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PHYSICS DESIGN AND BEAM DYNAMICS OPTIMIZATION OF THE SHINE ACCELERATOR

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Abstract

Shanghai HIgh Repetition Rate X-ray Free Electron Laser and Extreme Light Facility (SHINE) is a hard X-ray FEL facility which is driven by a 1.3 km superconducting Linac, aims to provide high repetition rate pulses up to 1 MHz. We present the physics design of the SHINE accelerator and considerations of beam dynamics optimizations. Start-to-end simulation results show that, a high brightness electron beam with over 1500 A quasi-flat-top current can be attained which fully meet the requirements of FEL lines. Furthermore, the design of bypass line is discussed.

INTRODUCTION

In recent years, high-repetition-rate XFEL based on superconducting Linac draws increasing attention due to its unique capability of providing Ångström performance at high average power. Several facilities have been built in the world such as EXFEL [1] and LCLS-II [2].

The SHINE facility currently under construction at SARI aims to deliver FEL pulses between 0.4 keV and 25 keV, which enable research in various fields, including biology, chemistry, and material science. To meet the requirements of FEL performance, the Linac of SHINE should provide 8 GeV high brightness electron beam up to 1 MHz, with normalized emittance of < 0.5 µm at nominal 100 pC and peak current over 1500 A. In this paper, we describe the beam dynamics studies including longitudinal working point optimization and lattice matching. Then the detailed start to end simulation results are presented. Finally, the design of a bypass line design is also discussed.

LAYOUT AND MAIN PARAMETERS

At the end of the injector, the bunch length is 1 mm and the peak current is about 10 A. In the Linac section, the beam will be further accelerated to 8 GeV in four acceleration sections (L1, L2, L3 and L4) which consist of seventy-five 1.3 GHz superconducting cryomodules. To obtain the desired peak current, the beam will be compressed to over 1500 A in two bunch compression sections (BC1 and BC2). In addition, two 3.9 GHz cryomodules are used before BC1 as linearizer.

Two beam collimation sections (COL0 and COL1) are placed before L1 and after BC1 to remove undesired stray electrons which can make the serious damages to the sensitive part of the machine. And a metallic corrugated structure section (DCP) is designed to cancel the linear chirp of the electron beam at the exit of the Linac. The transverse magnetic focusing is carefully optimized to minimize the emittance dilution due to transverse wakes, momentum dispersion and coherent synchrotron radiation in bending magnets. The layout of the SHINE Linac is shown in Fig. 1. The main parameters are listed in Table 1.

Table 1: Main parameters of the SHINE Linac

Parameter	Value	Unit
Beam energy	8	GeV
Bunch charge	100	pC
Max Rep-rate	1	MHz
Projected emittance	<0.5	µm
Peak current	>1500	A
Sliced energy spread	<0.015	%,rms

LONGITUDINAL BEAM DYNAMICS

The electron beam is generated by a VHF gun and then accelerated to about 100MeV then the beam is transported in to the L1 (two cryomodules) where the beam will be accelerated to 326 MeV. Off-crest acceleration creates the desired correlated energy spread along the bunch in the first compressor BC1. The two 3.9 GHz cryomodules tuned at the 3rd harmonic of 1.3 GHz frequency is placed right before the first bunch compressor BC1. The function of the structure is to provide cubic corrections of the correlated momentum distribution along the bunch in presence of the sinusoidal RF time curvature and the magnetic compressors non-linearity, which also decelerates the beam to 265 MeV. The beam is compressed in BC1 from 1 mm to 0.13 mm, the peak current is increased to 80 A accordingly.

The L2 structure (18 cryomodules) is located between the first and second bunch compressor, which accelerates the electron beam from 265 MeV to 2.2 GeV. It also provides the residual energy chirp needed for the second compressor BC2, in which the peak current will be further increased to over 1500 A. After BC2 the beam is accelerated to its final 8 GeV energy in the L3 and L4 structure (54 cryomodules).

The X-ray FEL refers using an electron beam with low emittance, small energy spread and a high core current to generate coherent radiation through the undulator, it's critical to avoid the single-spike or double-horn type beam current distribution. the final beam current profile is preferred to be a so-called "flat-top" distribution [3].

Meanwhile, the beam jitters including peak current, beam energy and beam arrival time also sensitive to longitudinal parameters such as RF settings. To achieve this, the

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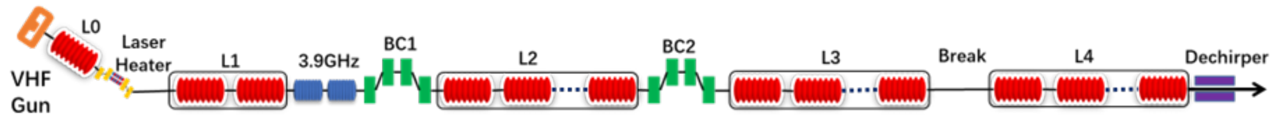

Figure 1: Schematic layout of the SHINE Linac.

working point of the Linac should be chosen carefully including the RF cavity amplitudes and phases of each accelerating section and configuration of bunch compressors. So, a global longitudinal beam dynamics optimization is studied. Some physical objectives including maximum core peak current and the flatness of beam current distribution need to be optimized simultaneously. By integrating the advanced Multi-Objective Evolutionary Algorithm (MOEA) into LiTrack code, the Linac beam dynamics optimization is demonstrated to be effective and reliable. Fig. 2 shows the Pareto front of the two objectives (length of flat-top current profile and peak current). As an illustration, we choose a solution from these Pareto front solutions where the peak current is around 1500 A.

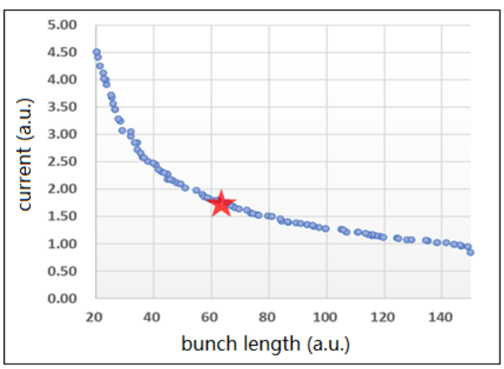

Figure 2: Pareto front of Linac longitudinal optimization.

During the optimization of Linac working point, take into consideration of potential failure of super conducting cavities, 6% of total cavities are not powered but available as a spare (one cavity for every two modules). The accelerating gradient of cryomodule is set to be 16 MV/m for TESLA-style 1.3 GHz cavities, the maximum beam energy can reach 8.7 GeV, which has near 10% energy margin. Fig. 3 shows the optimal longitudinal phase and beam current profile.

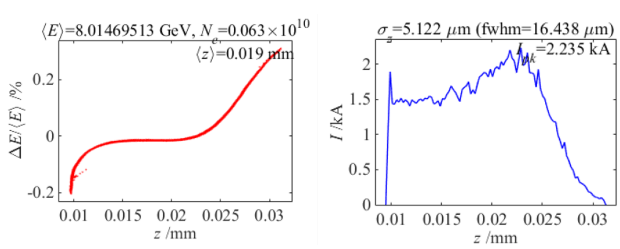

Figure 3: Longitudinal phase space (left) and beam current profile at the exit of Linac through MOEA.

TRANSVERSE BEAM DYNAMICS

The main considerations in the optics design are to minimize the transverse emittance dilution due to components misalignment during beam transportation and CSR effect during bunch length compression, and finally, to transport the electron beam to the undulator section.

The focusing lattice along the main Linac sections (L1, L2, L3 and L4) is set using cold quadrupole magnets at the end of each CM. Some warm quadrupoles are used around the bunch compressors to match the Twiss functions. The Linac lattice was studied and designed in detail using the computer code MAD and Elegant for particle tracking as shown in Fig. 4.

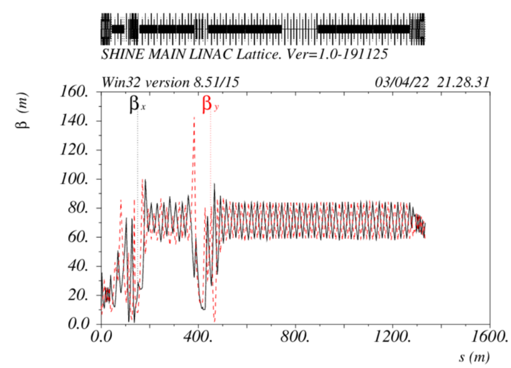

Figure 4: Beta function of the SHINE main Linac.

START TO END SIMULATIONS

Start to End (S2E) simulation including the injector and Linac, bunch compression is performed for the designed optics. In the injector section, the beam energy is relatively low where the space charge dominates, so the space charge tracking code Astra was adopted. When the beam energy is higher in Linac, the collective effects became main issue, the 6D particle tracking code ELEGANT was used, and further confirmed with IMPACT-Z.

As shown in Fig. 5, the results of longitudinal phase space at Linac exit from two codes are compared. Fig. 6 shows the final current distribution, sliced energy spread and normalized sliced emittance.

LINAC BYPASS LINE

Take in consideration of generating soft x-ray FEL lasing with relative low energy, we propose a design that extract the beam from BREAK section between L3 and L4. With this bypass line, the 4–5 GeV beam can be delivered into FEL-II undulator.

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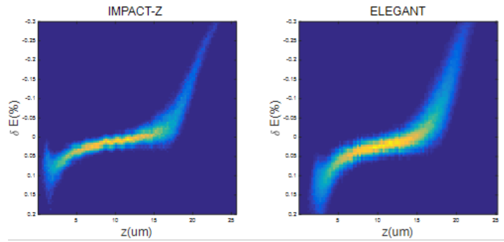

Figure 5: Phase space at exit of Linac with IMPACT-Z (left) and ELEGANT (right).

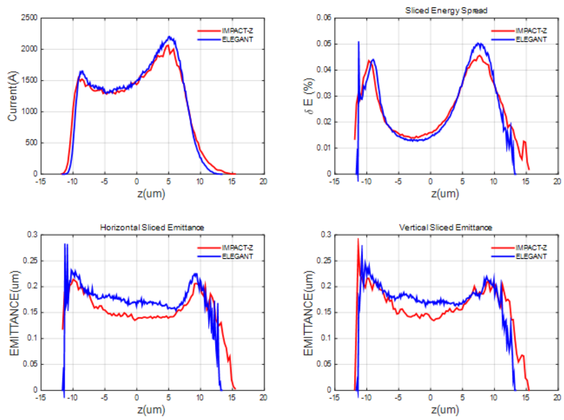

Figure 6: Final current distribution, sliced energy spread and normalized sliced emittance.

There are some requirements of bypass line:

- beam horizontal offset is 1.85 m.
- the beam is kicked out vertically, then bend back to original height.
- considering the CSR effect, the phase advance between BX2 and BX3 is close to π.
- dispersion in both planes should be cancelled, which means $R_{16}, R_{26}, R_{36}, R_{46} = 0$, and $\eta_{xy} = 0$, $\eta'_{xy} = 0$.
- no additional compression, which means $R_{56} = 0$.

In vertical plane, the beam separation is provided by 5 fast kickers, a set of three vertical septum and deflection by two quadrupoles. In horizontal plane, a set of four septum is used. At the exit of bypass line, a small chicane is adopted for R_{56} compensation. The layout of bypass line is shown in Fig. 7.

Start to end simulation based on layout described above shows that after the bypass line, all the requirements are fulfilled and there is no significant emittance growth or micro bunching instability observed. The beam parameters at entrance and exit of bypass line are shown in Fig. 8. The longitudinal phase space distribution is shown in Fig. 9.

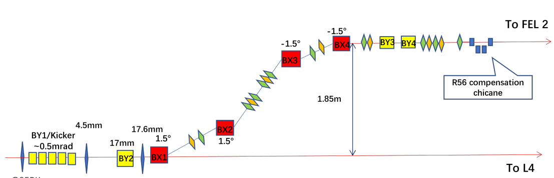

Figure 7: Layout of the bypass line.

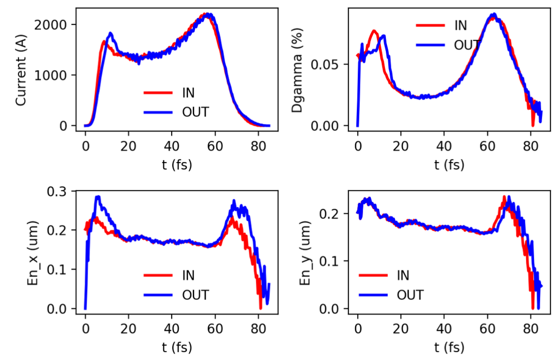

Figure 8: Comparison of beam parameters at entrance and exit of the bypass line.

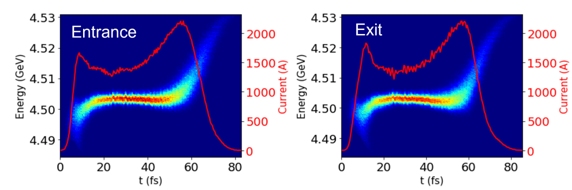

Figure 9: Phase space at entrance (left) and exit (right) of the bypass line.

CONCLUSION

In this paper, we present the physics design and optimization of the SHINE Linac. The start to end simulation results illustrate an 8 GeV high brightness beam with 1500 A flat-top current distribution as expected. The bypass line based on fast kicker and septum enables the beam extraction at lower energy.

ACKNOWLEDGEMENTS

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