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# TRANSVERSE DEFLECTING STRUCTURE DYNAMICS FOR TIME-RESOLVED MACHINE STUDIES OF SHINE

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*Abstract*

The transverse deflecting structure (TDS) has been widely used in modern free electron laser facilities for the longitudinal phase space diagnostics of electron beams. As the first hard x-ray free electron laser in China, the SHINE is designed to deliver photons with a repetition rate up to 1 MHz. In this paper, we present the beam dynamics study of the X-band TDS behind the undulator of SHINE. In order to prevent the screen from being damaged by electron bunches with a high repetition rate, the phase of the transverse deflecting cavity is designed to deviate from zero, and only those electron bunches that are kicked by the transverse deflecting cavity are sent to the screen. In addition, the evolutionary algorithm is introduced to optimize the lattice of the TDS line to reach the highest possible resolution.

## INTRODUCTION

Due to characteristics of high peak brightness, short pulse duration, and coherence, X-ray free electron lasers (XFELs) play an important role in many research fields. In recent years, the high-repetition-rate XFEL based on superconducting linac attracts increasing attention because of its ability to produce radiation with higher average brightness. SHINE [1] is designed to be a continuous-wave x-ray free electron laser generating photons between 0.5 keV and 30 keV with a repetition rate up to 1 MHz. The high resolution measurement of the longitudinal phase space of the electron bunch is critical for the XFEL operation.

In recent years, the transverse deflecting structure (TDS) has been widely used in the measurement of the length of electron bunch [2,3]. The transverse kick induced by the cavity translates the time coordinate into a transverse coordinate of the downstream screen. Therefore, the longitudinal properties of the electron beam can be probed. Combined with dipoles, the TDS can be used to reconstruct the longitudinal phase space of the electron beam. Moreover, the x-ray FEL temporal shape can be reconstructed through measuring the difference in the electron beam longitudinal phase space between FEL-on and FEL-off [4]. The TDS will be equipped after each undulator line of SHINE. However, the electron bunches with high-repetition-rate will easily damage the screen used for measurement.

In this paper, to separate the kicked electron bunches from the electron bunches that are not kicked by the TDS, we propose to provide an additional transverse kick to the electron beam by letting the phase of the TDS deviate from zero. In addition, the lattice of the TDS line are optimized to achieve the highest possible resolution.

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## LAYOUT OF THE TDS LINE

Since the design of TDS lines behind the undulator lines of SHINE is similar, the TDS line after FEL-III will be taken as an example in this paper. The schematic layout of the TDS line behind FEL-III is shown in Fig. 1. There are six quadrupoles before the transverse deflecting cavity to match the electron beams coming from the undulator to achieve a high temporal resolution of the TDS. Two X-band transverse deflecting cavities with a length of 2 m and a voltage of 20 MV are used to kick the electron bunch in the horizontal direction. Behind the transverse deflecting cavities, there are a bend that gently deflects the beams without generating significant synchrotron radiation in the forward direction and three strong bending magnets that deflect the beams to the screen or beam dump.

In general, the phase of the TDS is set to 0°to obtain the maximum deflection force. However, in this case, those electron bunches that are not kicked by the TDS are also sent to the screen. This causes the screen to be easily damaged when the machine is operated at a high repetition rate. In order to separate the kicked and un-kicked electron bunches, we set the phase of the TDS to -3°. Due to the extra transverse kicking force, those electron beams that are kicked by the TDS will be horizontally offset. As shown in Fig. 2, those electron bunches that have been kicked by the TDS can be offset in the horizontal direction by about 10 mm from the un-kicked electron bunches. Therefore, those two kinds of electron beams can be sent to the screen and dump, respectively. According to the basic theory of TDS [2], the temporal resolution can be calculated as:

$$\Delta_s = \frac{c(E/e)}{\omega V_0} \frac{\sqrt{\varepsilon_x}}{\sqrt{\beta_d \sin \Delta\psi \cdot \gamma}}, \quad (1)$$

where $\beta_\mathrm{d}$ is $\beta$ functions at the centre of the TDS, $\sin \Delta\psi$ is the phase advance between the TDS and screen. According to the Eq. (1), a high temporal resolution of the TDS can be achieved with high voltage of the deflecting cavity, large beta function at the deflecting cavity, and appropriate phase advance between the deflecting cavity and monitor. The optimal beta function and phase advance can be obtained by optimizing the lattice of the TDS line. Therefore, the strength of the twelve quadrupoles of the TDS line are

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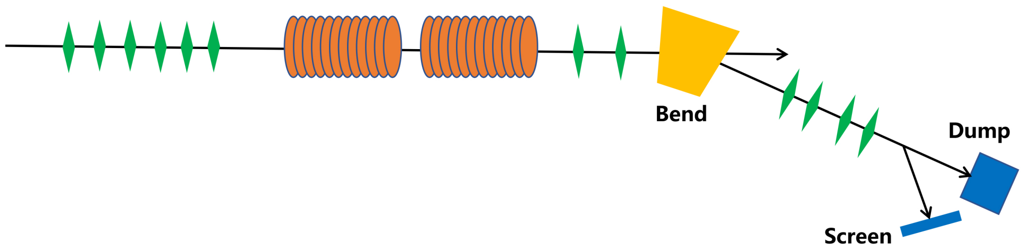


Figure 1: Schematic layout of the TDS beamline downstream the undulator section.

optimized with evolutionary algorithm [5] to achieve high temporal resolution. The optimization objectives consist of maximizing the horizontal $\beta$ function at the TDS and the phase advance between the deflecting cavity and the screen being as close as possible to $\pi/2$, while the $\beta$ function along the entire line and the vertical dispersion after the bending magnets are controllable.

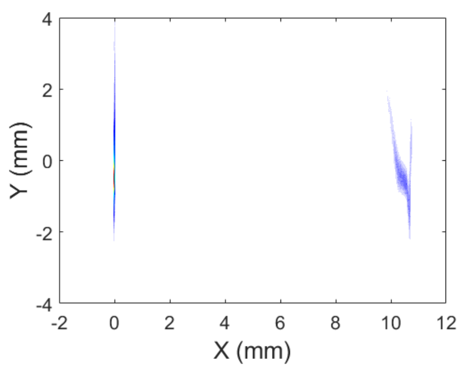


Figure 2: The un-kicked (left) and kicked (right) electron beams by the TDS when the phase of TDS the is set to -3°.

## OPTIMIZATION RESULTS OF THE TDS LINE

The optimized beam optics of the TDS line are presented in Fig. 3. As shown in Fig. 3 (left), the $\beta_x$ at the TDS is larger than 400 m. And the phase advance between the TDS and the screen is about $\pi/2$. According to the Eq. (1), the calculated temporal resolution is about 1 fs. To further verify the temporal resolution, the relationship between the horizontal electron beam size on the screen and electron beam length is analyzed based on the ELEGANT simulation. As presented in Fig. 4, based on the optimized lattice, the horizontal RMS beam size on the screen decreases linearly as the electron bunch length decreases. When the bunch length is shorter than 1 fs, the beam size on the screen is almost unchanged.

As mentioned previously, the TDS in combination with the dipole magnet can be used to reconstruct the longitudinal phase space of the electron bunch. Fig. 5 (top left) shows the beam image on the observation screen when the deflecting cavities switched off. While Fig. 5 (top right)

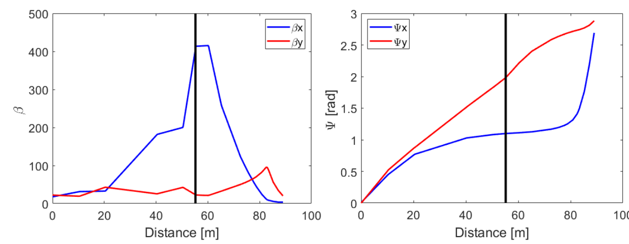


Figure 3: The beta functions (left) and phase advance (right) along the TDS line (to the screen). The vertical black line indicates the entrance of the TDS.

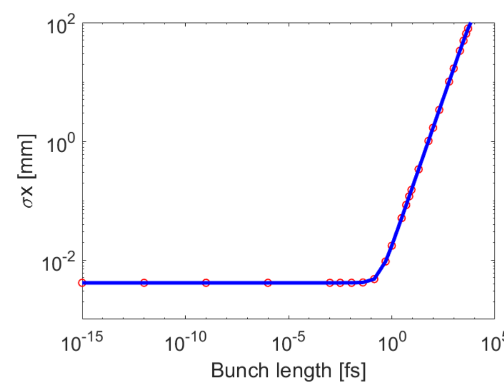


Figure 4: The relationship between the horizontal RMS beam size on the screen and the RMS bunch length.

presents beam image with TDS switched on and this will give a longitudinal resolution of 1 fs. Figure Fig. 5 (middle left) represents the original electron bunch longitudinal phase space at the entrance of the dump line. Fig. 5 (middle right) is presented in the reconstructed longitudinal phase space located at the observation screen, which derived from Fig. 5 (top right). It can be seen from the two figures that there are some differences between the reconstructed phase space and the original phase space. The main reason is that TDS introduces additional energy spread. The simulation results containing FEL lasing is presented in Fig. 5 (bottom). Besides, the tracked current profile and the reconstructed current profile is presented in Fig. 6, which shows a good agreement between the reconstructed profile and the original one.

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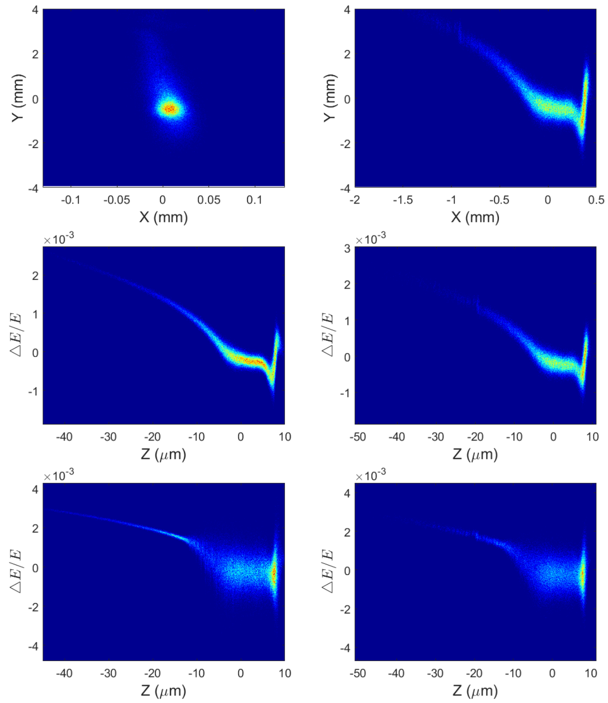


Figure 5: Simulated screen beam images with TDS off (top left) and TDS on (top right). Simulated longitudinal phase spaces of the FEL-off (middle) and FEL-on (bottom) including the original phase spaces (left) and the reconstructed phase spaces (right).

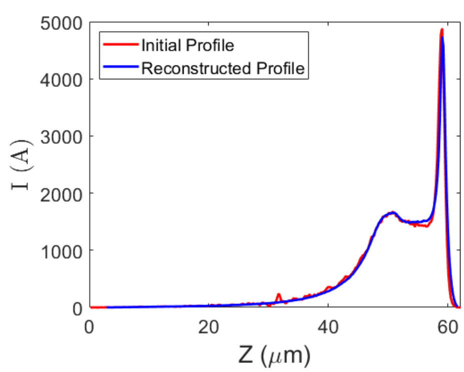


Figure 6: Comparison between the tracked current profile and the reconstructed current profile.

## CONCLUSION

In this paper, the schematic layout and lattice of the TDS line of the SHINE are described and optimized. To separate the electron beams that kicked by the TDS from those unkicked electron beams, the phase of the TDS is designed to deviate from zero. The strength of the twelve quadrupoles of the TDS line is optimized to achieve high temporal resolution. More research about the influence of the collective effects and timing jitter will be studied in future work.

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