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Analysis of transmission efficiency of SSRF electron beam transfer lines

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Abstract In this article, the main factors which influence transmission efficiency of the SSRF electron beam transfer lines are described, including physical requirements for magnet system, vacuum system, beam diagnostic system, trajectory correction system, etc. The dynamic simulation calculation and transmission efficiency analysis of the SSRF electron beam transfer lines are presented, and the studies show that the design purpose of efficient beam transmission and injection will be achieved.

Key words SSRF, Transfer line, Dynamic simulation, Transmission efficiency

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

1 Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) [1], 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) [3], a 3.5 GeV storage ring [4,5] and a series of synchrotron radiation beam lines and experimental stations. The injector of SSRF involves two electron-beam transfer lines. The first one is from linear accelerator to booster and is called low-energy transfer line, abbreviated as LT, while the second one is from booster to storage ring and is called high-energy transfer line, abbreviated as HT. The function of LT is to transfer the 150 MeV nominal energy electron beam from the extraction point of linear accelerator to the injection system of booster, and similarly, the function of HT is to transfer the 3.5 GeV energy electron beam from the extraction system of booster to the injection system of storage ring.

Unlike circular accelerator, the beam transfer line principally provides a physical connection from one machine to the next. And being a single pass system, in particular it must not be a bottleneck of the whole accelerator complex. In order to realize efficient beam transmission and injection into the booster and the storage ring, the physics design of electron beam transfer lines should be conservative and generous, and it is necessary to have rational magnet manufacture and installation tolerance, detailed physical acceptance, proper and precise diagnostic components, and rapid and nice trajectory correction.

2 Magnet system

The LT and HT magnet systems include 2 and 5 dipole magnets, 11 and 14 quadrupole magnets, and 8 and 10 correction magnets, respectively. The power

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supplies of magnet systems are all DC. The dipole magnets are powered in series, while the quadrupole magnets are powered independently.

In the beam transfer lines, the magnet manufacture and installation tolerances will cause not only the increase of beam effective envelopment and emittance, but also the variation of matched beam emittance ellipse's form, then reduce the beam transmission efficiency of beam transfer lines. Because the beam central orbit deformation is related to the manufacture and installation tolerance of magnets, and all the tolerances are reckoned to give the beam a kick θ, $\theta = \Delta Bl / B\rho$, where ΔBl is the field tolerance, and $B\rho$ is the rigidity of the electron beam. Then the good field area precision $\Delta B/B$ and magnetic field stability of dipole magnets are chosen to be 1×10^{-3} and 1×10^{-4}, and those of quadrupole magnets are chosen to be 2×10^{-3} and 2×10^{-4}, respectively. Meanwhile according to what is attainable at present and effectiveness of the installation tolerance, we can allocate the installation tolerances as shown in Table 1.

Table 1 Requirements for installation tolerance of magnets

Parameter	Dipole magnet	Quadrupole magnet	Correction magnet
Max ΔX	0.5 mm	0.2 mm	1.0 mm
Max ΔY	0.2 mm	0.2 mm	0.5 mm
Max ΔZ	0.5 mm	1.0 mm	1.0 mm
Max $\Delta\theta_X$	0.5 mrad	0.5 mrad	1.0 mrad
Max $\Delta\theta_Y$	0.5 mrad	0.5 mrad	1.0 mrad
Max $\Delta\theta_Z$	0.2 mrad	0.5 mrad	2.0 mrad

3 Vacuum system

According to the beam transmission dynamics theory, the Beam Stay Clear (BSC) is calculated from the following formula:

$$\mathrm{BSC} = n\sigma + d \tag{1}$$

where σ is standard deviation in Gaussian distribution, usually defined as half width of the beam, d is the beam central orbit deformation, and n is the beam quantum lifetime coefficient which is about 3.0 in LT and HT.

And the horizontal and vertical half width of the beam σ_x and σ_y in LT and HT are expressed as the following equations:

$$\sigma_x = [\beta_x\varepsilon_x + (\Delta p / p)^2 \eta_x{}^2]^{1/2} \tag{2}$$

$$\sigma_y = \left(\beta_y \varepsilon_y\right)^{1/2} \tag{3}$$

where β is the beta function, ε is the natural emittance, $\Delta p / p$ is the momentum deviation and η is the dispersion function.

Assuming that the half aperture of vacuum chamber is R in a beam transfer line, then the physical acceptance ε_m of transfer lines in x and y directions are defined as

$$\varepsilon_{mx} = (R^2{}_x / \beta_x)_{\min} \tag{4}$$

$$\varepsilon_{my} = (R^2{}_y / \beta_y)_{\min} \tag{5}$$

To attain higher beam transmission efficiency, the beam emittance must be less than the physical acceptance of transfer lines, and the form of beam emittance should also be similar to that of physical acceptance.

Then the aperture of vacuum chamber is determined by the beam's cross-section envelope and the beam central orbit deformation. The apertures of the vacuum chambers of LT and HT are 40 and 34 mm, respectively. In LT and HT, the horizontal and vertical half widths of the beam σ_x and σ_y do not exceed 6.5 and 2 mm (downstream from SLIT), and the root-mean-squares (RMS) of beam central orbit deformation related to the manufacture and installation tolerance of magnets do not exceed 4 mm at ordinary condition before beam trajectory correction. Figs. 1 and 2 show the beam envelopes of LT and HT.

The LT and HT are designed in such a way that the thickness of vacuum chamber is 2 mm, and the material used for the beam pipe is SS316L stainless steel. The quadrupole magnets have apertures of 50 and 40 mm, and the Beam Stay Clear is 42 and 34 mm, respectively. The dipole magnets have gaps of 40 and 32 mm, and the Beam Stay Clears in X direction are all 50 mm, and in Y direction are 30 and 24 mm, respectively.

To ensure the sufficient electron beam vacuum lifetime in LT and HT, the operating vacuum pressures of LT and HT are all specified to be lower than 2×10^{-5} Pa.

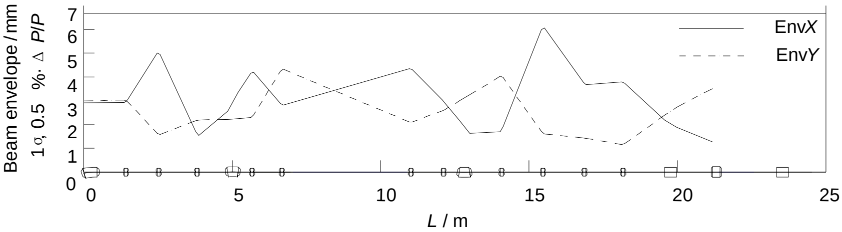

Fig.1 The nominal beam envelope of LT.

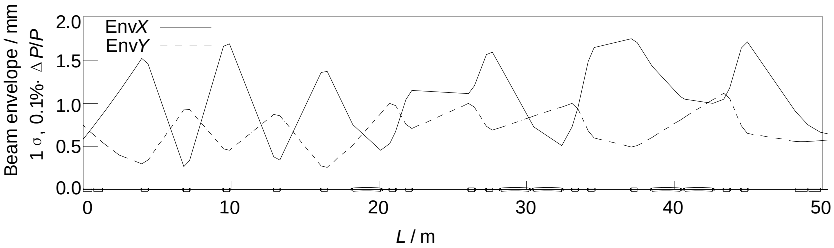

Fig.2 The nominal beam envelope of HT.

4 Diagnostic system

Some diagnostic components are necessary to acquire the beam transmission parameters of LT and HT on line, and testify the characteristics of the beam extracted from linear accelerator and booster. The diagnostic components of LT and HT are designed to ensure easy commission and rapid trajectory correction, and to monitor transmission efficiency. The diagnostic system of LT and HT, respectively, includes three and four fluorescent screen monitors (PROFILE) to measure the transverse profile and spatial position, two and three wall current monitors (WCM) to measure the maximum intensity, three and five beam position monitors (BPM) to measure the beam position. Further, to measure the average current, one bunch charge monitor (BCM) is installed in HT.

In addition, two horizontal momentum limit slits to measure energy spread are placed at downstream of the quadrupole magnets LTQ-01 and HTQ-11 in LT and HT, respectively, where the energy dispersion function is maximum. Two slits, whose momentum spread is below ±0.5% and ±0.1%, are used to allow the electrons to pass through so as to meet the beam matching requirements of the booster and storage ring injection system, and in the meantime to reduce the beam loss along the LT and HT. Furthermore, to raise working efficiency and to improve accelerator interlock protection two beam stoppers are installed at proper positions in LT and HT, respectively. Figs. 3 and 4 show the layout of corrector magnets and beam monitors of LT and HT.

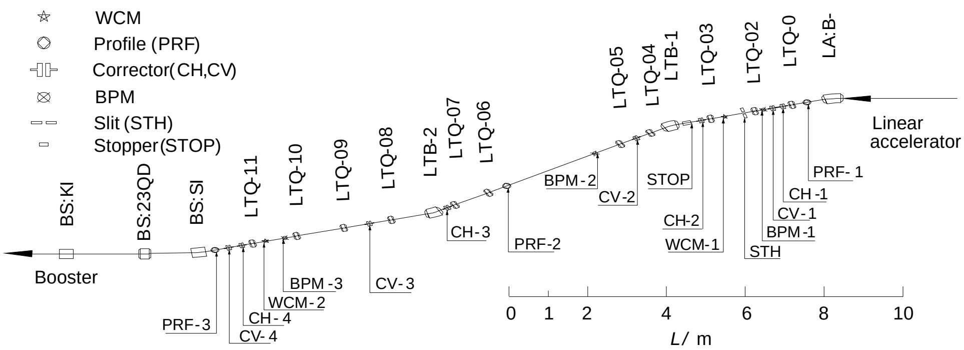

Fig.3 The layout of corrector magnets and beam monitors of LT.

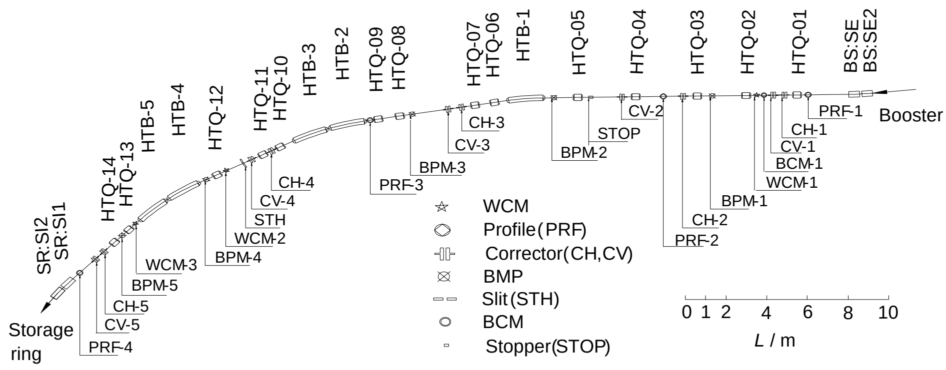

Fig.4 Layout of corrector magnets and beam monitors of HT.

5 Trajectory correction system

In LT and HT, the static beam trajectory correction system, which consists of beam position monitors (BPM) and corrector magnets, is adopted to adjust the beam deflection from central reference orbit, to minimize the static beam trajectory distortion and to maintain the transmission efficiency of LT and HT.

As regards the LT and HT, horizontal (vertical) phase advances are 1.20 (0.80) and 2.00 (1.20), respectively; the beam diagnostics components including 8 corrector magnets (four horizontal and four vertical) and 3 beam position monitors are adopted in LT, and those including 10 corrector magnets (five horizontal and five vertical) and 5 beam position monitors are adopted in HT. Each corrector magnet is placed at about 90° in phase advance from the corresponding BPM. The maximum corrector magnet strength is for a kick of ±2.0 mrad in LT and HT.

The trajectory correction includes the measurement and adjustment of beam trajectory distortion. In LT and HT, the measurement of beam trajectory distortion is taken by BPM, and the trajectory correction is calculated by using the singular value decomposition (SVD) algorithm of least-squares method (LSM). The work fields of corrector magnets are adjusted according to the results of beam orbit response matrix and SVD algorithm. After repeated measurements and corrections, the beam trajectory distortion is minimized ultimately. The SVD dynamic simulation calculation is based on Accelerator Toolbox for MATLAB 6.5 software[6]. Figs. 5 and 6 show the horizontal and vertical distortion before and after trajectory correction of LT, respectively. Figs. 7 and 8 show the horizontal and vertical distortion before and after trajectory correction of HT, respectively.

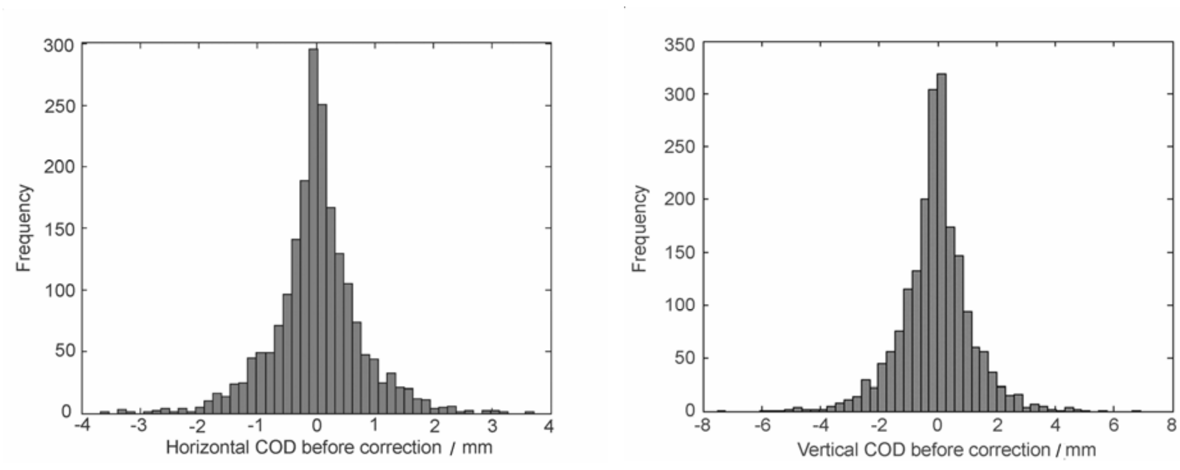

Fig.5 The horizontal and vertical distortion distributions before trajectory correction of LT.

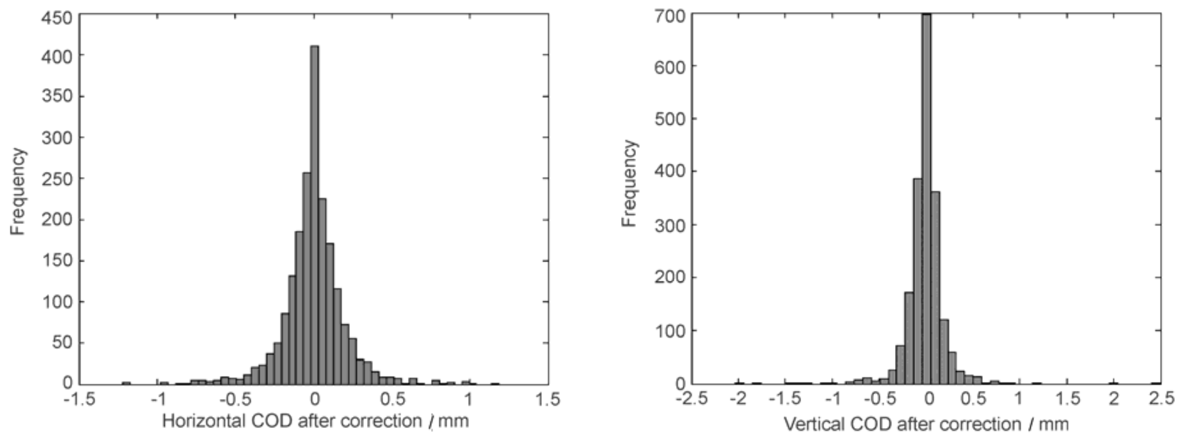

Fig.6 The horizontal and vertical distortion distributions after trajectory correction of LT.

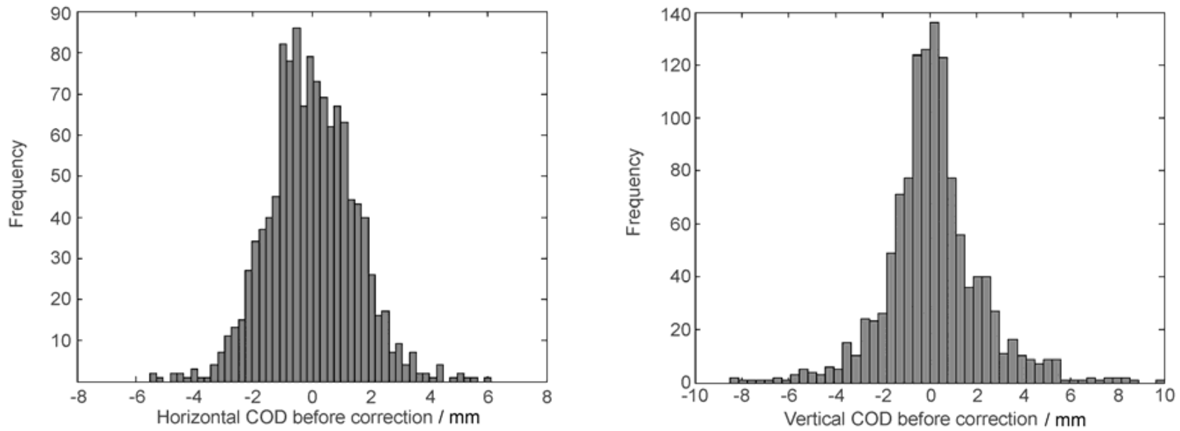

Fig.7 The horizontal and vertical distortion distributions before trajectory correction of HT.

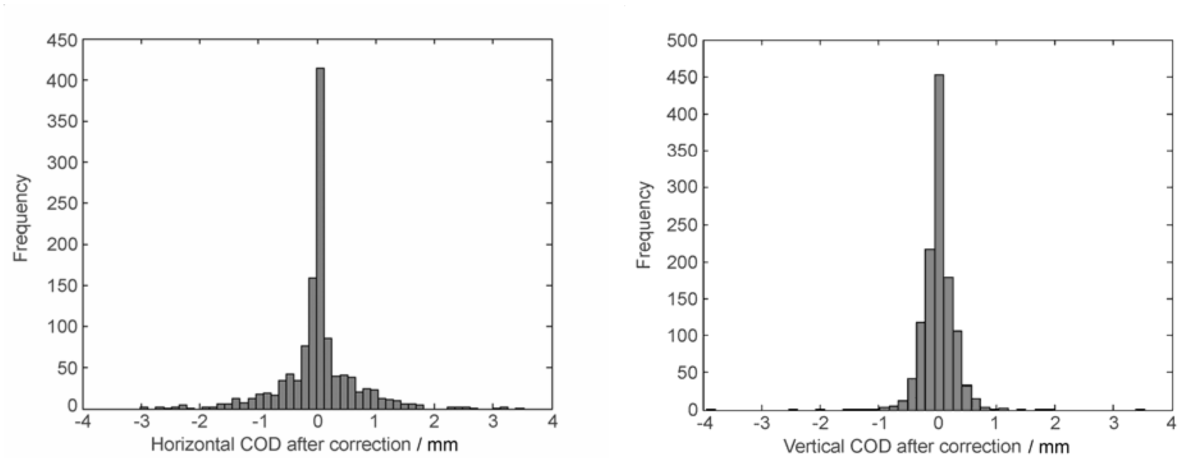

Fig.8 The horizontal and vertical distortion distributions after trajectory correction of HT.

6 Conclusion

The analyses of LT and HT transmission efficiency have been performed by using a computer program, the dynamic simulation code TURTLE[7], which is in determining many characteristics of a particle beam once an initial design has been completed. Charged particle beams are usually designed by adjusting various beam line parameters to obtain desired values of certain elements of a transfer or beam matrix. Such beam line parameters may describe certain magnetic fields and their gradients, lengths and shapes of magnets, spacings between magnetic elements, or the initial beam accepted into the transfer system. According to the initial six-dimensional Courant–Snyder parameters determined by beam matching condition of LT and HT, 5000 electrons are set in two-dimensional Gaussian distribution at the linear accelerator exit and booster extraction system, then the tolerance of manufacture and installation of the magnets, with the central trajectory corrected and energy spread of 5‰ in LT and 1‰ in HT, respectively, is taken into account. The two-dimensional Gaussian distributions of 5000 electrons at exit cross-section of LT and HT, are shown in Fig. 9, where A denotes 10 electrons, B denotes 11 electrons, C denotes 12 electrons, and so on. Without beam loss along LT and HT, 5000 electrons are transported from the linear accelerator exit and booster extraction system to the injection systems of the booster and storage ring efficiently.

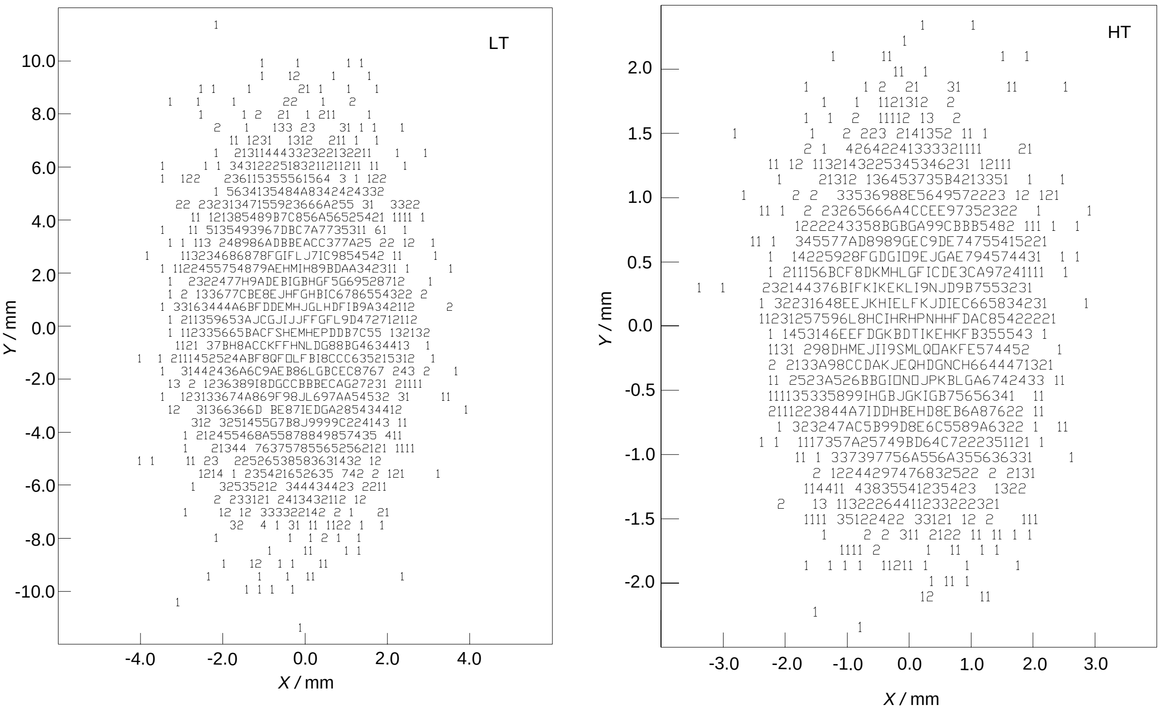

Fig.9 The two-dimensional distribution of 5000 electrons at exit cross-section of LT and HT.

The numerical simulations with the TURTLE program for different electron numbers (from 1000 to 500,000 particles) show that 150 MeV and 3.5 GeV electron beam transmission efficiencies at various beam parameters matching conditions are all above 98%, meeting the magnet lattice design specifications of LT and HT completely. Then, in the project construction of SSRF, with strict quality control and technical requirement, the physics design purpose of beam transmission and injection for the low- and high-energy transfer lines with high efficiency will be achieved.

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