ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU4P08

DESIGN AND COMMISSIONING OF THE BEAM SWITCHYARD FOR THE SXFEL-UF*

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Abstract

A beam switchyard is designed for the Shanghai soft X-ray FEL user facility to enable parallel operation of its two FEL lines. It is designed to keep the beam properties like low emittance, high peak charge and small bunch length from being spoiled by various beam collective effects such as the dispersion, coherent synchrotron radiation and micro-bunching instability. In this work, the detailed physics design of the beam distribution system is described and the recent commissioning result is reported.

INTRODUCTION

The Shanghai soft X-ray FEL (SXFEL) user facility aims to open the way of various application fields of XFEL in China [1,2]. It is designed to cover the whole water window range, i.e., X-ray in wavelength range of 2.3 nm ~ 4.4 nm. To accomplish this, the beam energy is accelerated to about 1.5 GeV by a normal conducting linac with a series of S-band and C-band RF structures. The bunch repetition rate is about 50 Hz. Two parallel undulator lines are installed in the undulator hall. Directly downstream of the linac it is a SASE-FEL line with radiation wavelength about 2 nm, which is named as the SBP line. A fully-coherent seeded-FEL line, which is renamed as the SUD line, is about 3 m right side of the SBP line with the radiation wavelength about 3 nm. The schematic layout of the SXFEL-UF is shown in Fig. 1. Some main beam parameters of SXFEL-UF are shown in Table 1.

Table 1: Main Parameters of SXFEL user facility Linac

Parameter	Value	Unit
E	1.5~1.6	GeV
σ_E/E (rms)	≤0.1 %	
ε_n (rms)	≤1.5	mm·mrad
l_b (FWHM)	≤0.7	ps
Q	500	pC
I_{pk}	≥700	A
f_{rep}	50	Hz

For the simultaneous operation of the two FEL lines, a beam switchyard is located between the linac and the undulator section. The electron bunch train from the linac is separated and directed in two subsequent directions: either to the SBP line or to the SUD line. Due to the high requirements of the externally seeded FEL, the beam switchyard should ensure a stable and precise transportation of the electron beam, while maintaining desirable 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.

BEAM SWITCHYARD DESIGN

General Layout

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 the longitudinal distance, the total deflection angle of the dog-leg is about 6°. The two reverse angle bending magnets of the dog-leg are replaced by two identical but symmetrical double-bend-achromatic(DBA) structures for reducing the deflection angle of a single bending magnet. An in-vacuum lumped-inductance kicker magnet acts as the first 3° bending magnet of the entrance DBA, with the capability of performing bunch-by-bunch beam separation and programmable for arbitrary separation pattern. To guarantee the beam trajectory stability in the SUD line, the field repetitive jitter of the kicker magnet should be less than 100 ppm.

Optics Design for CSR & MBI Suppression

Emittance growth due to coherent synchrotron radiation is a crucial beam dynamic issue of a dog-leg beam switchyard. It is necessary and possible to suppress the CSR induced emittance growth by well designed beam optics in an achromatic deflection structure. A straightforward method for mitigating emittance growth involves adjusting the beam size at the bending magnet, thereby reducing the strength of the CSR kick. Another method involves achieving mirror symmetry in the lattice of the switchyard dog-leg and adjusting the betatron phase advance between the two DBA cells to be an odd multiple of π, which is referred to as the ”optics balance” method [3]. With this method, the CSR induced longitudinal dispersion and transverse kick can be well canceled at the exit of the switchyard dog-leg. The betatron functions and dispersion functions of such an optics design for SXFEL-UF are shown in Fig. 2.

Special attention should also be paid to the micro-bunching instability in the beam switchyard with multi-bend deflection line, especially for the seeded-FEL scheme which requires a smoother longitudinal phase space for more effective density modulation. For this purpose, a small bending magnet (micro-bend) is inserted in the middle of the DBA

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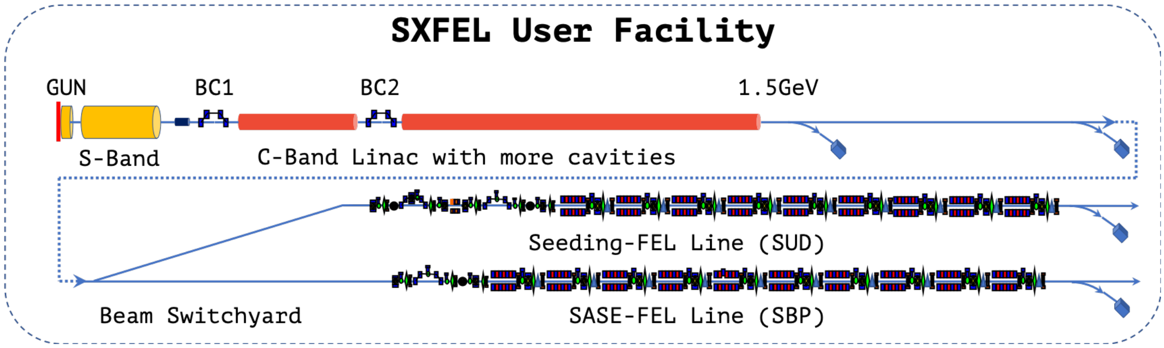

Figure 1: Schematic view of the SXFEL-UF.

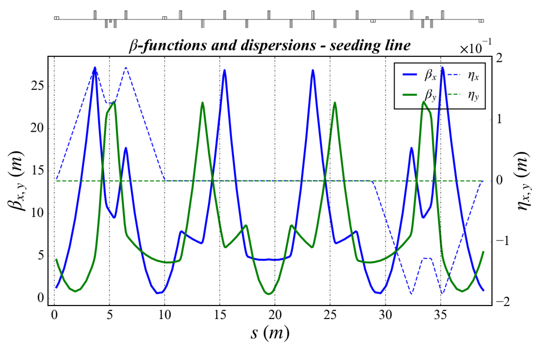

Figure 2: $\beta_{x,y}$ functions and dispersion $\eta_{x,y}$ evolution along the beam switchyard.

cell with a small angle reverse to the DBA deflection angle. With this design, the R_{56} of each DBA becomes zero. Apply this design to both of the DBA cells of the switchyard, it becomes globally isochronous, as is seen in Fig. 3. 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.

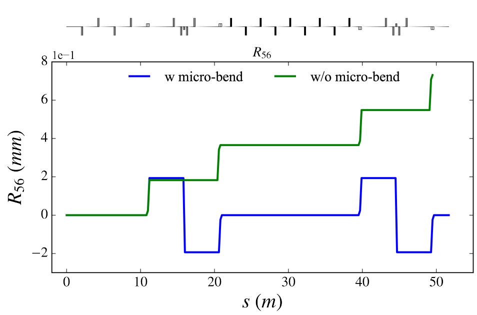

Figure 3: R_{56} evolution along the switchyard.

S2E Tracking Results

The start-to-end tracking from the linac end throughout the beam distribution section is performed by the code ELEGANT [4]. The longitudinal phase space at the linac exit is shown in Fig. 4.

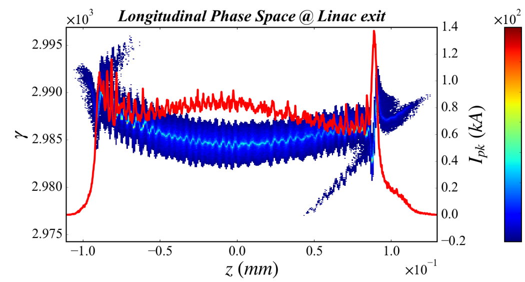

Figure 4: Longitudinal phase space at the linac exit.

Figure 5 illustrates the evolution of normalized emittance (excluding the dispersion contribution) based on the S2E tracking results. These findings clearly showcase that the combined lattice design methods substantially alleviates emittance growth.

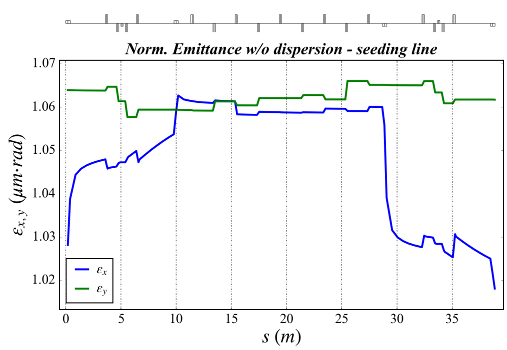

Figure 5: Normalized emittance along the beam switchyard.

For investigating the micro-bunching gain, a comparison of the t-x phase space and current profile before and after the switchyard is shown in Fig. 6. For the case that $R_{56} \neq 0$, it shows an 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.

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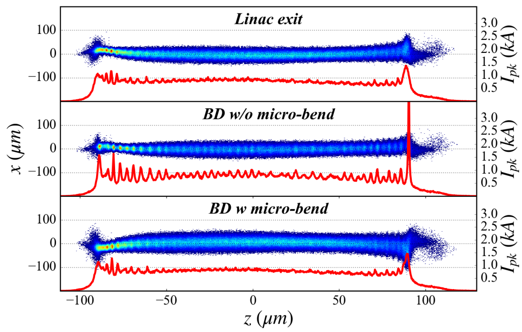

Figure 6: Comparison of the t-x phase space and the current profile at linac exit (upper), switchyard exit without micro-bend (middle) and switchyard exit with micro-bend (lower).

COMMISSIONING RESULTS

Commissioning of the Deflection Line

The commissioning of the switchyard and the Seeding-FEL line has started at the beginning of November 2021. The dispersion function is measured by fitting the orbit change slope at the beam position monitor (BPM) with different beam energy, as is shown in the upper figure of Fig. 7. It should be noted that, in this measurement, we actually did not change the beam energy directly but instead of changing the current of the bending magnets as an equivalent. Fig. 7 also shows the horizontal dispersion measured at all the BPMs from the beam switchyard to the entrance of the SUD line based on this method. The horizontal dispersion is well eliminated to be less than 1 mm at the exit of the switchyard and is well preserved downstream.

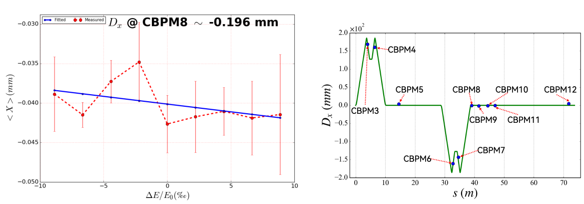

Figure 7: Horizontal dispersion measurement results.

While keeping the theoretical configuration of the magnets in the beam switchyard, the betatron matching is done by matching its entrance parameter from the linac. The emittance and twiss parameters are measured by varying the quadrupole and fitting the beam spot variation on a downstream screen. Then the beam is matched from linac exit to the entrance of beam switchyard by an automatic algorithm based on the code *Ocelot* [5]. Fig. 8 shows the comparison between the observed beam spot on each screen and the theoretical beam spot after matching, which shows a good agreement. The emittance is measured downstream of the beam switchyard and compared with the emittance in front. The results show that the emittance growth is well suppressed with less than 10 % growth.

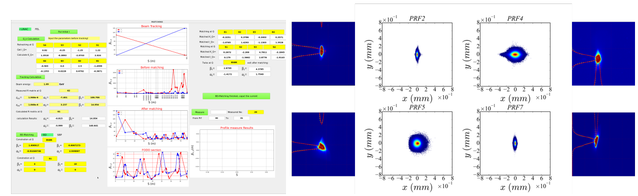

Figure 8: Automatic matching algorithm for beam switchyard.

Parallel Operation of the Two Lines

The kicker magnet has been installed online in middle of 2022, with its field stability reaching the required criteria. This enables the simultaneous commissioning and operation of the two undulator lines. Fig. 9 shows the installed kicker magnet and its high-stability-pulsed power supply in the undulator tunnel.

Figure 9: Kicker magnet and its high stability pulsed power supply installed in the undulator tunnel.

Soon afterward, a simultaneous lasing of the two FEL lines has been realized, as is seen in Fig. 10. This demonstrates the final success of the design and commissioning of the beam switchyard of SXFEL-UF.

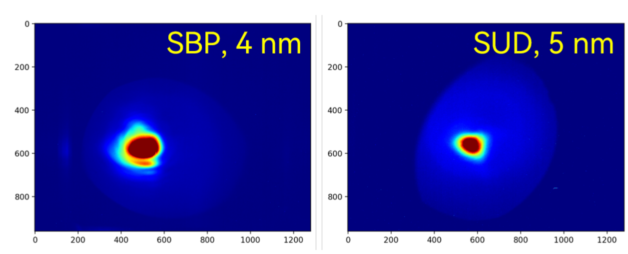

Figure 10: Simultaneous lasing of the two FEL lines.

ACKNOWLEDGMENT

The author would like to thank all the colleagues working on the SXFEL-UF. Special thanks to Duan Gu and Zhen Wang for providing the electron distributions used in this

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study. Many useful discussions with Bart Fattz and other members of the physics and commissioning team are also gratefully acknowledged.

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