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Magnet lattice design of the SSRF electron-beam transfer lines

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Abstract Under three-dimensional plane geometrical constraints (X, Y, θ), with two asymmetric achromatic sections, the combined three-section structural FODO-like magnet lattice design is adopted and finely optimized in the SSRF electron-beam transfer lines. The magnet lattice has high flexibility and robustness, and the Courant–Snyder parameters can be easily adjusted within a wide range to meet the requirements of transmission and injection for different operation modes of the linear accelerator, booster synchrotron, and storage ring. In this article, the main parameters of the linear optics design of the SSRF electron-beam transfer lines are described, involving the physical design criteria, the total geometrical layout, the magnet lattice, and the beam Courant–Snyder parameters matching. The studies of the variant beam dynamic simulation program calculations show that the design purpose of the efficient beam transmission and injection will be basically achieved.

Key words SSRF, Transfer line, Geometrical layout, Magnet lattice, Beam matching

CLC number TL501^{+}.5, TL503.7

1 Introduction

The Shanghai Synchrotron Radiation Facility[1] (SSRF), as one of the national important scientific projects, is a third-generation intermediate energy, low-emittance and high-brightness light source under construction. The SSRF accelerator complex consists of a 150 MeV pre-injector (linear accelerator), a 3.5 GeV full-energy injector[2] (booster synchrotron and beam transfer lines), a 3.5 GeV storage ring[3,4] and a series of synchrotron radiation beam lines and experimental stations. The injector of SSRF involves two electron beam transfer lines; the first from the linear accelerator to the booster is called the low-energy transfer line (LT), and the second from the booster to the storage ring is called the high-energy transfer line (HT). The LT is designed to transfer the 150 MeV electron beam from the extraction point of the linear accelerator to the injection system of the booster, while the HT is designed to transfer the 3.5 GeV electron beam from the extraction system of the booster to the injection system of the storage ring.

Unlike circular accelerators, the beam transfer line principally provides a physical connection from one machine to the next machine. As it is a single pass system, in particular it should not be a bottleneck of the whole accelerator complex. To meet the main design goal of the efficient beam transmission and injection, correlative engineering constraint requirements for the magnet lattice design of the beam transfer line must be satisfied. Moreover, the physical considerations and the rational lattice design should be made to simplify the construction and maintenance, so as to reduce the cost of production and operation.

2 Design criteria

The beam transfer line should be arranged according to the concrete locations of the linear accel-

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erator, the booster synchrotron and storage ring, the three-dimensional geometrical constraints (X, Y, θ), and the total bend angle that should be considered to combine the extraction point to the injection point of the next accelerator. Furthermore, Courant–Snyder parameters of the electron beam, which are determined by the physical design of the magnet lattice of the beam transfer lines, must satisfy the joint matching of the beam's energy dispersion function and the transverse phase space from one machine to the next. Without vertical bending, the SSRF accelerator complex is at the same horizontal level, and thus the beam parameters matching is six dimensional with regard to β_x, β_y, α_x, α_y, η_x, and $\eta_{x'}$. Because the beam makes just one pass through a transfer line, the requirements on beam losses are relatively relaxed, but the beam acceptances must be defined particularly by the machines on both sides of the transfer line. To realize efficient beam transmission and injection, flexible adjustment is also necessary to match the beam parameters for different operational modes of the linear accelerator, the booster, and the storage ring.

In addition, the general physical design of LT and HT should be optimized to satisfy the following criteria:

1) simple and robust;
2) reliable and easy to operate;
3) conservative and generous;
4) efficient and economical.

3 Geometrical layout

In practice, the local layout design of LT and HT should be decided by the particular positions of the linear accelerator, the booster synchrotron, and the storage ring within the main building arrangement of SSRF. Fig.1 shows the schematic layout of the injector.

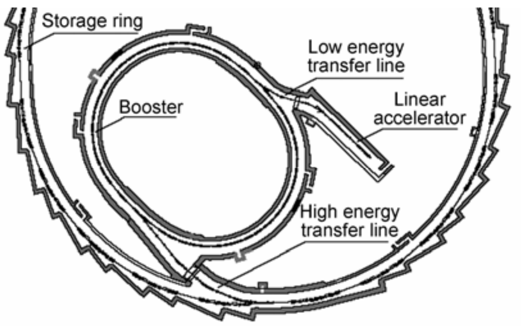

Fig.1 Schematic layout of the injector.

As the linear accelerator, booster, and storage ring will be installed in independent tunnels, there will be drift spaces of suitable lengths and appropriate positions to isolate the tunnels with shielding walls. The total lengths of LT and HT are designed to be about 21.18 m and 50.32 m, respectively, and their total bending angles are 0.00 mrad and 830.86 mrad, respectively. On the other hand, the geometrical layouts of LT and HT must ensure adequate drift spaces for positioning diagnostic components and the correction magnets.

In view of the above-mentioned principles, the LT is chosen to be of a combined three-sectional structure. In the first section, which is 5.20 m long, the beam is bent twice 261.80 mrad by the analysis magnet LA:B-1 at the extraction of the linear accelerator and by the dipole magnet LTB-1. Downstream, the second section is a straight section of 7.45 m length, where the shield wall of the linear accelerator bunker passes through. Finally, in the third section of 8.53 m length, the beam is bent –261.80 mrad by the dipole magnet LTB-2. After LTB-2, the beam goes into the booster single-turn and on-axis injection system, and is then deflected –244.60 mrad by the septum magnet SI. After a drift space and the quadrupole magnet QD, the beam is bent –7.93 mrad because of the beam trajectory deviation 22.94 mm from the magnetic center of the quadrupole magnet QD. The beam then goes forward to cross the booster axis at the center of the injection fast kicker magnet by an intersect angle. At this moment, the beam is kicked onto the booster reference orbit by –9.27mrad.

Similarly, the HT has to precisely connect the points where the electron beam leaves the booster extraction septum and where it enters the storage ring injection septum. To ensure that the three-dimensional geometrical matching is accurate, the MAD program[5] is used to provide the engineering survey coordinates. Moreover, a technical service gallery should be provided in the HT domain: a person should be able to cross the HT by bending down once under a section of free beampipe to walk separately around the tunnels of the booster and the storage ring. The HT is also functionally divided into three sections. The first section is about 20.12 m long from the front edge of the second extraction septum magnet BS:SE2 of the booster to the first dipole magnet HTB-1, the beam is bent

61.13 mrad by the septum magnets BS:SE2, BS:SE3, and the dipole magnet HTB-1 at this section. Downstream, the second section is 8.13 m long, being a straight section without dipole magnets, through which the shield wall of the storage ring tunnel passes. Finally, the third section is about 22.07 m long, where the beam is bent 659.73 mrad by the dipole magnets HTB-2, HTB-3, HTB-4, and HTB-5, and the placement of the last bending magnet is dictated by the need to stay at a considerable distance from the storage-ring reference orbit by avoiding conflict with the injection septum magnets. Eventually, the electron beam passes through the multiple turns of storage ring and the off-axis injection system and is deflected 110.00 mrad by the injection septum magnets SR:SI1 and SR:SI2 and then arrives at the injection point of the storage ring.

4 Magnet lattice

According to the theory of accelerator physics, six quadrupole magnets at adequate locations are necessary and sufficient to perform the six-dimensional Courant–Snyder parameters matching in the transfer lines. However, more quadrupole magnets are added to allow more variations of the linear optical solutions, and then with two asymmetric achromatic sections, the combined three-section structural FODO-like magnet lattice design is adopted and finely optimized in two electron beam transfer lines. The magnet lattice has high flexibility and robustness, and the Courant–Snyder parameters can be easily adjusted within a wide range to meet the requirements of transmission and injection for the different operation modes of the linear accelerator, the booster synchrotron and the storage ring.

Functionally, both LT and HT are made up of matching sections of three different beam parameters , and all quadrupole magnets are powered individually to allow the fine-tuning of the transverse-phase space parameters.

In LT, the first achromatic section is composed of the analysis magnet LA:B-1, the dipole magnet LTB-1, and three quadrupole magnets LTQ-01, LTQ-02, and LTQ-03. These three quadrupole magnets provide the required magnetic field, not only to restrict the horizontal and vertical beam envelopes, but also to match the energy dispersion function to zero at the exit of the dipole magnet LTB-1. The second nondispersive straight section is composed of four quadrupole magnets LTQ-04, LTQ-05, LTQ-06, and LTQ-07. These four quadrupole magnets provide the required magnetic field, which is independent of the energy dispersion function in an ideal situation, and thus can be used to adjust the beam envelope independently, without affecting the optics functions in the downstream when the matching conditions are changed; also, it is convenient to match the beam envelope at the booster injection point. The third achromatic section is composed of the dipole magnet LTB-2 and four quadrupole magnets LTQ-08, LTQ-09, LTQ-10, and LTQ-11. The final transverse-phase space matching at the booster injection point is performed by the above four quadrupole magnets together with the septum magnet BS:KI. Fig. 2 shows the magnet lattice of LT.

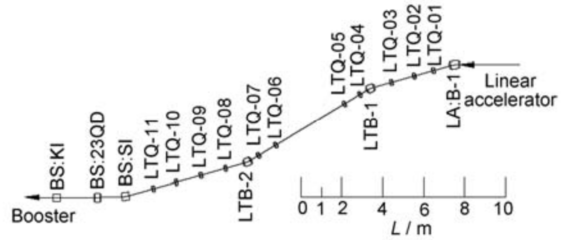

Fig.2 The magnet lattice of LT.

Similarly, the first achromatic section in HT is composed of the dipole magnet HTB-1 and five quadrupole magnets HTQ-01, HTQ-02, HTQ-03, HTQ-04, and HTQ-05. The second nondispersive straight section is composed of four quadrupole magnets HTQ-06, HTQ-07, HTQ-08, and HTQ-09. The third achromatic section is composed of four dipole magnets HTB-2, HTB-3, HTB-4, and HTB-5, and five quadrupole magnets HTQ-10, HTQ-11, HTQ-12, HTQ-13, and HTQ-14. The final transverse phase space and energy dispersion matching at the storage-ring injection point is optimized by the above five quadrupole magnets together with the injection septum magnets SR:SI1 and SR:SI2. Fig.3 shows the magnet lattice of HT.

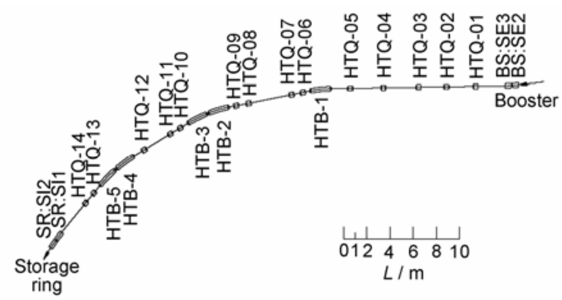

Fig.3 The magnet lattice of HT.

5 Beam matching

The six-dimensional Courant–Snyder parameters matching and optimization of LT and HT are performed with the beam dynamic simulation calculation program TRANSPORT[6], which adopts the first-order linear optics optimization design mode. In the process of beam parameters fitting, the second-order aberrations of the Taylor expansions have also been examined and are found to be negligible.

Furthermore, to minimize the beam loss along the transfer lines, the beta functions and the dispersion functions must not become very high, and thus the limits of both horizontal and vertical beta functions of not more than 20 m and 30 m are set in LT and HT, respectively, and the horizontal dispersion function is set below 1.0 m and 2.0 m, respectively. To reduce the complexity and cost involved in the manufacture of the quadruple magnets, the focusing intensity is controlled under $\pm 10\ \mathrm{m}^{-2}$ of 0.1 m magnet length and $\pm 1.6\ \mathrm{m}^{-2}$ of 0.4 m magnet length in LT and HT, respectively. Hence, the concrete positions and magnetic field gradients of the quadruple magnets had to be adjusted and optimized finely within these strict physical restrictions on LT and HT.

To realize the more effective beam matching and mismatching injection, the more flexible operating mode of LT is required. According to the calculation of the PARMELA[7] program, the design specification of the linear accelerator indicates that the electron energy is 150 MeV, the natural emittance is 1.00 mm·mrad, and the momentum deviation is 5.00‰. Table 1 lists the nominal initial beam parameters at the linear accelerator exit.

Table1 Beam parameters at the linear accelerator exit

β_x/m	α_x	β_y/m	α_y	η_x/m	$\eta_{x'}$
9.00	0.00	9.00	0.00	0.00	0.00

Besides the nominal betas as listed in Table 1, the high flexibility of LT also allows beam matching with the booster for rather different initial conditions, similar to a wide, divergent beam of $\beta_x = \beta_y = 12$ m and $\alpha_x = \alpha_y = +0.5$ (large betas) or a narrow focused beam of $\beta_x = \beta_y = 6$ m and $\alpha_x = \alpha_y = -0.5$ (small betas).

The final injection beam parameters are given by the periodic solution of the booster optics. There can be some variations depending on the tuning of the booster (achromatic mode and nonachromatic mode), but the range is not extensive. Table 2 lists the nominal beam parameters of the booster injection.

Table2 Beam parameters of the booster injection

β_x/m	α_x	β_y/m	α_y	η_x/m	$\eta_{x'}$
1.59	0.39	12.43	–2.39	0.00	0.00

Figs.4 and 5 show the nominal beta function and eta function along LT, respectively.

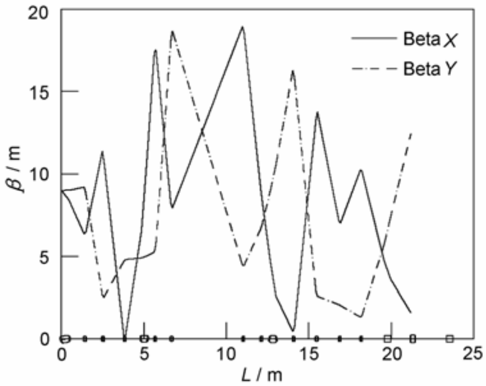

Fig.4 The nominal beta-function along LT.

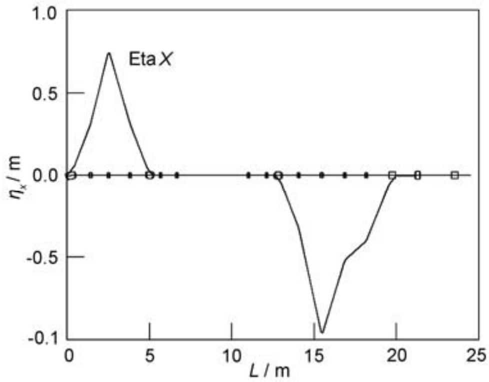

Fig.5 The nominal eta-function along LT.

Similarly, the initial extraction beam parameters in HT are obtained from the booster periodic solution, but the range of variation is less. The achromatic mode can be basically distinguished from the nonachromatic mode of the booster operation: the electron energy is 3.5 GeV, the natural emittance is 0.10 mm·mrad, and the momentum deviation is 1.00‰. Table 3 lists the nominal initial beam parameters of the booster extraction.

Table 3 Beam parameters of the booster extraction

β_x/m	α_x	β_y/m	α_y	η_x/m	$\eta_{x'}$
2.01	–0.67	10.65	2.18	–0.03	–0.01

The final injection-beam parameters at the storage ring may also vary according to the mode of operation. Here, the DII mode with zero dispersion straight section is distinguished from the DI, DIII, and DIV modes with dispersion straight sections for reduced emittance: the matching range of the beam parameters β_x and β_y at the storage-ring injection point are 2.50~12.00 m and 5.00~8.00 m, respectively; α_x and α_y are –0.15 and –0.25, respectively; and η_x and $\eta_{x'}$ are 0.00~0.15 m and 0.00, respectively. Table 4 lists the nominal beam parameters of the storage-ring injection.

Table 4 Beam parameters of the storage-ring injection

β_x/m	α_x	β_y/m	α_y	η_x/m	$\eta_{x'}$
2.75	–0.15	6.00	–0.25	0.15	0.00

Figs.6 and 7 show the nominal beta function and the eta function along HT, respectively.

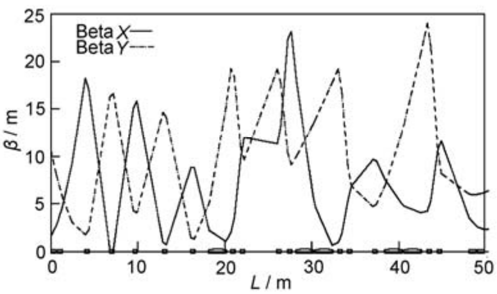

Fig.6 The nominal beta-function along HT.

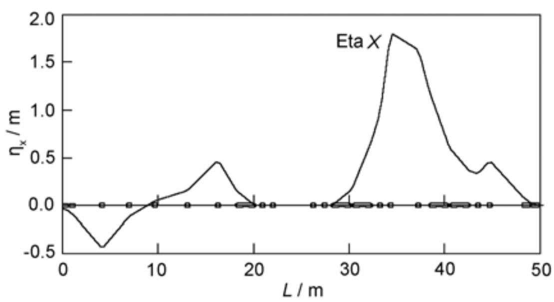

Fig.7 The nominal eta-function along HT.

6 Conclusions

On the basis of the detailed investigations on similar domestic and foreign synchrotron radiation light sources and the various beam dynamic simulation program calculations, the magnet lattice design of the SSRF low- and high-energy transfer lines has been basically determined. Furthermore, the main factors that influence the transmission efficiency of the electron-beam transfer lines have been taken into consideration, involving the physical requirements for the vacuum system, the beam diagnostic system, the trajectory correction system, and the magnet manufacture and installation tolerance. The numerical dynamic simulations for the different electron number cases show that the 150 MeV and 3.5 GeV electron-beam transmission efficiency at the matching conditions of the various beam parameters attain almost 100%[8], and thus completely meet the magnet lattice design specifications of LT and HT. Thus, in the project construction of SSRF, with rational technical requirements and strict quality control, the physical design purpose of beam transmission and injection with high efficiency of the low- and high-energy transfer lines will be achieved.

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References

1 Shanghai Synchrotron Radiation Facility (SSRF) conceptual design report, November 2004. **3**: 74-78

2 Li D M. The new scheme of SSRF injector, APAC 2004, TUP-14018.

3 Dai Z M, Liu G M, Huang N. Nucl Sci Tech, 2003, **14**(2): 89

4 Dai Z M, Liu G M, Huang N. Nucl Sci Tech, 2003, **14**(3): 157

5 Owen H L. SRD Accelerator Physics Group. CLRC Daresbury Laboratory. United Kingdom. MAD. Version 8.23DL. July 2000.

6 Carey D C. Fermi National Accelerator Laboratory. Batavia, Illinois. Brown K L, Rothacker F. Stanford Linear Accelerator Center. Stanford, California. TRANSPORT. October 1998.

7 Bob G. Los Alamos National Laboratory. PARMELA. November 2004.

8 Han Y A, Hou J, Liu G M, *et al*. Nucl Sci Tech, 2006, **17**(2): 65.