A Beam Switchyard for Parallel Operation of Multiple Beamlines at the SXFEL User Facility

Authors: Si Chen

Date: 2023-02-22T00:00:00+00:00

Abstract

As an important measure for improving the efficiency and usability of X-ray free electron laser facilities, parallel operation of multiple undulator beam lines realized by a beam switchyard has become a standard configuration in recently built XFEL facilities. SXFEL-UF, the first soft X-ray free electron laser user facility in China, has recently completed construction and commissioning. The electron beams from the linac are alternately separated and delivered to two parallel undulator beam lines through a beam switchyard. A stable and fast kicker magnet is used to achieve bunch-by-bunch separation. Optics measures are applied to mitigate the impact of various collective effects, such as coherent synchrotron radiation and micro-bunching instability, on beam quality after passing through the deflection line of the beam switchyard. This study describes the comprehensive physical design of the beam switchyard and presents the latest results of its commissioning process.

Full Text

Preamble

A Beam Switchyard for Parallel Operation of Multiple Beamlines at the SXFEL User Facility

Si Chen,[1],† Kaiqing Zhang,[1] Zheng Qi,[1] Tao Liu,[1] Chao Feng,[1] Haixiao Deng,[1] Bo Liu,[1] and Zhentang Zhao[1],‡

[1]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China

As an important measure for improving the efficiency and usability of X-ray free electron laser facilities, parallel operation of multiple undulator lines realized by a beam switchyard has become a standard configuration in recently built XFEL facilities. SXFEL-UF, the first soft X-ray free electron laser user

facility in China, has recently finished construction and commissioning. The electron beams from the linac are separated and delivered alternately to two parallel undulator beamlines through a beam switchyard. A stable and fast kicker magnet is used to achieve bunch-by-bunch separation. Optics measures are applied to mitigate the impact of various collective effects, such as coherent synchrotron radiation and micro-bunching instability, on the beam quality after passing through the deflection line of the beam switchyard. In this study, the comprehensive physical design of the beam switchyard is described and the latest results of its commissioning process are presented.

Keywords: X-ray free electron laser, beam switchyard, double bend achromat, coherent synchrotron radiation

Introduction

With the rapid development of high-gain Free Electron Laser technology, X-ray Free Electron Laser (XFEL) facilities have emerged as powerful infrastructure that supports various scientific fields including but not limited to bioscience, material science, chemistry, and physics [?]. To meet the growing demand from various users in different scientific communities, several X-ray Free Electron Laser user facilities have been built worldwide, including several hard X-ray FEL facilities [?] and several soft X-ray FEL facilities [?, ?].

XFEL facilities require extremely high-brightness electron beams with not only small transverse emittance but also small energy spread and high peak current. Typically, a high-performance RF linear accelerator is used to provide the high-quality beam for an XFEL facility, and thus its capacity for user beamlines is limited compared with those of storage-ring based synchrotron radiation light sources. The growing number of users and their various photon parameter requirements naturally create a demand for building more user beamlines with different configurations. As compared to the high cost of building a new XFEL facility, a more efficient and economical approach is to improve the beam utilization efficiency by distributing the beam to several separated undulator lines, which is realized by a beam switchyard (sometimes also referred to as the beam distribution system). In recently built XFEL facilities, the beam switchyard is becoming a standard configuration in order to accommodate multiple undulator lines with various X-ray parameters for feeding more beamlines [?, ?]. In such a beam switchyard, electron bunches from the linear accelerator are separated by switching magnets and delivered alternately to each undulator line on a predetermined model, either pulsed or bunch-by-bunch. At the same time, the beam quality should be well maintained during the beam distribution process, especially when the beam current is high, which is usually necessary for high-gain XFEL.

In recent years, several XFEL facilities have been built or proposed in China. The Shanghai soft X-ray FEL (SXFEL) facility, as the first X-ray FEL facility in China, started commissioning in 2021. A high repetition rate hard X-ray FEL facility named SHINE has also started construction. Both facilities are designed to have multiple undulator beamlines. For the SXFEL facility, two undulator lines are driven by a normal conducting RF linac with 50 Hz bunch repetition rate, as described in Section II. A beam switchyard is used between the linac and undulator section for simultaneous operation of the two undulator lines.

In this paper, the physics design and start-to-end simulation results of the beam switchyard, with consideration of suppressing beam collective effects such as coherent synchrotron radiation (CSR) and micro-bunching instability (MBI), are described in Section III. The commissioning results are presented in Section IV, followed by a summary in Section V.

II. The SXFEL Facility

The SXFEL facility aims to open up the enormous field related to XFEL in China and to accumulate indispensable technical experience for constructing and utilizing future hard x-ray FEL facilities. It is developed in phases. First, a test facility (SXFEL-TF) with an 840 MeV linac was built for generation of 8.8 nm fully coherent soft X-ray radiation and technical validation of various seeded FEL mechanisms. In 2020, it achieved its goal with the demonstration of two-stage HGHG-HGHG cascade and two-stage EEHG-HGHG cascade schemes.

Soon afterwards, the SXFEL-TF was upgraded and integrated into the user facility (SXFEL-UF) [?]. It is designed to cover the whole water window range. To accomplish this, the beam energy was upgraded to about 1.5 GeV by adding more C-band RF structures to the linac. Two individual undulator lines are installed in parallel in the newly built undulator hall. Directly downstream of the linac is a brand new SASE-FEL line with radiation wavelength about 2 nm. The existing seeding-FEL line of SXFEL-TF was moved to about 3 m right of the SASE-FEL line with an upgrade of more undulator sections for radiation wavelength about 3 nm. The schematic layout of the SXFEL-UF is shown in Fig. 1 [Figure 1: see original paper]. Some main beam parameters of SXFEL-UF are shown in Table 1 .

For maximizing the operation efficiency of the facility, it is naturally expected that the two undulator lines can provide FEL radiation to multiple users simultaneously. As seen in Fig. 1, for parallel operation of the two FEL lines, a beam switchyard is located between the linac and undulator section. The 50 Hz electron bunch train from the linac is distributed in two directions, either to the SASE-FEL line or to the seeding-FEL line. Because of the high requirements of external seeded FEL, the beam switchyard should be able to guarantee stable, precise transportation of the electron beam with well-maintained beam quality properties, such as low emittance, high peak charge, and short bunch length. In the following sections, the physics design and commissioning results of such a beam switchyard are described in detail.

III. Beam Switchyard Design of SXFEL-UF

A. General Layout

The first step of beam distribution is the separation of bunch trains to different directions. The beam switchyard uses a fast switching kicker magnet with the ability of bunch-by-bunch distribution of the 50 Hz electron bunch train from the linac. It is also designed to be programmable for an arbitrary distribution pattern, which means the bunch frequency of each undulator line can be easily modified based on the requirements of user experiments. When the kicker magnet is triggered on, the electron bunch is deflected horizontally to the seeding-FEL line through a deflection switchyard; otherwise it goes straight to the SASE-FEL line directly downstream of the linac without any deflection.

Since the two FEL lines lie parallel in the undulator hall, the deflection line uses a dog-leg structure to bring the kicked beam to the entrance of the seeding-FEL line. Due to the limitation of longitudinal distance, the total deflection angle of the dog-leg is about 6°. The most immediate effect of the dog-leg is the dispersion function. When an electron bunch with non-zero energy spread passes through a bending magnet, dispersion introduces coupling between the transverse position and the energy of each electron in the bunch so that the electrons spread transversely afterwards. The transverse phase space can be severely destroyed by this effect. In order to cancel the dispersion of the beam distribution dog-leg, its entrance and exit bending magnets are replaced by two identical double-bend-achromat (DBA) sections, respectively.

In such a configuration, both the dispersion element (R16) and the dispersion divergence element (R26) are cancelled locally after each DBA and globally after the whole dog-leg. The dispersion evolution along the dog-leg is shown in Fig. 3 [Figure 3: see original paper] as the dashed lines. Between the two DBA sections, several quadrupoles are inserted for beam matching. The position of the elements is adjusted carefully to avoid conflict between the straight line and the deflected line. The total projected length of the dog-leg is about 39 m. A schematic view of such a dog-leg is shown in Fig. 2 [Figure 2: see original paper].

B. Optics Design for CSR & MBI Suppression

For high-gain XFEL facilities, typically a high peak current, low emittance electron beam is necessary for obtaining higher gain in a shorter gain length. However, when such an intense electron beam passes through the deflection line of the beam switchyard, several kinds of beam collective effects, such as emittance growth induced by coherent synchrotron radiation and micro-bunching instability, may spoil both the transverse and longitudinal phase space of the electron beam and further reduce the performance of the x-ray free electron laser. To avoid this, it is necessary to consider suppression of beam collective effects of intense electron beams passing through the deflection switchyard in the optics design.

Coherent synchrotron radiation (CSR) induced emittance growth is one of the critical beam dynamics issues of the beam distribution dog-leg. When the electron bunch passes through the bending magnet, synchrotron radiation is emitted. If the bunch length is short enough that it is comparable with the radiation spectral components, the synchrotron radiation becomes coherent. CSR from the bunch tail may catch up with the head part and interact with the electrons inside as the bunch goes by. Both the transverse and longitudinal phase space distribution can be changed by this process. In the longitudinal direction, the CSR field introduces an energy modulation along the longitudinal coordinate of the bunch so that the energy spread increases. In the transverse direction, the CSR field mainly acts as a special term of dispersion due to the longitudinal energy variation and thus the emittance in the bending direction grows. The growth of the projected emittance due to the CSR effect can be estimated as: (cid:39) δ,CSR where β is the transverse Twiss function at the bending magnet, is the deflection angle, and $\sigma\delta$,CSR is the CSR induced emittance growth, which is expressed as [**?**]: where re is the electron radius, N is the electron population of the bunch, R is the bending radius, and σz the RMS bunch length.

Eq.1 indicates that it is necessary and possible to suppress or even cancel the CSR induced emittance growth by well-designed beam optics in an achromatic bending structure such as the beam distribution switchyard of SXFEL-UF. According to the proportional relation between the emittance growth and the β function on the bending plane of the bending magnet, the first approach of suppressing the emittance growth is simply by matching the beam envelope at the bending magnet to be a small beam waist. Another approach is by matching the lattice of the switchyard dog-leg to be mirror symmetrical and adjusting the betatron phase advance between the two achromats to be an odd multiple of π, which is the so-called "optics balance" method [**?**]. With this approach, the CSR induced longitudinal dispersion and transverse kick are canceled at the exit of the dog-leg. For the beam distribution switchyard of SXFEL-UF, a lattice design for mitigation of CSR emittance growth is shown in Fig. 3.

Fig. 3 shows the Twiss functions (βx,y) and dispersion functions (x,y) evolution along the dog-leg. The βx at the entrance kicker magnet is optimized to be around 1.6 m so that all the bending magnets have similar values with the symmetrical optics. The maximum values of β and | | are also optimized for a smaller beam stay-clear area. $\sigma\delta$,CSR = 0.2459re 3(cid:112)R2$ $4

Another critical beam dynamics issue of the beam switchyard is micro-bunching instability (MBI). It results from an interplay of various collective effects such as longitudinal space charge (LSC) effect, coherent synchrotron radiation (CSR) in dipole magnets, and the energy-dispersion correlation in magnetic bunch length compressors. An energy modulation is introduced in the beam longitudinal phase space and it is easily converted to a density modulation while passing through a dispersive magnetic optics section with non-zero R56. The amplified density modulation further drives even larger energy and density modulations downstream, thus the beam quality is significantly downgraded. Micro-bunching gain should be well suppressed in the beam switchyard with multi-bend deflection line to guarantee high spectral brilliance, especially at output radiation wavelengths in the EUV and soft x-ray range. For this purpose, a small bending magnet (micro-bend) is inserted in the middle of the DBA cell with a small angle reverse to the DBA deflection angle. With this design, the R56 of each DBA becomes zero. Applying this design to both DBA cells of the switchyard makes it globally isochronous, as shown in Fig. 4. With the isochronous configuration, the deflection line of the beam switchyard is substantially transparent to any incoming modulation induced by micro-bunching instability in the linac.

Fig. 4 shows R56 evolution along the dog-leg. Without micro-bend, the global R56 is over 700 µm, while with the micro-bend, the R56 is eliminated to less than 1 µm, which is negligible for micro-bunching growth.

C. S2E Tracking Results

The start-to-end tracking from the linac end throughout the beam distribution section is performed by the code ELEGANT [**?**]. The longitudinal phase space at the linac exit is shown in Fig. 5 [Figure 5: see original paper]. Two-stage compression brings the 500 pC electron bunch from 10 ps after the injector to less than 0.7 ps at the exit of the linac with a long flat top in the longitudinal phase space, which is necessary for multi-stage energy modulation in some complex seeding-FEL mechanisms. A laser heater is used for smoothing the longitudinal phase space and a slice energy spread of about 1×10^{-4} is obtained at last. The peak current on the flat top part is about 800 A and the normalized emittance is about 1.0 mm · mrad.

As seen in Fig. 5, although the laser heater is used, some residual micro-bunching structures still appear in the longitudinal phase space. Besides, there is a horn with peak current over 1.5 kA in the bunch head part. A comparison of the t-x phase space and current profile before and after the switchyard is shown in Fig. 7 [Figure 7: see original paper]. For the case that R56 $\neq$ 0, it shows obvious growth of the micro-bunching structure in the longitudinal phase space, especially on the head horn part. For the isochronous case with micro-bend, only imperceptible micro-bunching gain can be observed. The longitudinal phase space is well preserved after the distribution dog-leg.

Fig. 6 [Figure 6: see original paper] shows the normalized emittance growth (x,f/ x,o) with respect to the betatron phase advance (ϕ) between the two DBA cells, where the f and o subscripts indicate the values at the end of linac and the beam distribution dog-leg respectively. It is clear that the emittance growth is almost completely eliminated with π phase advance, which indicates that the current optics well satisfies the requirement of suppressing CSR-induced emittance growth.

D. Trajectory Stability

For sufficient and stable interaction between beam and seed laser, the seeded FEL line requires transverse beam position jitter less than 0.1σx. The major sources of horizontal trajectory jitter come from magnet power fluctuations, especially the kicker magnet power jitter. The vertical jitter mainly comes from quadrupole misalignment jitter due to ground vibration.

A simulation of the trajectory jitter of the beam switchyard is performed with kicker power jitter 100 ppm, bending magnet power jitter 50 ppm, and ground vibration amplitude 200 nm in both horizontal and vertical directions (all RMS). Fig. 8 [Figure 8: see original paper] shows the transverse trajectory jitter along the beam distribution dog-leg for 200 random seeds of the jitter source. The horizontal position jitter (RMS) at the exit of the dog-leg is less than 0.1σx and the vertical position jitter (RMS) is less than 1% of σy. However, further simulation shows that the trajectory jitter is dominated by the kicker jitter and grows almost linearly with it. In summary, 100 ppm is the criteria amplitude of acceptable kicker power jitter.

IV. Commissioning Results

A. Commissioning of the Deflection Line

The beam switchyard of SXFEL-UF was installed in the front part of the newly built undulator hall in late 2020. Commissioning of the switchyard and seeding FEL line started at the beginning of November 2021. However, since the power supply of the kicker magnet had not reached the expected stability requirement, as described in the previous section, it was not acceptable for stable operation of the seeding-FEL line. Therefore, the kicker magnet was absent in this stage of commissioning until it became stable enough, and its function was temporarily replaced by a DC bending magnet.

The dispersion function measurement is based on measuring the orbit change at each cavity BPM with different beam energies. As seen in Eq. 3, if the dispersion is closed, the orbit data will not change with energy change; otherwise, an orbit vs. relative energy change slope will be observed. By fitting the slope, the dispersion function and even higher-order dispersion terms can be obtained: $x = x_0 + R_{16}\delta + T_{166}\delta^2 + \cdots$

Fig. 9 [Figure 9: see original paper] shows the measurement result of horizontal dispersion at the exit of the distribution dog-leg. The residual horizontal dispersion after the dog-leg is cancelled to less than 1 mm, which is much smaller than the required 10 mm value. To ensure ’ is also well cancelled, dispersion is measured at more CBPMs downstream. Fig. 10 [Figure 10: see original paper] shows the measured dispersion at all the CBPMs from the beam switchyard to the entrance of the FEL line in comparison with the theoretical value. The result not only confirms the reliability of measurement but also confirms a well cancellation of ’ .

The betatron matching of the beam switchyard is done by keeping the theoretical configuration of magnets while matching the entrance parameters from the linac. The emittance and Twiss parameters are measured by varying the quadrupole and fitting the beam spot variation on a downstream OTR screen. Then the beam is matched from the linac exit to the entrance of the beam switchyard by an automatic algorithm based on the code Ocelot. Fig. 11 [Figure 11: see original paper] shows the comparison between the observed beam spot on each screen and the theoretical beam spot after matching, which shows good agreement. With such optics, the emittance is measured after the dog-leg. To reduce the fluctuation of emittance measurement, an average of multiple measurements has been taken, and the result shows an emittance growth of only about 3%, which is well below the requested 10% emittance growth.

B. Parallel Operation of the Two Lines

The kicker magnet was installed online in mid-2022, with its field stability reaching the required criteria. This enables simultaneous commissioning and operation of the two undulator lines. Fig. 12 [Figure 12: see original paper] shows the installed kicker magnet and its high-stability pulsed power supply in the undulator tunnel.

A comparison of the transverse position jitter before and after the dog-leg is shown in Fig. 13 [Figure 13: see original paper]. With the high-stability kicker magnet, combined with the well-cancelled dispersion and CSR emittance growth in the deflection line, the growth of transverse position jitter after the dog-leg is less than 10%. Soon afterward, simultaneous lasing of the two undulator lines was realized, as seen in Fig. 14 [Figure 14: see original paper]. This demonstrates the final success of the design and commissioning of the beam switchyard of SXFEL-UF.

V. Summary

A beam switchyard for SXFEL-UF is designed to perform bunch-by-bunch separation of the 50 Hz electron beam to the two undulator lines respectively. With properly optimized optics, beam collective effects that may spoil beam quality can be well suppressed. The beam distribution system has been installed in the undulator tunnel and started commissioning in November 2021. The commissioning results show that the beam quality after passing through the beam switchyard is well preserved with the present design. The electron beam has been delivered to the downstream FEL line and exponential FEL power growth has been obtained, which indicates the beam quality after the beam switchyard well satisfies the requirements of soft X-ray FEL. With the kicker magnet satisfying the stability requirement, simultaneous operation and lasing of the two undulator lines has been realized. The efficiency of SXFEL-UF is significantly improved by the beam switchyard. Beyond that, it provides an important reference for the beam switchyard of future hard X-ray free electron laser facilities.

VI. Acknowledgment

The authors would like to thank all colleagues working on SXFEL-UF. Special thanks to Duan Gu and Zhen Wang for providing the electron distributions used for this study. Many useful discussions with Bart Faatz and other members of the physics and commissioning team are also gratefully acknowledged.

References

[1] Z.T. Zhao. Storage Ring Light Sources. Reviews of Accelerator Science and Technology. Vol. 03, No. 01, pp. 57-76 (2010). DOI:10.1142/S1793626810000361

[2] N. Huang, H.X. Deng, B. Liu et al., Features and Futures of X-ray Free-Electron Lasers. The Innovation. 2(2), 100097. DOI:10.1016/j.xinn.2021.100097

[3] P. Emma, R. Akre, J. Arthur et al. First lasing and operation of an ångstrom-wavelength free-electron laser. Nature Photon 4, 641–647 (2010). DOI:10.1038/nphoton.2010.176

[4] T. Ishikawa, H. Aoyagi, T. Asaka et al. A compact X-ray free-electron laser emitting in the sub-ångström region. Nature Photon 6, 540–544 (2012). DOI:10.1038/nphoton.2012.141

[5] H.S. Kang, C.K. Min, H. Heo et al. Hard X-ray free-electron laser with femtosecond-scale timing jitter. Nature Photon 11, 708–713 (2017). DOI:10.1038/s41566-017-0029-8

[6] E. Prat, R. Abela, M. Aiba et al. A compact and cost-effective hard X-ray free-electron laser driven by a high-brightness and low-energy electron beam. Nature Photonics 14, 748–754 (2020). DOI:10.1038/s41566-020-00712-8

[7] W. Decking, S. Abeghyan, P. Abramian et al. A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator. Nature Photonics 14, 391–397 (2020). DOI:10.1038/s41566-020-0607-z

[8] W. Ackermann, G. Asova, V. Ayvazyan et al. Operation of a free-electron laser from the extreme ultraviolet to the water window. Nature Photon 1, 336–342 (2007). DOI:10.1038/nphoton.2007.76

[9] E. Allaria, R. Appio, L. Badano et al. Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet. Nature Photon 6, 699–704 (2012). DOI:10.1038/nphoton.2012.233

[10] Z.T. Zhao, D. Wang, Q. Gu et al., SXFEL: A Soft X-ray Free Electron Laser in China. Synchrotron Radiation News, Vol.30(2017) 6, pp.29-33. DOI:10.1080/08940886.2017.1386997

[11] B. Liu, C. Feng, D. Gu et al., The SXFEL Upgrade: From Test Facility to User Facility. Appl. Sci. 2022,12,176. DOI:10.3390/app12010176

[12] Z.T. Zhao, D. Wang, Z.H. Yang et al., "SCLF: An 8-GeV CW SCRF Linac-Based X-Ray FEL Facility in Shanghai" , in Proc. 38th Int. Free Electron Laser

Conf. (FEL' 17), Santa Fe, NM, USA, Aug. 2017, paper MOP055, pp. 182-184, ISBN: 978-3-95450-179-3, DOI:10.18429/JACoW-FEL2017-MOP055, 2018.

[13] T. Hara, K. Fukami, T. Inagaki et al., Pulse-by-pulse multi-beam-line operation for x-ray free-electron lasers. Phys. Rev. Accel. Beams 19, 020703 (2016). DOI:10.1103/PhysRevAccelBeams.19.020703

[14] T. Hara, C. Kondo, T. Inagaki et al., High peak current operation of x-ray free-electron laser multiple beam lines by suppressing coherent synchrotron radiation effects. Phys. Rev. Accel. Beams 21, 040701 (2018). DOI:10.1103/PhysRevAccelBeams.21.040701

[15] Y. Nosochkov, P. Emma, T. Raubenheimer et al., Development of the LCLS-II Optics Design. in Proceedings of IPAC2016, Busan, Korea, MOPOW048. DOI:10.18429/JACOW-IPAC2016-MOPOW048

[16] N. Golubeva, V. Balandin, W. Decking, Optics for the Beam Switchyard at the European XFEL. in Proceedings of IPAC2011, San Sebastián, Spain, WEPC008.

[17] N. Milas and S. Reiche, Switchyard Design: ATHOS, in Proceedings of FEL2012, Nara, Japan, MOPD37.

[18] M. Borland, Simple method for particle tracking with coherent synchrotron radiation. Phys. Rev. S.T. - Accel. Beams 4, 070701 (2001). DOI: 10.1103/PhysRevSTAB.4.070701

[19] S. Di Mitri, M. Cornacchia, and S. Spampinati, Cancellation of Coherent Synchrotron Radiation Kicks with Optics Balance. Phys. Rev. Lett. 110, 014801 (2013). DOI:10.1103/PhysRevLett.110.014801

[20] M. Borland, elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation, Advanced Photon Source LS-287, September 2000.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.