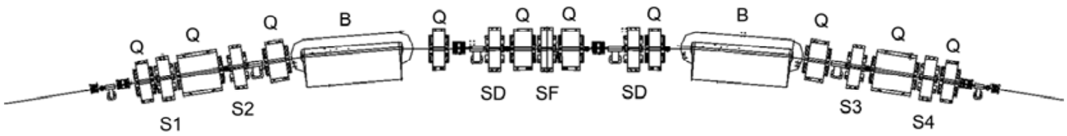

Fig.1 Layout of one DBA cell of the storage ring.

Table 1 Major parameters of the storage ring

Operation energy E (GeV)	3.5
Number of cells N_C	20
Circumference C (m)	396
Straight length (m):	
Long straight × number	7.24×10
Short straight × number	5.0×10
Beam current I(mA):	
Multi-bunch	200~300
Single-bunch	5
Injection energy E_I (GeV)	3.5
Natural emittance ε_{x0} (nm· rad)	5~12
Lifetime (h)	>20
Harmonic number	660
RF frequency (MHz)	599.654
RF voltage (MV)	4.0
Single turn loss U_0 (MeV)	1.256
Natural energy spread σ_E	9.23×10^{-4}
Damping time $\tau_x/\tau_y/\tau_s$ (ms)	7.35/7.36/3.68

The new DBA lattice of the SSRF 3.5 GeV storage ring has high flexibility. The tunes and beta functions in middle of straight sections can be easily adjusted within wide range to meet the requirements of many operation modes. Four different operation modes of the storage ring, including high-beta mode with or without dispersion in straight sections and hybrid-beta mode with or without dispersion in straight sections, have been studied. The main lattice parameters for different operation modes are given in Table 2.

In the following, we report the design results in detail for the hybrid beta mode with non-zero dispersion in straight sections. The horizontal beta functions are 12 m in the middle of long straight sections and 0.8 m in the middle of short straight sections. The storage ring tunes Q_x=22.19 and Q_y=8.23 have been chosen to get low emittance, to avoid strong resonances in the working diagram and obtain large dynamic aperture, and to provide an efficient horizontal tune for injection. Here, the dispersion is distributed in straight sections to achieve lower emittance. The resulting structure has a natural horizontal emittance ε_{x0}=5.8 nm·rad and lattice functions shown in Fig.2.

Table 2 Summary of main parameters for different modes

Operation mode	Hybrid beta	Hybrid beta	High beta	High beta
Emittance (nm· rad)	11.8	5.8	12.1	4.8
Betatron tune Q_x/Q_y	22.19/8.23	22.19/8.23	18.81/8.77	18.81/8.77
Momentum compaction (×10^{-4})	6.9	4.9	6.9	7.7
Natural chromaticity ξ_x/ξ_y	52.8/24.3	52.8/24.4	44.2/23.0	41.2/23.1
Dispersion in long straights η_x(m)	0.0	0.15	0.0	0.20
Dispersion in short straights η_x(m)	0.0	0.06	0.0	0.18
Beta functions in long straights β_x(m) /β_y(m)	12.0/3.5	12.0/3.5	12.0/3.5	12.0/3.5
Beta functions in short straights β_x(m) /β_y(m)	0.9/3.5	0.8/3.5	12.0/2.5	9.0/2.5

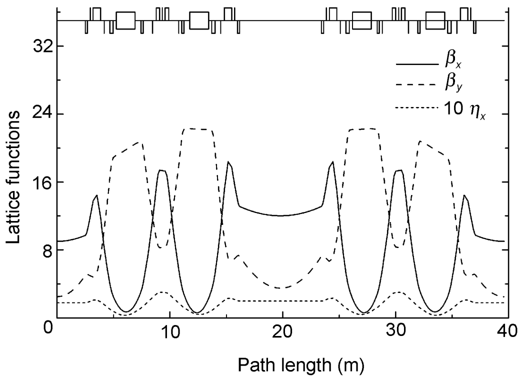

Fig.2 Lattice functions through two cells of dispersion- distributed hybrid-beta mode.

3 Dynamic aperture

For high injection efficiency and long beam lifetime, the storage ring must have large enough dynamic aperture. The dynamic aperture is determined by the nonlinear magnetic fields such as sextupoles, magnet errors, and insertion devices.

In the SSRF magnet lattice, there are 7 sextupoles in each DBA cell (see in Fig.1). Three of them (SDs and SF) are located in the arc between two bending magnets, and the others (S1, S2, S3, and S4) are equipped in the quadrupole triplets at both ends of the straight sections. For the normal operation mode with dispersion-free straight sections, SDs and SF are used for chromaticity correction to combat the head-tail instability, and the others are employed for harmonic correction to enlarge the dynamic aperture. For the low-emittance operation mode with dispersion-distributed straight sections, all sextupoles are used together for chromaticity correction and harmonic correction. Extensive studies on optimisation of the location and strength of the sextupoles for different operation modes have been carried out. It was found that the magnet lattice with asymmetry arrangement of the defocusing sextupoles SDs in the arc (see in Fig.1) has large enough dynamic aperture and momentum acceptance for both high beta mode and hybrid beta mode, and is easy to arrange the septa and kickers for injection.

Fig.3 shows the dynamic aperture in the middle of long straight section for the dispersion-distributed hybrid beta mode without errors. The tune variations versus horizontal and vertical amplitude of betatron oscillations with 1% coupling are shown in Fig.4. And the dependence of the tunes upon momentum deviation is given in Fig.5. From these figures, one can see that the horizontal on-momentum dynamic aperture in the middle of long straight section reaches 35 mm and the energy acceptance is larger than 3%. It indicates that the dynamics of the present magnet lattice without errors are good enough.

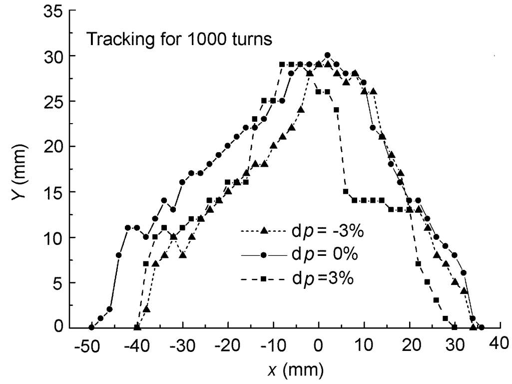

Fig.3 Dynamic aperture in the middle of long straight section for dispersion-distributed hybrid mode.

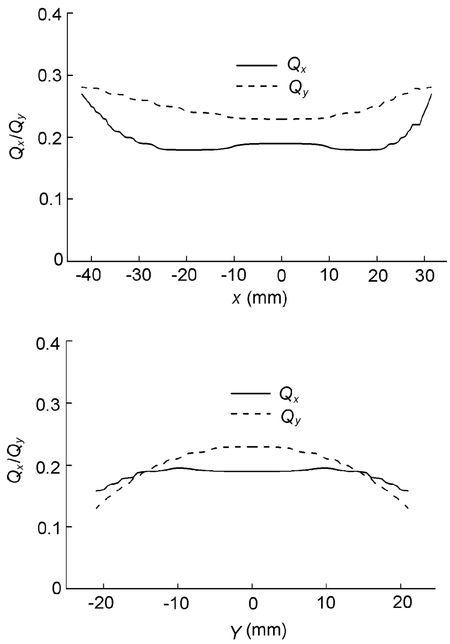

Fig.4 Dependence of tune upon horizontal and vertical amplitude for dispersion-distributed hybrid mode.

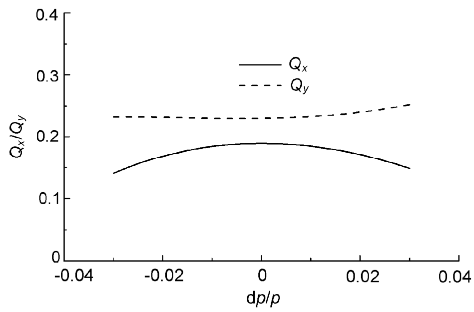

Fig.5 Momentum-dependent tune variation for dispersion-distributed hybrid mode.

The effects of systematic multipole errors and random multipole errors of magnets have been also studied. Fig.6 shows that the on-momentum horizontal dynamic aperture is larger than ±20mm in the presence of magnet multipole errors. Fig.6 also indicates that the reduction in the dynamic aperture with ±3% energy oscillation is smaller than 20%.

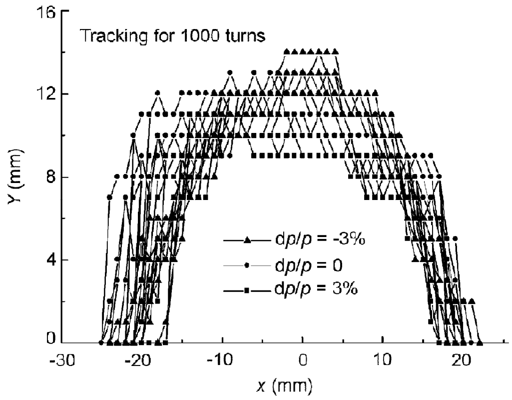

Fig.6 Dynamic aperture in long straight sections of dispersion-distributed hybrid mode with magnet errors.

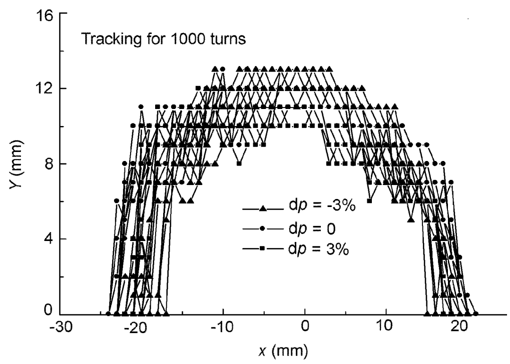

Fig.7 Dynamic aperture with magnet errors and 10 IDs.

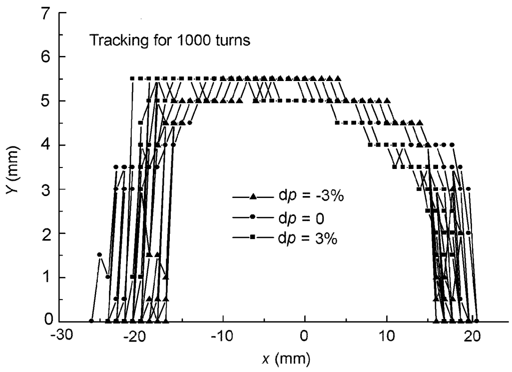

Fig.8 Dynamic aperture with magnet errors, IDs and 12mm ID vertical aperture limit.

The effects of insertion devices (IDs) on dynamic aperture in the storage ring have also been studied. Fig.7 shows the dynamic aperture in the middle of long straight section with magnet errors and 10 IDs. And Fig.8 gives the dynamic aperture with magnet errors, 10 IDs and 12 mm vertical ID aperture limit. It can be seen from Fig.6, Fig.7 and Fig.8 that the magnet multipole errors dominate the ring dynamic aperture, and the on-momentum horizontal dynamic aperture is larger than ±20 mm in the presence of magnet multipole errors and IDs. The ±20 mm aperture allows efficient capture of the booster beam injected with 15 mm displacement. These figures also indicate that the reduction in the dynamic aperture with ±3% energy oscillation is smaller than 25%. Such off-momentum dynamic apertures are large enough for long beam lifetime consideration. From these figures, one can also find that the dynamic aperture with magnet multipole errors and IDs is larger than the vertical ID aperture limit. It turns out that the dynamics of the SSRF storage ring is good enough.

4 Conclusion

It has been shown that the DBA lattice of the 3.5 GeV storage ring has high flexibility, and the tunes and beta functions can be easily adjusted within a wide range to meet the requirements of different operation modes, including high beta mode and hybrid beta mode. Tracking studies turn out that even in the presence of conservative magnetic multipole errors and insertion devices the dynamic aperture and momentum acceptance of the storage ring are adequate for injection and beam lifetime considerations.

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