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DESIGN AND STATUS OF THE BEAM SWITCHYARD OF THE SHANGHAI SOFT X-RAY FEL USER FACILITY*

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Abstract

SXFEL-UF, a soft X-ray FEL user facility located in Shanghai, has been upgraded from the existing test facility. Electron energy increases from 840 MeV to 1.5 GeV and a SASE FEL line will be added besides the existing seeding FEL line. It has started commissioning since early this year. In order for simultaneous operation of the two FEL lines, a beam switchyard is built between the linac and the two FEL lines. In this paper, the physics design of the beam switchyard is described.

INTRODUCTION

The Shanghai Soft X-ray Free-Electron Laser facility is the first coherent X-ray light source built in China [1]. It is developed in phases. First a test facility (SXFEL-TF) with a 840 MeV linac is built for generation of 8.8 nm full coherent soft X-ray radiation and demonstration of various seeded FEL mechanisms. It has achieved its goal in 2020 and been upgraded to the user facility (SXFEL-UF) afterwards [2]. The beam energy is upgraded to about 1.5 GeV by adding more C-band RF structures to the linac. Two individual undulator lines are parallelly installed in the newly built undulator hall. Directly downstream of the linac it is a brand new SASE-FEL line with radiation wavelength about 2 nm. The existing seeded FEL line, with radiation wavelength about 3 nm, is moved to about 3 m right side of the SASE-FEL line. The schematic layout from SXFEL-TF to SXFEL-UF is shown in Fig. 1. Some main beam parameters of SXFEL-TF and SXFEL-UF is shown in Table 1.

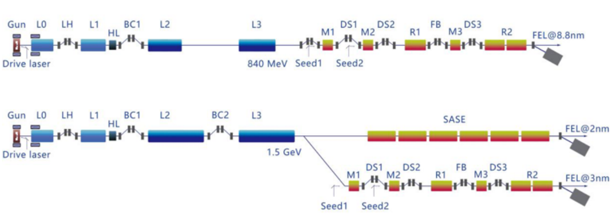

Figure 1: SXFEL-TF (upper) and SXFEL-UF (lower).

Between the linac and the undulator lines, a beam switchyard section is installed for deflecting the electron beam to the seeding-FEL line. Because of the high requirement of the seeded FEL, the switchyard should be able to guarantee a stable, precise transportation of the electron beam with a well maintained beam quality properties, such as the low emittance, high peak charge and small bunch length.

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Table 1: Main Parameters of the SXFEL Linac

Parameters	Units	SXFEL-TF	SXFEL-UF
E	GeV	0.84	1.5~1.6
σ_E/E (rms)		≤0.1%	≤0.1%
ε_n (rms)	mm·mrad	≤2.0	≤1.5
l_b (FWHM)	ps	≤1.0	≤0.7
Q	pC	500	500
I_{pk}	A	≥500	≥700
f_{rep}	Hz	10	50

For simultaneous operation of the two undulator lines, the switchyard should also be able to perform a fast and stable bunch-by-bunch separation of the 50 Hz electron beam. The detailed physics design of the switchyard is described below.

SWITCHYARD DESCRIPTION

General Layout

The beam switchyard section uses a dog-leg structure to bring the beam to the entrance of the seeded FEL line. The dog-leg consists of two double-bend-achromats (DBA) in reverse bending direction. The total deflection angle is about 6°. At the entrance of the dog-leg it is a fast kicker magnet which acts as the first bending magnet of the entrance DBA. The kicker is designed to perform a bunch-by-bunch separation of the 50 Hz electron beam and is programmable for arbitrary separation pattern. Between two DBAs, several quadruples are inserted for beam matching. The position of elements is adjusted carefully to avoid conflict between the straight line and the deflecting 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.

Optics Design

The optics design of the beam switchyard is to have as less damage as possible to the beam quality. The emittance growth caused by the deflection should be suppressed. The structure of the longitudinal phase space should be kept well after passing through the switchyard. For this purpose, the dog-leg should first be achromatic. As is described above, it is realized by applying the DBA structure instead of a single bend. Another main reason of emittance is the CSR kick in the bending magnets. For suppressing this effect, the optics of the dog-leg is carefully optimized. The optics of the whole dog-leg is matched to be symmetrical and the β functions at the dipoles are optimized to be very small for reducing the strength of CSR kick. Besides, the phase advance between each two successive dipole is match to be π in order for further cancelling the CSR kick [3]. Figure 3 shows

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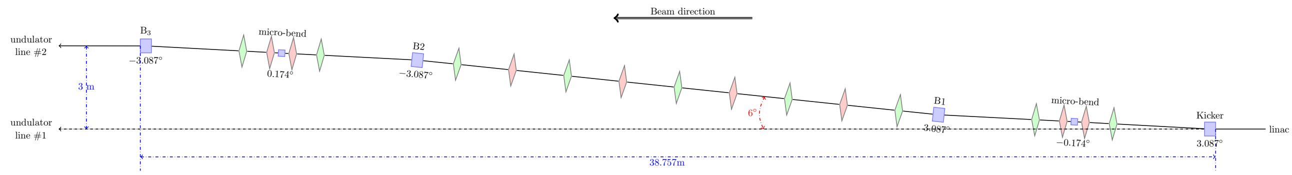

Figure 2: Schematic layouts of the beam switchyard of SXFEL-UF. Beam comes from the right side.

the β functions and the dispersion function of the beam switchyard. Figure 4 shows the evolution of the normalized emittance based on S2E tracking. The emittance growth due to dispersion and CSR kick can be well suppressed with the current optics design, less than 10%.

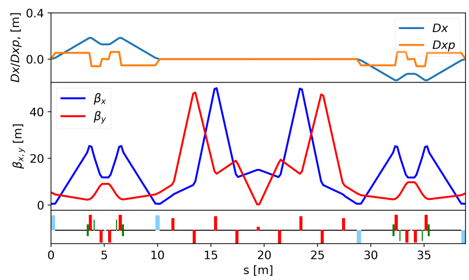

Figure 3: β functions and dispersion functions of the dog-leg.

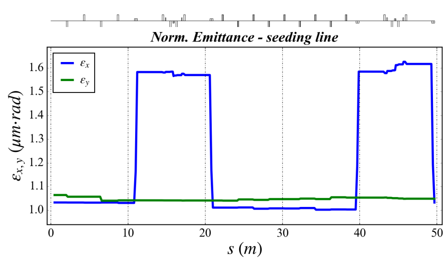

Figure 4: Normalized emittance along the beam switchyard.

MICROBUNCHING INSTABILITY

Microbunching instability (MBI) is another key beam dynamic issue of the switchyard. The microbunching structures in the beam longitudinal phase space is usually harmful to the FEL process, especially for the seeded FEL. In SXFEL-UF, microbuching structure appears in the longitudinal phase space at the end of linac due to two stage compressions and even the laser heater is insufficient for suppressing it, as is shown in Fig. 5. During the deflection of the switchyard, a R_{56} of about 0.8 mm is generated by the bending magnets. The existing microbunching structure may have a severe growth with such a R_{56}. Thus, suppression of microbunching gain has to be considered in the switchyard design.

For solving this problem, 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 R_{56} of each DBA becomes zero. Apply this design to

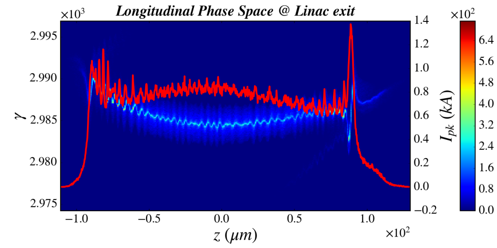

Figure 5: Longitudinal phase space at the linac exit.

both of the DBA cells of the switchyard, it becomes globally isochronous. The longitudinal phase space of the electron beam can be well kept without microbunching gain after the switchyard. A comparison of current profile before and after the switchyard is shown in Fig. 6. It is based on the S2E tracking result using the code ELEGANT [4]. For the case that $R_{56} \neq 0$, it shows a obvious growth of the microbunching structure in the longitudinal phase space, especially on the head of the beam where a shape horn appears. For the isochronous case with micro-bend, almost no visible microbunching gain can be observed. The longitudinal phase space is well preserved after the switchyard.

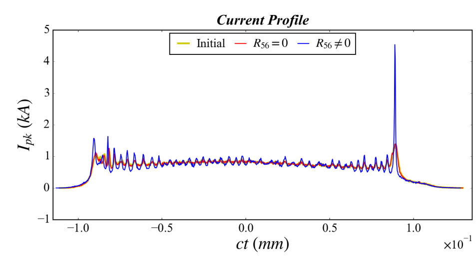

Figure 6: Comparison of the current profile before and after passing through the beam switchyard.

JITTER ANALYSIS

For sufficient and stable interaction between beam and seed laser, the seeded FEL line requires a transverse beam position jitter less than $0.1\sigma_x$. One of the major sources of the horizontal position jitter comes from the kicker magnet power fluctuation, while the vertical jitter mainly comes from the quadrupole misalignment jitter. Figure 7 shows the transverse position jitter at the exit of switchyard. With the kicker jitter (RMS) ~100 ppm and a typical value of quadrupole position misalignment jitter, the horizontal position jitter (RMS) at the exit of switchyard is less than $0.1\sigma_x$ but very close and the vertical position jitter (RMS) is less than 5% of σ_y. This gives an important criterion to the construction and installation of the key elements.

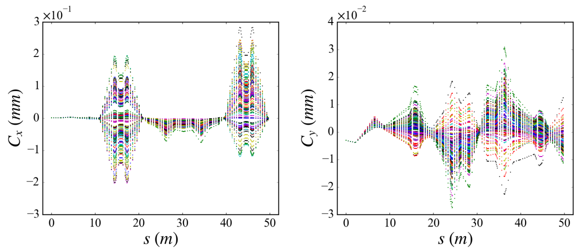

Figure 7: Transeverse position jitter of 100 cases of magnet power supply jitter.

CURRENT STATUS

The beam switchyard of SXFEL-UF has been installed in the front part of the undulator tunnel, as is shown in Fig. 8. It was planned to have the commissioning of the switchyard early this year. However, due to the schedule change, the commissioning has been postponed to late this year until we finished the commissioning of SASE FEL line.

Figure 8: The switchyard has been installed online.

FUTURE UPGRADE

At present, the SXFEL-UF is running in the single-bunch mode. The beam parameters to the two FEL lines are the same. In the future, it is expected to upgrade the facility to a double-bunch mode with a bunch time separation of about 50 ns and a pulse repetition rate of 50 Hz. The two bunches in a pulse are separated and delivered to the two undulator lines respectively. It is obvious that the current kicker is not able to provide such a fast separation. New scheme should be considered for the new requirement.

Considering the limited space of the beam switching section, it's better not affect too much to the current beam switchyard. Therefore, the present kicker magnet is replaced by a DC Lamberson septum with the same deflection angle. A set of resonant kickers combined with dipoles is put upstream the septum for fast beam separation. Unkicked beam passes through the field region of the septum and enters the transverse deflection dog-leg. Kicked beam passes through the field free region of septum and is deflected back to the original direction afterwards. A schematic view of such a new kicker-septum scheme is shown in Fig. 9.

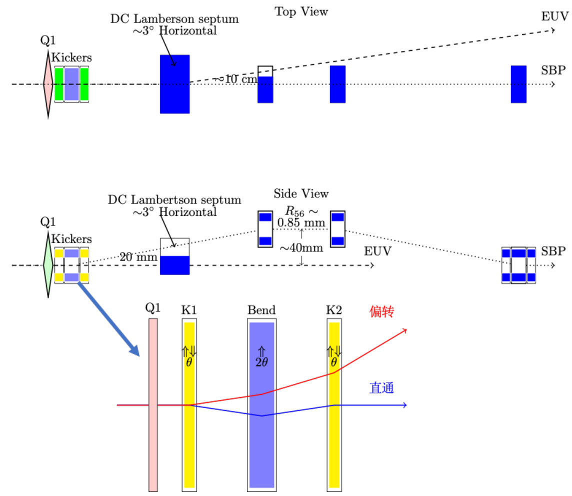

Figure 9: Resonant kicker set and DC Lamberson septum scheme for two bunch mode operation.

SUMMARY

The beam switchyard of SXFEL-UF is designed to perform a bunch-by-bunch distribution of the 50 Hz electron beam to the two undulator lines respectively. With properly optimized optics, some beam collective effects that may spoil the beam quality can be well suppressed. The beam switchyard has been installed in the tunnel. It is scheduled to start commissioning soon. It is expected to be the first beam distribution system in operation in China. In the future, the SXFEL-UF may be upgraded for double bunch mode operation. The design of the beam switchyard has to be modified to meet the new requirement.

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