A SCHEME OF FULLY COHERENT X-RAY FREE ELECTRON LASER FOR THE SHINE BASED ON FRESH-SLICE

Y. X. Liu†, T. Liu
Shanghai Institute of Applied Physics, Chinese Academy of Sciences Shanghai, China
University of Chinese Academy of Sciences, Beijing 100049, China
Shanghai Advanced Research Institute Chinese Academy of Sciences, Shanghai, China

Abstract

In this paper, the fresh-slice self-seeding free electron laser scheme is studied, and the feasibility of its application in the SHINE project is analyzed. The scheme used the fresh-slice method to generate the beam with adjustable spatial distribution, which can effectively improve the longitudinal coherence and stability of the self-seeding output radiation. Through the FEL simulation, we demonstrated that this scheme can produce a highly stable, narrow bandwidth pulse output under the SHINE's parametric conditions, which will be beneficial to further improve the performance of this device in the future.

INTRODUCTION

Conventional SASE pulses originate from stochastic noise and are essentially random [1], which significantly affects the stability and output power of the self-seeding FEL. However, when a self-seeding scheme generates FEL using an ultra-short, high-current electron beam with a specific duration [2], the level of fluctuations can be reduced to a few percent while also maintaining a temporally coherent FEL output, resembling an ideal laser or an external-seeded FEL.

The fresh-slice method, also paving the way to very high peak power and high brightness XFEL pulses [3], uses either two different electron bunches or two single bunch slices, one to generate the seed signal and the other to amplify it in a tapered undulator to very high peak power. The method effectively eliminates the compromise between the seed power at the monochromator exit and the energy spread of electron slices within the seeded undulator section [4], thereby enhancing electron capture and reducing susceptibility to sideband instability [5].

Using the fresh-slice method to enhance the stability and power of self-seeding is an extremely appealing choice, while the SHINE project focuses on studying self-seeding FEL schemes covering the 5-15 keV hard X-ray range [6]. The changes to the self-seeding approach would contribute to improve the future performance of the SHINE. In this manuscript, we will demonstrate the simulation results of a bunch with high-current head using the fresh-slice method, which will provide some insights for the design of SHINE in the future.

* Work supported by the CAS Project for Young Scientists in Basic Research (YSBR060), the Shanghai Natural Science Foundation (23ZR1471300), and the CAS-Helmholtz International Laboratory on Free Electron Laser Science and Technology (HZXM2022500500).
† email address: liuyixuan@sinap.ac.cn.

FRESH-SLICE SELF-SEEDING

A schematic of the fresh-slice self-seeding used in the simulation is shown in Fig. 1. Selectively lasing with different slices of the electron beam is achieved with the fresh slice method. The electron bunch experiences a head-tail transverse kick by the wakefield generated in the D1 dechirper, set to an offset from the machine axis. Before the initial undulator phase, orbit correctors are utilized to direct the bunch into a head-lasing orbit. A saturated photon pulse is produced in the first section of the high-current bunch head. Then the photon pulse transmits from the diamond monochromator and generates a narrow bandwidth portion of it that is diffracted. The transmitted X-ray pulse presents a short, wide-bandwidth pulse followed by a stable, long, narrow-bandwidth tail. The chicane is used to delay the electron bunch tail such that it is overlapped with the narrow-bandwidth tail of the photon pulse. The bunch orbit is switched to a tail-lasing one around the chicane, and the monochromatic seed is amplified by the fresh electrons on the bunch tail in the second undulator section.

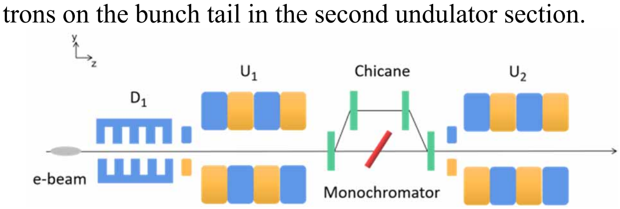

Figure 1: Schematic layout of the proposed scheme based on fresh slices.

Beam Parameters

Based on the proposed scheme, FEL simulations were performed using the code Elegant [7] and Genesis 1.3 [8]. The overall electron beam parameters and radiation parameters used in the simulations are presented in Table 1.

Table 1: Electron Beam and Radiation Parameters

Parameter	Value	Unit
Beam energy	8	GeV
Energy spread	0.01	%
Normalized emittance	0.5	mm • mrad
Undulator period	2.6	cm
Undulator strength K	1.3415	-
FEL wavelength	0.1	nm

ISBN: 978-3-95450-265-3 doi:10.18429/JACoW-SAP2023-MOPB027

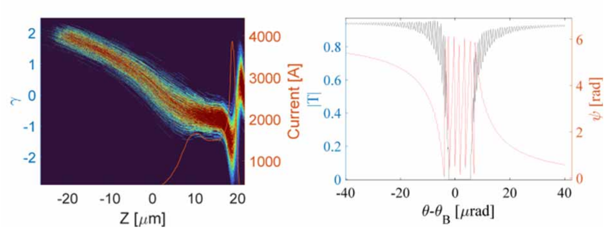

Figure 2: The beam profile and the modulus and phase of the transmissivity function (sigma polarization) from a diamond crystal in the Bragg (400) diffraction with a thickness of 0.1 mm.The relevant data was obtained by using the open X-ray software XOP [9].

In the first stage of the scheme, the on-axis high-current head of the bunch generates saturated single-spike-like SASE pulses which will effectively modulate the bunch tail in the second stage, so as to maintain the energy spread and improve output stability.

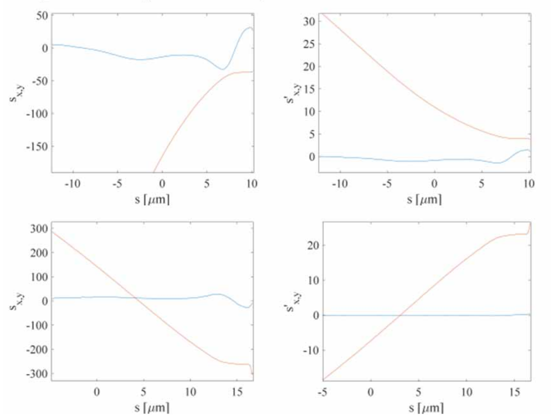

Figure 3: The sliced transverse offsets (top-left) and the angular deviation (top-right) of x (blue) and y (red) after the dechirper. Before the seeded stage (bottom). Bunch tail is at the left side of s coordinate axis.

The beam envelope of s = 0 position is matched for FEL radiation. The matched results are shown in Fig. 3. It is noted that the mismatch and offset of the beam exist, that will impact on the radiation pulse performance.

SIMULATIONS

Each undulator module in the beamline is a 4-m-long planar structure with 152 periods of λu = 26 mm and an adjustable magnetic gap. The simulation of enhanced self-seeding and fresh-slice self-seeding schemes was performed under the undulator condition, and the beam parameters were the same.

SASE Stage

A series of 50 separate GENESIS runs have been performed to analyze the statistical fluctuation of the radiation pulse. Figure 4 presents the 12.4 keV SASE FEL performance. For the enhanced self-seeding scheme, the output radiation in both the time domain and frequency domain is similar to the SASE radiation because of the low current contrast and the lack of taper in the SASE stage to maintain the energy spread of the bean portion with flat current. For the fresh-slice scheme, the output has a relatively low power but a "pure" spectrum.

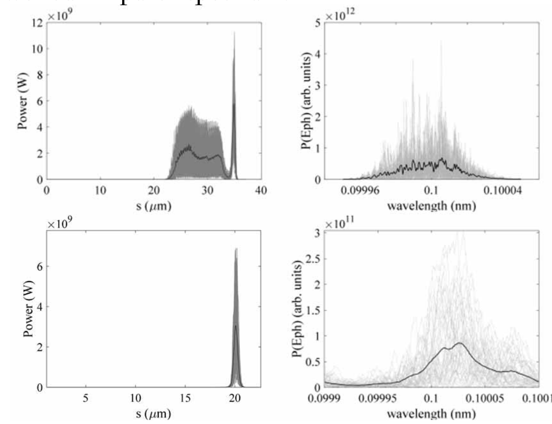

Figure 4: The saturation power distribution (left) and the spectrum (right) of 50 SASE pulses. (Top) Ehanced self-seeding. (Bottom) With fresh-slice method.

Seeded Stage

Figure 5 shows the seed power profile from the enhanced self-seeding and the fresh-slice self-seeding. Obviously, the high current spike reaches saturation at the mono, which significantly reduces intensity fluctuations of the seed compared to enhanced self-seeding, where the signal is interfered with by the wide-bandwidth regime. Comparing wake monochromator power, the seed with a fresh-slice SASE pulse has a more stable mode than a normal SASE pulse with the same beam parameters.

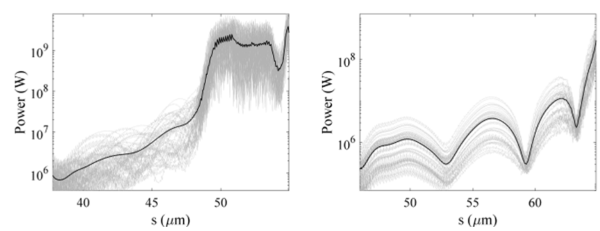

Figure 5: The seed power after the mono filter of the enhanced self-seeding scheme (left). With the fresh-slice method (right).

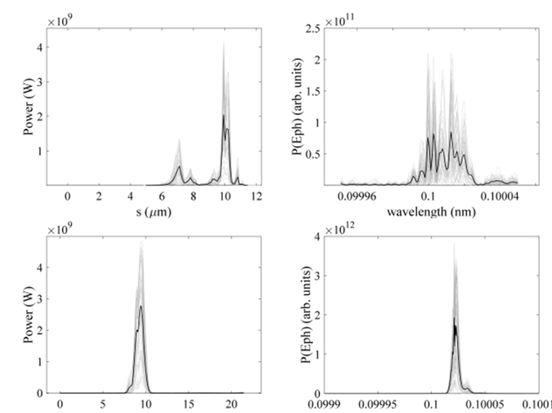

Figure 6: Results of power profile (top-left) and spectrum (top-right) of the self-seeding. (Bottom) With fresh-slice method.

As shown in Fig. 6, the output radiation with the fresh-slice method at the exit of the radiation undulator is about 3 GW, with a normalized spectral width (FWHM) of 8× 10^{-5} reduced about 4 times compared with the enhanced self-seeding scheme under the same beam parameters. The gain curve of average power is shown in Fig. 7. The average seed power is over 1MW, and the result of exponential gain is about 10μJ (saturation).

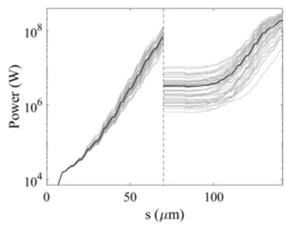

Figure 7: FEL power along the undulator beamline for the fresh-slice scheme.

The final result shows a considerable margin for improvement. The high-current still produces spikes within the wide-bandwidth pulse, leading to inadequate control over the power fluctuations of the seed. To enhance the stability of the system, one possible approach is to compress the beam, which would allow for better control over the number of spikes. Furthermore, this scheme exhibits notable benefits in terms of harmonic lasing self-seeding. It effectively overcomes the trade-off between seed power and electron slice energy spread, which is a crucial factor influencing the performance of the harmonic. This aspect warrants further investigation and exploration.

CONCLUSION

Through the beam parameters of the SHINE, the enhanced self-seeding results combined with fresh-slice are simulated. Shot-to-shot results prove the reliability of the scheme. To improve the stability of the output and generate high-quality harmonics through this scheme, the related work is ongoing.

REFERENCES

[1] Saldin, Evgenij L., Evgeny A. Schneidmiller, and M. V. Yurkov, "Statistical properties of radiation from VUV and X-ray free electron laser", *Optics communications*, vol. 148.4-6, pp. 383-403, 1998.

[2] Hemsing, Erik, Aliaksei Halavanau, and Zhen Zhang. "Enhanced self-seeding with ultrashort electron beams", *Physical Review Letters*, vol. 125.4, p. 044801, 2020.

[3] Emma, C. *et al.*, "Experimental demonstration of fresh bunch self-seeding in an X-ray free electron laser", *Applied Physics Letters*, vol. 110.15, 2017.

[4] Ben-Zvi, Ilan, K. M. Yang, and L. H. Yu, "The "fresh-bunch" technique in FELS", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 318.1-3, pp. 726-729, 1992.

[5] Emma, C., *et al.*, "High efficiency, multiterawatt x-ray free electron lasers", *Physical Review Accelerators and Beams*, vol. 19.2, p. 020705, 2016.

[6] Liu, Tao, X. Dong, and C. Feng, "Start-to-end simulations of the reflection hard X-ray self-seeding at the SHINE project", *Proceedings of the 39th international free electron laser conference—FEL*, vol. 19, 2019.

[7] M. Borland, *User's Manual for Elegant*, APS-ANL, Chicago, IL, 2017.

[8] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL-simulation code", *Nucl. Instrum. Methods Phys. Res. A*, vol. 429, no. 1-3, p. 243, 1999. doi:10.1016/S0168-9002(99)00114-X.

[9] ESRF, X-ray Oriented Programs Software Package, https://www.aps.anl.gov/Science/Scientific-Software/XOP.