LAYOUT OF THE UNDULATOR-TO-DUMP LINE AT THE SHINE*

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Abstract

The Shanghai HIgh repetitioN rate XFEL and Extreme light Facility as the first hard X-ray free-electron laser (FEL) facility in China, is currently under construction in the Zhangjiang area, Shanghai. It aims to deliver X-ray covering photon energy range from 0.4 to 25 keV, with electron beam power up to 800 kW. Downstream of the undulator line, the beam transport design of the undulator-to-dump line is critical which is mainly used for realization of FEL diagnostics based on transverse deflecting structure and beam absorption in the dump. In this manuscript we describe the current layout of this system.

INTRODUCTION

In recent years, the high-repetition-rate XFEL based on superconducting LINAC attracts increasing attention due to its ability to generate radiation pulse with higher average brightness and plays an important role in many research fields. The Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE) aims to join the exclusive XFEL club as one of the most advanced user facilities by delivering femtosecond X-ray pulses with high repetition rate. It is designed to deliver photons between 0.4 keV and 25 keV with repetition rate up to 1 MHz using a superconducting LINAC [1,2]. It consists of an 8 GeV continuous-wave superconducting RF Linac, 3 undulator lines, 3 X-ray beamlines and 10 experimental stations in phase-I, which has started its construction from April of 2018.

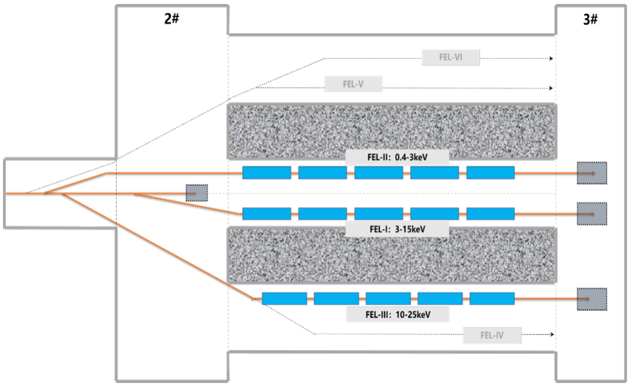

Figure 1: Undulator system at the SHINE. Main dump is located at the beam switch-yard system in the tunnel 2♯, and the other three dumps are at the downstream of the undulator systems in the tunnel 3♯.

For the nominal parameters of the electron beam output at the SHINE, the operating beam energy is 8 GeV with repetition rate up 1 MHz and bunch charge of 100 pC, so that it would provide electron with beam power up to 800 kW. According to the current design requirements, there are four beam dump lines at 8 GeV, as shown in Fig. 1. One of them is the linac-to-dump (L2D) line, which is mainly used for the beam energy and energy spread measurements. The other three are the undulator-to-dump (U2D) lines, ensuring that the electron beam transport into and absorbed in the dumps. To take the commissioning and operation into consideration at the SHINE, the design of the three U2D lines mainly meets the following three basic abilities. The first one is absorbing electron beam power up to 800 kW in the dump, the second one is measurements of the incoming beam energy and energy spread, and the third one is measuring the longitudinal phase space of the electron beam. It is worth mentioning that beam expanding and rotation are required for dump absorbing, together with beam longitudinal phase space measurement online. The total length of the U2D line is approximately 90 m, in which the distance from the analyzing magnets to the dump is less than 20 m. This means the beam transport design of the line is great challenging under severe spatial constraints. Besides, the magnets are also specified to operate within the beam energy range from 4.0 to 10.0 GeV.

LAYOUT OF THE U2D LINE

The electron beam specifications at the SHINE are given in Table 1. On the one hand, due to such high beam power up to 800 kW, the specific dump design is essential associated with beam expanding and rotation. On the other hand, beam longitudinal phase space measurement should be operated online and the time resolution should be the femtosecond level since the bunch length is about 30 fs.

The design of the three U2D lines are very similar with slightly different arrangement in details. Therefore, we take the U2D line of the FEL-I undulator beamline as an example. As shown in Fig. 2, the scheme design is as follows:

1) A set of quadrupoles is required upstream of the transverse deflection structure (TDS) to match the beta functions of the electron beam at the center of the TDS, which aims to achieve ultra-high time resolution.

2) X-band TDS introducing transverse-to-longitudinal correlation is to present the longitudinal phase space of the electron beam and the measurement of several related beam and FEL parameters.

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* Work supported by the National Natural Science Foundation of China (11905277, 12122514, 11975300), the CAS Project for Young Scientists in Basic Research (YSBR060), the Shanghai Natural Science Foundation (23ZR1471300), the Youth Innovation Promotion Association CAS (2023302), and the CAS-Helmholtz International Laboratory on Free Electron Laser Science and Technology (HZXM2022500500).

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Table 1: SHINE Baseline Beam Parameters

Parameter	**Value**	**Unit**
Electron beam energy	8	GeV
Sliced energy spread (rms)	0.01-0.02	‰
Total charge	100	pC
Peak current	1.5	kA
Bunch length (rms)	8	µm
Transverse emittance	0.45	mm·mrad
Repetition rate	1.0	MHz

3) A small angular deflection magnet is located in front of the main analyzing bending magnets, causing the electron beam to deflect slightly towards the dump tunnel, thereby ensuring that the synchronous radiation generated by the electron beam in the main bending magnet is tilted downwards to minimize transmission to the beamline station downstream.

4) Two main bending magnets are used to deflect the electron beam to the beam dump and analyze the beam energy and energy spread.

5) A set of quadrupoles downstream of the TDS are adopted to optimize the transverse dispersion, the beam envelope and the phase advance between the TDS and the measurement point.

6) Scanning dipoles and additional quadrupoles are to rotate the beam periodically together with beam expanding in the front of the beam dump.

7) A beam dump is capable of absorbing all the power of the 800 kW electron beams.

8) Beam measurement devices such as CBPMs, SBPMs, and imaging profiles are also required to observe and measure the characteristics of the electron beam.

For our scheme, the beam is designed to be deflected vertically by 15° using two 3 m long bending magnets and a small bending magnet with a length of 0.5m. The small one has a deflection of 0.2° with 0.19 T, and therefore its synchronous radiation power is only 3% of that of the large two. During the high repetition rate operation, to achieve beam diagnosis online with repetition rate less than 50 Hz, it is necessary to operate such 50 Hz beam off axis. And matching requires a large beam size at the position of the TDS, phase advance of 90° from the TDS to the measurement point, and a small beam size at the measurement point [3]. Meanwhile, facing the problem of beam power up to 800 kW, radiation protection requires high repetition rate beams to achieve a beam expansion of 0.2 mm×2 mm at the dump entrance and rotation with scanning radius of 15 cm.

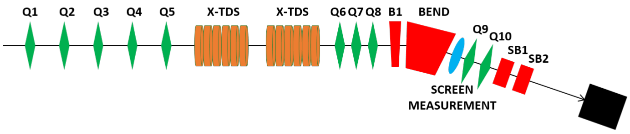

Figure 2: layout of the U2D line at the SHINE.

According to the TDS basic theory, the temporal resolution can be calculated as

$$\Delta_s = \frac{cE}{e\omega V_0}\frac{\sqrt{\varepsilon_x}}{\sqrt{\beta_x}\sin\Delta\phi\cdot\gamma} \tag{1}$$

where β_x is β function at the center of the TDS, $\sin\Delta\phi$ is the phase advance from the TDS to the measurement point. And the energy resolution can be expressed as

$$\Delta_\delta = \frac{\sqrt{\beta_y\varepsilon_y}}{\eta_y} \tag{2}$$

with η_y energy dispersion. The lattice design of the U2D line is shown in Fig. 3. The TDS phase is 1.5°, and the β functions are 400 m and 15 m at the TDS and measurement point, respectively. The phase advance from the TDS to measurement point is $\pi/2$. Therefore the time resolution of the TDS is less than 1 fs and the energy resolution is 2.4e-5, which can be used for phase space diagnostics and FEL pulse reconstruction. Besides, due to the 1.5° phase of the TDS, the horizontal deviation of the 50 Hz beam is about 9 mm far from the high repetition beam on axis, as shown in Fig. 4.

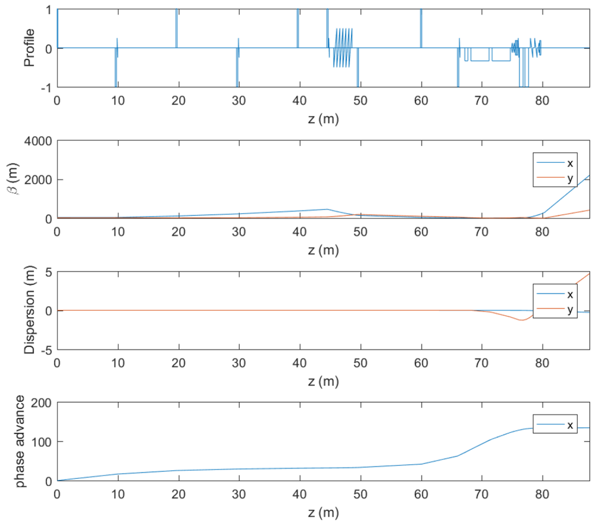

Figure 3: Lattice design of the U2D line at the SHINE, including lattice profile, β functions of x and y, y dispersion, and phase advance in the line.

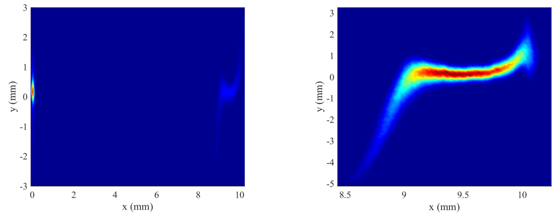

Figure 4: Beam profiles on the screen switching on/off the TDS.

To meet the requirements of dump absorbing, two quadrupoles with length of 0.6 m are arranged downstream of the measurement point, and the beam size can be expanded at 100 µm-level horizontally and vertically, and meanwhile the vertical dispersion is reserved intentionally, so that the beam size requirement of 0.2 mm × 2 mm can be achieved. The scanning dipoles in both horizontal and vertical directions with a scanning angle of 1.0° can achieve rotation with a radius of 15 cm, also meeting the needs of radiation protection. The high repetition beam profile after expanding and rotation is presented in Fig. 5, and the spot at the measurement point is also presented with a same scale as as a comparison.

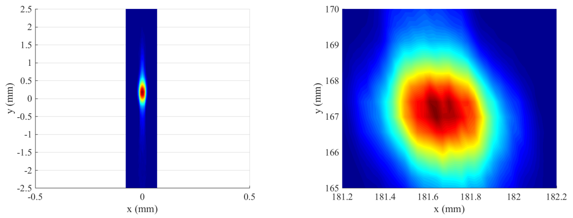

Figure 5: Beam profiles without TDS at the measurement point and the dump.

BEAM CLEAR APERTURE

According to the physical scheme design, we have provided the beam area aperture of the U2D line, as shown in Fig. 6. The top two show the beam clear apertures of the entire line in both horizontal and vertical directions, where the main beam with high repetition rate (blue) surrounds the axis center and reaches at the range of ±15 cm at the entrance of the dump, and while the horizontal distribution of the off axis beam (red) considering both off axis and phase jitter of the TDS, reaches at the range from -10 to 30 cm, which also puts additional requirements for radiation protection. The bottom two show partial enlarged views of the analysis magnets, the beam measurement point and downstream. It can be seen that the beam clear aperture inside the analysis magnet is (-10, 12) mm, and the positive horizontal side of the beam measurement point is beyond 15 mm, posing new requirements for beam measurement. The beam clear aperture at the position of the beam expanding magnets is (-10, 28) mm. The first scanning magnet performs vertical scanning, followed by horizontal scanning since the beam clear aperture of the vertical scanning position is (-10, 30) mm, and while the horizontal scanning position is beyond 30 mm. The horizontal scanning magnet can achieve larger horizontal free space to meet the beam clear area requirements. The beam clear aperture for the beam measurement area downstream of the scanning magnets will be expanded continuously, which also puts forward high requirements for beam measurement and vacuum chamber.

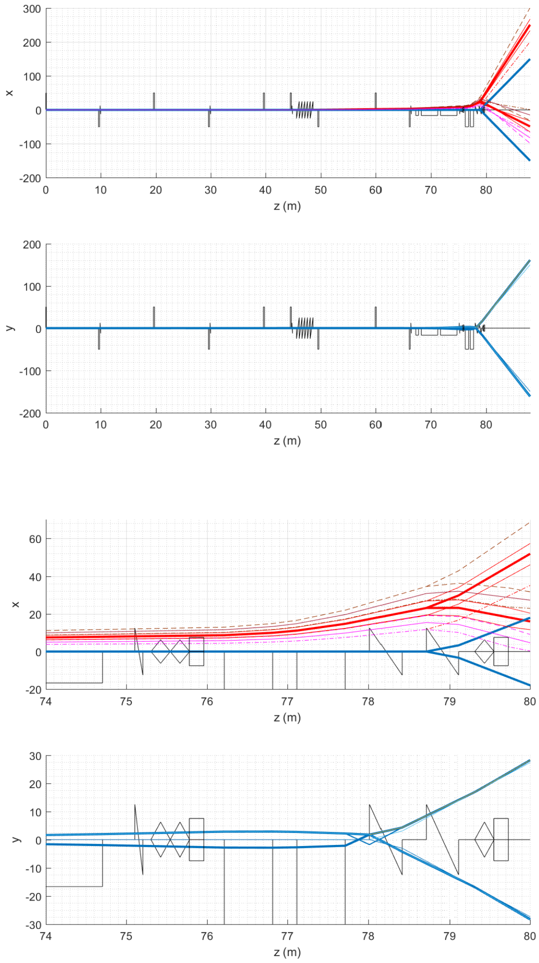

Figure 6: Beam clear aperture at the U2D line. The top two are the entire U2D line in both x and y directions. And the bottom two are the partial enlarged views for on-axis beam (blue) and off-axis beam (red).

CONCLUSION

The layout and optics design of the U2D line at the SHINE are presented in this manuscript, consisting of high precision time resolution based on the TDS, phase space diagnostics online of the 50 Hz off-axis beam, beam expanding and rotation and the corresponding beam clear aperture. The results satisfy the geometrical constraints and requirements coming from the beam dynamics, and ensures flexible operation of the system. Accompanied by the advancement of the process design of the dump, the layout will be updated through the iterative optimization.

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