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PHYSICAL DESIGN AND FEL PERFORMANCE STUDY FOR FEL-III BEAMLINE OF SHINE

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Abstract

The first hard X-ray free electron laser (XFEL) facility in China, the Shanghai High-Repetition-Rate XFEL and Extreme Light Facility (SHINE), is under construction, which allows for generating X-ray pulses in the photon energy range from 3 keV to 25 keV. To produce X-ray pulses with photon energy up to 25 keV, FEL-III undulator line of SHINE employs superconducting undulators. However, the smaller gap of the superconducting undulator poses serious wakefield effect reducing the FEL power, compared to the normal planar undulator. For a setup design optimization, the design and performance of the FEL-III undulator line are presented using start-to-end beam simulations at self-amplified spontaneous emission (SASE) and self-seeding mode. The wakefield impact on FEL performance is then investigated. A linear undulator tapering technique is adopted for recovering the FEL power to the non-wakefield level.

INTRODUCTION

Advanced high brightness X-ray light sources, X-ray free electron lasers (XFELs), bring significant opportunities to many fields for scientific exploring. The Shanghai High-Repetition-Rate XFEL and Extreme Light Facility (SHINE) is the first hard X-ray FEL facility in China [1], that will be fed by a superconducting linac at a high repetition rate, up to 1 MHz, and is being designed under a multi undulator line collaboration to generate X-ray of photon energy range from 3 keV to 25 keV. One of the undulator lines, FEL-III, will cover the spectral range between 10 keV and 25 keV. Reaching such wide spectral range requires high tunability of undulator parameter owing to the resonance condition of the FEL process. Superconducting undulator with a short period length is probably a better choice. However, the designed FEL performance is degrading due to resistive wall wakefield effects along the superconducting undulator line, which is more serious compared to normal conducting one.

Thus, it is necessary to investigate the wakefield impact on FEL performance of FEL-III, e.g., the pulse energy and FEL bandwidth. While various advanced FEL concepts are being explored for SHINE, this paper presents the detailed FEL simulations in only the self-amplified spontaneous emission (SASE) and self-seeding case for start-to-end electron beam coming from the superconducting linac. The basic parameters are listed in Table 1. The slice parameters of the start-to-end electron beam are illustrated in Fig. 1. The core of the bunch has relatively flat energy with a current of 1500 A, slice energy spread 0.8 MeV and slice emittance of 0.2 mm-mrad. The generations of 15 keV X-ray pulse based on a 8 GeV electron beam are performed. The FEL simulations were carried out by the time-dependent mode of GENESIS [2]. The interaction between X-ray pulse and crystal is calculated by BRIGHT [3].

Table 1: Normal Electron Beam and Undulator Parameters

Parameter	Value	Unit
Electron beam energy	8	GeV
Slice energy spread	0.8	MeV
Total charge	100	pC
Photon energy	15	keV
Undulator period length	16	mm
Undulator segment length	4	m
Break length	1	m
Total length	200	m

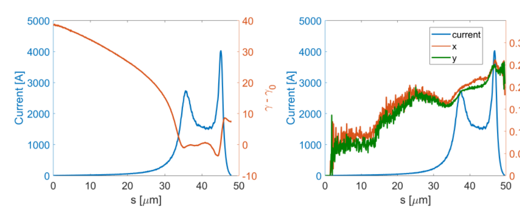

Figure 1: Slice energy (left), x (red) and y (green) slice emittance (right) of the start-to-end electron beam.

FEL PERFORMANCE

According to the project targets, several different operating modes have been explored for the different undulator line of SHINE. These modes include, but are not limited to, SASE, self-seeding [4], echo-enabled harmonic generation (EEHG) [5] and cascading schemes. FEL-III beamline is envisioned to operate from 10-25 keV in the SASE and self-seeding mode using the superconducting undulator. To estimate the capacity of FEL-III, we begin with the start-to-end simulation results without wakefield effects at 15 keV photon energy for SASE and self-seeding mode.

Fig. 2 illustrates the SASE performance of 15 keV output. The final pulse energy is about 380 μJ, corresponding to

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1.6×10^{11} X-ray photons. The peak power exceeds 20 GW at the flat profile of peak current 1500 A. At the exit of the undulator, the full width at half maximum (FWHM) bandwidth equals to nearly 40 eV, while the FWHM temporal duration is around 50 fs. The low transverse emittance of start-to-end electron beam generates a short saturation length. Thus, there is significant room to explore post-saturation tapering for higher pulse energy and spectral brightness.

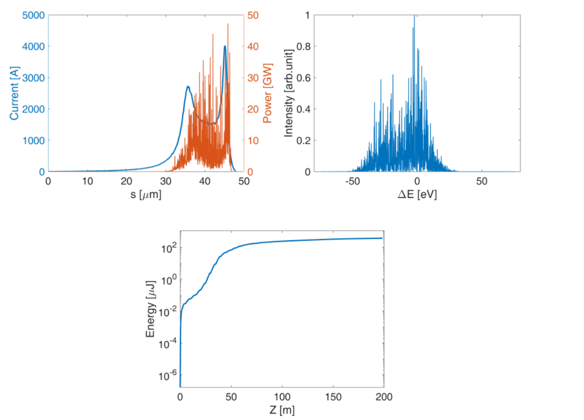

Figure 2: The radiation properties from FEL-III at photon energy of 15 keV: power along the FEL pulses (top left), spectra (top right) and pulse energy growth along the undulator (bottom).

The temporal coherence of SASE FEL can be improved with self-seeding scheme. An "8 cells + 32 cells" scheme with single crystal has been chosen in this simulation, in which 8 upstream undulator segments are used for SASE growth, and 32 downstream undulator segments serve as an FEL amplifier of the seeding. The simulation results are shown in Fig. 3.

The top left plot in Fig. 3 illustrates the gain curve of two undulator sections. The FEL pulse amplifies to just over 10 μJ in the first stage of amplification where single SASE spikes typically reach 3 GW. The monochromatized radiation had an average power of about 5 MW after the crystal filter function was applied, seen in the top right plot in Fig. 3, which is much larger than the shot noise power of refreshed electron beam. Most SASE power transmits through the crystal and becomes the background noise without interaction between delayed electron beam in the second stage. The final pulse energy exceeds 350 μJ, corresponding to 1.4×10^{11} X-ray photons. At the exit of the undulator, the spectrum bandwidth equals to nearly 0.35 eV (FWHM). A room to explore post-saturation tapering can be seen again.

WAKEFIELD IMPACT ON FEL PERFORMANCE

In order to achieve a 25 keV FEL photon energy with 8 GeV beam energy, a superconductive undulator with 16 mm period length and gap 4 mm is chosen. One of the critical issues of the superconductive undulator is the smaller

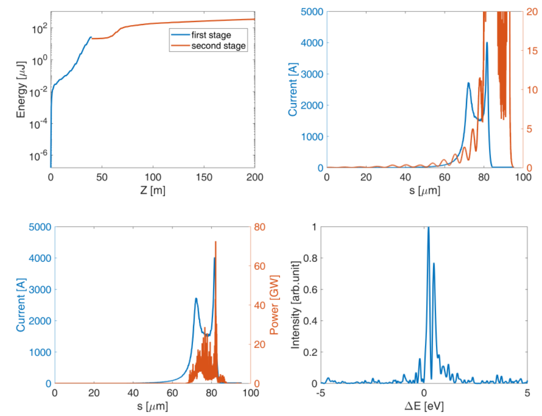

Figure 3: The self-seeding performance of FEL-III. The pulse energy gain curve (top left), the filtered pulse (top right), power along the FEL pulses (bottom left) and its spectra (bottom right) is shown. The flat part of the current profile covers a monochromatic seed generated by filtering of the diamond crystal (400).

operation gap, which is mainly related to the wakefield effect. Based on our previous wakefield study of the SXFEL facility [6, 7], an analytical formula is used to calculate the wakefield generated in the resistive wall. If a slice energy change on the order of the FEL Pierce parameter occurs due to the resistive wall wakefield, the FEL performance could be impacted. The slice energy change over the bunch length with the current can be seen in Fig. 4. The max beam energy losses due to the resistive wall wakefield are 190 keV/m from the theory. Then, the wakefield energy loss is imported timely and locally on the electron beam in GENESIS.

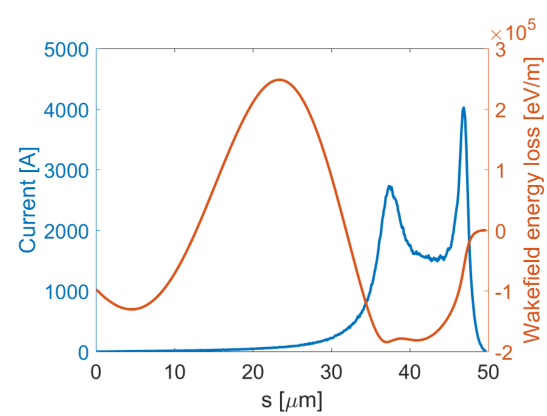

Figure 4: The peak current (blue) and the wakefield energy loss (red) along the bunch coordinate are shown.

The SASE performance is affected by the wakefield significantly. Fig. 5 illustrates the FEL power evolution along undulator (top left), final electron beam energy distribution (top right), FEL temporal profile (bottom left) and output spectrum (bottom right). It can be seen that wakefield will produce a non-linear energy modulation along the undulator. In the absence of the wakefield-induced energy loss (Fig. 2),

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the 15 keV FEL can finally achieve 380 µJ pulse energy with a peak power of approximately 20 GW. However, when the wakefield is considered (Fig. 5), the FEL pulse energy drops to 60 µJ and the spectrum degrades and broadens. The results show that the pulse energy of the final 15 keV FEL pulse will be degraded by a factor of 6 with a gradual beam energy loss of 38 MeV along the whole undulator section.

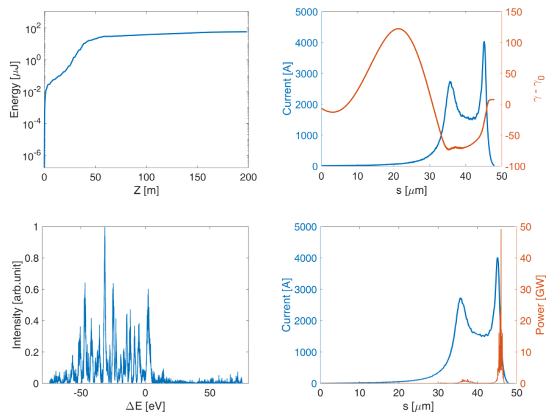

Figure 5: The pulse energy growth along undulator (top left), final energy distribution (top right), power along FEL pulse (bottom left) and spectrum (bottom right) is shown. After 200 m undulator line, a large energy modulation caused wakefield can be seen in energy distribution. The energy loss of electron beam results in resonant condition detune terminating the FEL process and degrading FEL pulse energy.

UNDULATOR TAPERING

The FEL pulse energy reduction caused by the continuous beam energy loss can be compensated by gradually tapering the undulator. In this section, a linear taper of SHINE undulator is adopted to bring pulse energy back to the level without wakefield effect. Besides the conventional linear taper, there are significant spaces to explore the undulator taper to reach a very high brightness. But a complicated algorithm for tapering optimization is beyond the scope of what we can address in this paper.

Fig. 6 shows the start-to-end simulation results of SASE and self-seeding mode with an undulator taper coefficient of 0.7% on whole 200 m undulator line. The SASE results reach 390 µJ pulse energy which returns to the level without wakefield. Due to the resonant energy detune caused by tapering effect, the radiation power from the peak of current 4000 A is smaller than the result without wakefield. The self-seeding mode can generate 360 µJ pulse corresponding $1.5{\times}10^{11}$ photons per pulse with narrower bandwidth (FWHM) of 0.17 eV. The first tapered undulator part in self-seeding mode causes a lower SASE background resulting in a richer signal-to-noise ratio.

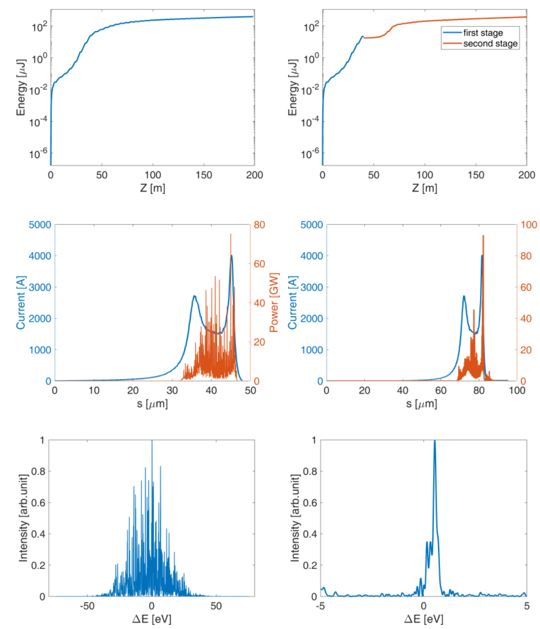

Figure 6: Left curves show the SASE results, and right curves show self-seeding results. Pulse energy along undulator(top), power along FEL pulse (center) and related spectrum (bottom) are shown. With a linear 0.7% tapering along whole 200 m undulator, the radiation could recover to the level without wakefield impact.

CONCLUSION

We performed the start-to-end simulations for SASE and self-seeding mode at the FEL-III of SHINE. In the case of SASE, about $1.6{\times}10^{11}$ photons per pulse with 40 eV bandwidth can be generated. With a self-seeding scheme, the output at 15 keV is $1.4{\times}10^{11}$ photons per pulse with 0.35 eV spectral bandwidth, corresponding to $4{\times}10^{14}$ photons/s/meV spectral flux. In the start-to-end SASE simulation with the wakefield effects, the total beam energy loss of 38 MeV along the undulator line causes serious degradation of FEL performance: the pulse energy drops to 60 µJ from original 380 µJ. The FEL performance loss caused by wakefield can be compensated with a linear undulator taper of 0.7%. Besides, there are significant spaces to explore the undulator taper to reach a very high brightness. More in-depth studies will be done in future.

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REFERENCES

[1] C. Feng and H.-X. Deng, “Review of fully coherent free-electron lasers”, *Nuclear Science and Techniques*, vol. 29, p.160, 2018. doi:10.1007/s41365-018-0490-1

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP063

[2] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 429, pp. 243–248, 1999. doi:10.1016/S0168-9002(99)00114-X

[3] N.-S. Huang, K. Li, and H.-X. Deng, "BRIGHT: the three-dimensional X-ray crystal Bragg diffraction code", *Nuclear Science and Techniques*, vol. 30, p. 39, 2019. doi:10.1007/s41365-019-0559-5

[4] J. Amann *et al.*, "Demonstration of self-seeding in a hard-X-ray free-electron laser", *Nature Photonics*, vol. 6, p. 693, 2012. doi:10.1038/nphoton.2012.180

[5] G. Stupakov, "Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation", *Physical Review Letters*, vol. 102, p. 074 801, 2009. doi:10.1103/PhysRevLett.102.074801

[6] M. Song, K. Li, C. Feng, H. Deng, B. Liu, and D. Wang, "Wake-field issue and its impact on x-ray photon pulse in the sxfel test facility", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 822, pp. 71–76, 2016. doi:10.1016/j.nima.2016.03.089

[7] M.-H. Song, C. Feng, D.-Z. Huang, H.-X. Deng, B. Liu, and D. Wang, "Wakefields studies for the sxfel user facility", *Nuclear Science and Techniques*, vol. 28, no. 7, p. 90, May 2017. arXiv:1611.00883