A bunch-by-bunch polarization switching scheme for high-repetition-rate hard X-ray FELs

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Abstract

Over the past two decades, rapid advancement of free electron laser (FEL) technology has effectively addressed extensive research requirements. Currently, nearly all FEL facilities generate high-quality radiation with controllable polarization via devices like APPLE-type undulators or DELTA undulators. However, elliptically polarized undulators alone cannot achieve hertz-level or above polarization switching, which complicates experiments such as time-resolved circular dichroism spectroscopy. To solve this, based on the FEL-II beamline of the Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility, this study proposes integrating a custom-designed bunch-by-bunch phase shifter into APPLE-type undulator arrays (following crossed-planar undulator design logic). We analyzed factors influencing post-superposition radiation polarization under ideal Gaussian mode propagation, determined optimal parameters for both fast polarization switching performance and fixed-polarization radiation quality, conducted validation via start-to-end simulations, and presented the phase shifter' s detailed design. Results show high-frequency undulator-section polarization switching is achievable with only slight polarization purity trade-off, and the scheme is universally applicable to FEL facilities with high-energy electron beam.

Full Text

Preamble

A bunch-by-bunch polarization switching scheme for high-repetition-rate hard X-ray FELs∗ Zhang-feng Gao,1 Yong-fang Liu,1 Rui-ping Wang,1 Yong-mei Wen,1 Qi-sheng Tang,1 Tao Liu,1 Duan Gu,1 and Hai-xiao Deng1, † 1Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201200, China Over the past two decades, rapid advancement of free electron laser

(FEL) technology has effectively ad- dressed extensive research requirements. Currently, nearly all FEL facilities generate high-quality radiation with controllable polarization via devices like APPLE-type undulators or DELTA undulators. However, ellipti- cally polarized undulators alone cannot achieve hertz-level or above polarization switching, which complicates experiments such as time-resolved circular dichroism spectroscopy. To solve this, based on the FEL-II beamline of the Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility, this study proposes integrating a custom-designed bunch-by-bunch phase shifter into APPLE-type undulator arrays (following crossed-planar undulator design logic). We analyzed factors influencing post-superposition radiation polarization under ideal Gaussian mode propagation, determined optimal parameters for both fast polarization switching performance and fixed-polarization radiation quality, conducted validation via start-to-end simulations, and presented the phase shifter’ s detailed design. Results show high-frequency undulator-section polarization switching is achiev- able with only slight polarization purity trade-off, and the scheme is universally applicable to FEL facilities with high-energy electron beam.

Keywords: Free electron laser, Fast polarization switch, Bunch-by-bunch phase shifter, Crossed-planar undulators

INTRODUCTION

X-ray free electron lasers (XFELs) produce X-rays by rel- ativistic electrons passing through periodic magnetic struc- tures, offering radiation spanning the electromagnetic spec- trum (from terahertz to X-ray) with high brightness and ultra- fast time characteristics[1]. Initially, global XFEL facilities (or their baselines) relied on self-amplified spontaneous emis- sion (SASE) and only generated horizontally polarized light, as they used planar undulators exclusively as radiators[2–4].

Later, more XFELs achieved fully coherent radiation via high gain harmonic generation (HGHG) or echo-enabled harmonic generation (EEHG)[5-8]. At first, all these XFEL facili- ties remained limited to horizontally polarized light, preventing them from detecting chiral structures or molecules.Chiral molecules typically exhibit identical chemical and physical properties, yet behave differently in chiral environments and possess opposite optical activities: when interacting with polarized radiation, one enantiomer rotates the polarization plane clockwise, while the other rotates it counterclockwise.

Given that circularly polarized light is critical for electron spin detection and vital to researching chiral molecules and magnetic materials with chiral structures, circularly polarized FELs have been developed over the past decade using ellip- tically polarized undulators (EPUs) such as APPLE-type and DELTA undulators[9-12]. These undulators replace planar magnetic fields with spiral ones, enabling electron beams to oscillate simultaneously in horizontal and vertical directions.

Circular dichroism (CD) is an analytical technique that studies the differential absorption of left-handed and right- ∗ Supported by the National Natural Science Foundation of China (12125508, 12541503), the National Key Research and Development Pro- gram of China (2024YFA1612104), and Shanghai Pilot Program for Ba- sic Research -Chinese Academy of Sciences, Shanghai Branch (JCYJ- SHFY-2021-010). † Corresponding author, denghx@sari.ac.cn. handed circularly polarized light by chiral molecules. Chi- ral substances, lacking mirror symmetry, interact unequally with these two polarizations, producing measurable CD sig- nals. Among circularly polarized light applications, CD spectroscopy is indispensable for characterizing chiral molecu- lar structures with two typical types: natural circular dichro- ism (natural CD) and magnetic circular dichroism (MCD).

Natural CD arises from structural asymmetry (a static prop- erty independent from external fields) and is widely used in biochemistry research and pharmaceutical analysis, such as detecting the α-helicity and the unfolding/folding of pro- teins as well as the enantiomeric excess determination[13–15]. MCD, by contrast, is magnetic-field-induced: external magnetic fields cause Zeeman splitting of electronic energy levels in any molecule (chiral or achiral), leading to differential absorption. It is commonly applied in inorganic chem- istry and materials science. For instance, X-ray MCD at the Fe K edge has been observed[16], time-reversal sym- metry breaking in altermagnets confirmed[17], and com- plex magnetization configurations identified via MCD[18].

Early CD applications relied on steady-state techniques, for which EPU-generated FELs fully meet measurement needs.

However, addressing current research questions about rapid- process intermediate states (e.g., protein dynamics) requires faster methods to probe secondary structure change time scales. Chiral change observation demands studying time ranges from seconds to femtoseconds, depending on the molecule type—potentially measurable via time-resolved cir- cular dichroism (TRCD) spectroscopy or time-dependent op- tical rotation[19–23]. Photoelastic modulators can serve as a solution to rapidly modulate measuring light polarization for TRCD, but are limited to 20–100 kHz and cannot reach X-ray or higher photon energies. Combining standard CD detection with stopped-flow or temperature-jump techniques works for micro-/millisecond time regimes[24, 25], while pump-probe setups extend to sub-picosecond and femtosec- ond domains[26, 27]. If FEL facilities achieve ultrafast po- Fig. 1 [Figure 1: see original paper]. Layout of SHINE. larization switching (1 MHz) via undulators, it will be much more efficient and convenient for direct TRCD spectroscopy and expand possibilities for pump-probe TRCD experiments.

Notably, FELs, especially with ultra-high time resolu- tion and repetition rate, exhibit unique advantages over syn- chrotron radiation for ultrafast process detection, analogous to ’ filming’ dynamic processes of samples in real time. However, EPUs face a critical limitation in polarization switch- ing speed. They cannot change their operating state at fre- quencies above 1 Hz, as their polarization adjustment relies on mechanical adjustments of gap and phase shift. Specifically, for facilities like FERMI (where all undulators are EPUs), switching polarization takes several minutes; even when EPUs only function as afterburners, the process still re- quires several seconds. To improve this, a theoretical solution involves using multiple kickers in conjunction with a pair of EPUs, which can potentially achieve polarization switching at a higher frequency of tens of Hz[28], though it remains far from the MHz-level demand for ultrafast TRCD. Beyond EPUs, another validated approach to generating circularly po- larized X-ray FELs was proposed by K.-J. Kim, which em- ploys crossed-planar undulators (CPUs)[29, 30]. In this con- figuration, the electron beam sequentially passes through hor- izontal and vertical magnetic field regions. The polarization state of the emitted FEL radiation is predominantly deter- mined by the phase difference between the horizontal and vertical radiation components. This intrinsic correlation cre- ates the possibility of fast, arbitrary polarization switching, addressing a key technical bottleneck of EPUs for ultrafast chiral dynamics studies.

In spite of the advantage of CPUs in enabling fast polar- ization switching, the circular polarization degree of CPU ra- diation under the SASE mode is theoretically constrained to above 80%. This limitation arises from two key factors: the relative slippage between the horizontal and vertical compo- nents of the photoelectric field in vertical undulators, and the distortions in both intensity and phase between the vertical and horizontal radiation fields. In contrast, the polarization degree of the EPU afterburner is significantly higher, reaching nearly 100% [31]. Given that harder electron beams, charac- terized by higher beam energy, exhibit superior phase space stability, rendering them less susceptible to the space charge effect during the drift section. Such enhanced stability holds the potential to improve polarization performance. Notably, the Shanghai High Repetition Rate X-ray Free-Electron Laser and Extreme Light Facility (SHINE) is well-suited to meet the demand for high-energy electron beams, with beam en- ergy up to 8 GeV, and will operate at a maximum repetition rate of 1 MHz. However, this combination of high beam en- ergy and high repetition rate introduces substantial challenges in the design of an electron beam phase shifter. Specifically, the core challenge lies in achieving a balanced optimization the phase-shift capability, among three critical parameters: the pulsating current intensity, and the overall length of the device.

The paper is structured as follows. In Sec. II, the parame- ters of SHINE and the method of calculating the polarization degree of FELs are described. The simulation results of the polarization switch in SHINE facility are presented in Sec.

III. In Sec. IV, there is the design of such a bunch-by-bunch phase shifter. The conclusions and outlook are summarized in Sec. V.

IV. BRIEF DESCRIPTION OF SHINE AND POLARIZATION CALCULATION SHINE, currently under construction in Shanghai, repre- sents the first hard X-ray FEL facility in China. As a flagship project of the Na-

> tional Science and Technology Infrastruc- ture Program, its core objective is to generate ultra-bright and ultra-short X-ray pulses with a repetition rate of up to 1 MHz, enabling the probing of matter at the sub-nanometer spatial scale and femtosecond temporal scale. At present, SHINE has two undulator lines under construction, designated as FEL-I and FEL-II respectively, as shown in Fig. 1 [32]. Specifically, FEL-I is designed to cover a photon energy range of 3–15 keV and will operate in both SASE and self-seeding modes, with polarization restricted to the horizontal direction. The planar undulators for FEL-I are 4 meters in length, featur- ing a period of 26 mm and a maximum peak magnetic field of approximately 1.05 T. In contrast, FEL-II functions as the soft X-ray line, spanning a photon energy range of 0.2–3 keV, with the first lasing planned for 2026. Its operational modes include SASE, EEHG, and cascaded EEHG, among others, and it possesses the capability to switch polarization across its entire wavelength range. The key parameters of FEL-II are summarized in Table. 1. Owing to the lower photon en- ergy requirement of FEL-II, its undulator periods are signifi- cantly longer than those of FEL-I, while the undulator length Fig. 2 [Figure 2: see original paper]. Layout of the polarization switch scheme. remains consistent with that of FEL-I. It is noteworthy that when the photon energy approaches the lower end of FEL- II' s range, the facility must operate under the condition of reduced electron beam energy—for instance, around 4 GeV.

In addition to the planar undulators, 4 EPUs are installed downstream of them, serving as an afterburner. These EPUs are capable of operating in horizontal, vertical, or circular po- larization modes with an undulator period of 55 mm, consis- tent with that of the planar undulators and aiming at achieving comparable radiation wavelength and quality. Following pre- bunching of the electron beam by the reverse-tapered undula- tors, the EPUs can generate FEL radiation with variable po- larization and high polarization purity (exceeding 99%). This high purity is achieved when all the EPUs are synchronized to emit either left-handed or right-handed circularly polarized light. At specific wavelengths, the pulse energy of the radia- tion may reach 500 µJ or higher. Beyond standard polariza- tion control, schemes for fast polarization switching have also been proposed based on these EPUs. These schemes leverage the EPUs' diverse operating modes and require minimal ex- ternal auxiliary equipment. Notably, thanks to the ultra-high repetition rate of the electron beam, the theoretical maximum polarization switching frequency can reach up to 1 MHz, and this breakthrough opens up new avenues for related experi- mental applications.

TABLE 1 . Main parameters of FEL-II Value Unit

1 MHz

Parameter Beam energy Repetition rate Slice relative energy spread 0.015 % Normalized emittance Peak current Bunch charge Undulator period Undulator length 0.45 µrad 0.055 m To determine the polarization degree of FEL radiation at the measurement location, Stokes parameters are commonly employed. These parameters can be derived from the inten- sity and phase information of the photoelectric field, as shown in Eq. 1:

S0 = (cid:10)Ex S1 = (cid:10)Ex 2(cid:11) + (cid:10)Ey 2(cid:11) − (cid:10)Ey 2(cid:11) 2(cid:11) S2 = 2 Ex Eycos (ϕx (t) − ϕy (t)) S3 = 2 Ex Eysin (ϕx (t) − ϕy (t)) This set of four real numbers fully characterizes the po- larization state of electromagnetic radiation, irrespective of its coherence. Specifically, S0 quantifies the total intensity of the radiation; S1 distinguishes between horizontal (when S1 > 0) and vertical (when S1 < 0) polarization; S2 differ- entiates between linear polarization oriented at $+45^\circ$ (when S2 > 0) and -45° (when S2 < 0); S3 describes the circular polarization component, where positive values correspond to right-handed circular polarization and negative values to left- handed circular polarization. All four Stokes parameters can be obtained through FEL simulations.

Following the pre-bunching of electron beams in the pla- nar undulator section, two approaches are available to achieve fast polarization switching: the crossed-planar undulator scheme and the crossed-circular undulator scheme. For the crossed-planar undulator scheme, the FEL radiation gener- ated from two sources exhibits distinct polarization direc- tions. One source is the pre-bunching section combined with the first undulator in the afterburner, which produces horizon- tally polarized FEL radiation; the other is the final undulator in the afterburner, which generates vertically polarized FEL radiation. Due to this clear distinction in polarization direc- tions, the Stokes parameters can be readily determined, and the degree of circular polarization can be expressed by Eq. 2.

Dcir = |2 ExEysin (ϕx (t) − ϕy (t)) | 2(cid:11) + (cid:10)Ey (cid:10)Ex 2(cid:11) While in the case of the crossed-circular undulator scheme, the pre-bunching section still produces horizontally polarized FEL radiation, albeit with extremely low intensity. By con- trast, the undulators in the afterburner generate FEL radiation with distinct circular polarizations. One emits left-handed cir- cularly polarized radiation, and the other emits right-handed circularly polarized radiation. To facilitate subsequent anal- ysis, these two circularly polarized FEL signals need to be decomposed into their horizontal and vertical linear polar- ization components. Specifically, the left-handed and right- handed circularly polarized radiation is decomposed into hor- izontal and vertical linear components with a phase difference of $+90^\circ$ and -90° respectively. Based on this decomposition, the degree of linear polarization can be expressed by Eq. 3.

Dlin = (cid:112) 2 + S2 (cid:113)(cid:0)(cid:10)Ex 2(cid:11) − (cid:10)Ey 2(cid:11)(cid:1)2 + (2 ExEycos (ϕx (t) − ϕy (t)))2 2(cid:11) (cid:10)Ex 2(cid:11) + (cid:10)Ey Given that the two schemes share similar operating principles, and considering the greater focus on circular polar- ization switching, this paper will primarily discuss the CPU scheme. In the simulations, a properly designed reverse ta- per is applied to the pre-bunching section. This design results in the FEL radiation intensity from the afterburner being two orders of magnitude higher than that from the pre-bunching section—an outcome that implies the FEL field component from the upstream pre-bunching section can be neglected.

As a numerical example, the three-dimensional FEL simu- lations are conducted by Genesis 1.3[33]. The electron beams are chosen to be Gaussian profile and the radiation field file is obtained 100 m downstream of the last EPU. As the phase information may be incorrectly changed during the long drift section, Optics serves as a substitute in the simulation. After that, the start-to-end (S2E) simulations will be conducted to obtain a credible conclusion.

III. SIMULATION RESULTS For conventional polarization schemes, EPUs are arranged sequentially and uniformly downstream of the planar undulators, serving as an afterburner. All these EPUs operate in an identical mode. For instance in SHINE, the basic FODO (Focusing-Defocusing) module consists of 4-meter- long EPUs paired with 1-meter-long drift sections. This con- figuration generates circularly polarized FEL radiation with an ultra-high polarization purity exceeding 0.99. In contrast, the fast polarization switching scheme adopts a different ar- chitecture. All EPUs are divided into two groups, where each group operates in a consistent mode (e.g., one group in hori- zontal polarization mode and the other in vertical polarization mode, or one in left-handed circular polarization mode and the other in right-handed circular polarization mode). Ad- ditionally, one of the drift sections is extended and replaced with a new bunch-by-bunch phase shifter, which enables the coupling of radiation with different polarization states. This configuration is illustrated in Fig. 2. To ensure that each group can produce sufficient radiation intensity, the 4 EPUs are evenly split into two groups. From the perspective of polarization purity, two key conditions must be met. First, the intensity of FEL radiation generated by EPU1 and EPU2 should be comparable to that generated by EPU3 and EPU4; second, the phase distributions of the radiation from the two groups must be well-matched.

Assuming the new drift section has a length of 3 meters, the FEL wavelength is 1 nm, and 8 planar undulators are used as the pre-bunching section, the simulated total polarization re- sults are presented in Fig. 3 Figure 3: see original paper. These results fall far short of expectations: the degree of circular polarization is below 0.6, while the linear polarization component is even significantly Fig. 3. (a) Polarization degree at 1 nm. Blue: total polarization, green: 45°/135° linear polarization, red: circular polarization, yel- low: 0°/90° linear polarization. (b) Power profiles of different radia- tion. Red: EPU1&2, green: EPU3&4. (c) Horizontal FEL spots. (d) Vertical FEL spots. stronger than the circular component. This phenomenon indi- cates a substantial discrepancy in radiation intensity between the two groups of EPUs—a conclusion further confirmed by Fig. 3(b), which shows that the radiation intensity from the latter group of EPUs is nearly 10 times higher than that from the former group. In principle, this intensity imbalance arises because the enhancement of vertically polarized radiation is much more pronounced than that of horizontally polarized ra- diation as the electron beam bunching factor increases. To mitigate this significant intensity difference, the subsequent simulation was adjusted based on the gain curve. Only one EPU was operated in the vertical polarization mode, while the others remained in the horizontal mode. The results of this modified simulation are illustrated in Fig. 4 [Figure 4: see original paper]. In this case, the FEL radiation intensities from the two polarization channels are relatively well-matched, leading to a significant improve- ment in polarization performance. The degree of circular po- larization reaches approximately 0.93, and the total degree of polarization is as high as 0.98. Although this polarization purity is not comparable to that of schemes without fast po- larization switching, it is sufficient to meet the requirements of numerous experimental scenarios. Notably, all simulations were performed before the FEL reaches saturation in order to minimize the impact of phase distortion between the horizon- tal and vertical radiation components. 0246Phase shift/rad00.20.40.60.81Polarization050100150Time/fs024681012Power/GW

5 5.5 m. Evidently, the phase difference between the horizon- tal and vertical radiation components—strongly influenced by both FEL wavelength and drift length, which plays a critical role in the degradation of both total and circular polarization purity. This effect becomes particularly pronounced for the 2.344 nm wavelength case when the drift length reaches 4.5 m or longer. The core factor underlying this phenomenon is deemed to be the drift length normalized by the radiation’ s Rayleigh length [34]—a hypothesis that aligns well with the differing results observed for the two wavelengths. As a re- sult, to ensure polarization purity for relatively low photon energies, the drift length must not be excessively long, with a suggested maximum limit of approximately 5 m. Notably, for the 2.344 nm wavelength case, the side length of the square receiving surface in simulation was set to 2 mm, rather than 1 mm used for the 1 nm wavelength case.

Fig. 5 [Figure 5: see original paper]. Polarization degree varies with the drift length. Dashed: 1 nm, solid: 2.344 nm, blue: total polarization, red: circular polariza- tion.

The curves corresponding to the 2.344 nm wavelength in Fig. 5 are less smooth than anticipated, which may be at- tributed to inadequate matching during the long drift section, resulting in slight variations in radiation size and divergence.

In principle, a smaller divergence is conducive to higher po- larization purity; thus, the results for different beam sizes in the pre-bunching section are presented in Fig. 6 Figure 6: see original paper. As the transverse beam dimension decreases, the total polarization evolves from remaining nearly constant to declining increas- ingly rapidly, eventually converging with the circular polarization—consistent with theoretical predictions. However, for large beam sizes, a significant discrepancy persists be- tween the circular and total polarizations. Notably, this deficit in circular polarization purity could potentially be mitigated by reducing the intensity difference between the two FEL pulses. Nevertheless, detuning of the afterburner is unaccept- able, as it would result in poor phase coherence and severely degraded total polarization. Correspondingly, the beam size in the afterburner exerts minimal influence on the total polar- ization, but its effect on the circular polarization is relatively (a) Polarization degree. Blue:

Fig. 4. Optimized polarization purity, FEL power profiles and FEL spots at 1 nm. total polarization, green: 45°/135° linear polarization, red: circular polarization, yel- low: 0°/90° linear polarization. (b) Power profiles of different radia- tion. Red: EPU1&2, green: EPU3&4. (c) Horizontal FEL spots. (d) Vertical FEL spots.

The 3-meter-long drift section demonstrates excellent per- formance in terms of polarization purity; however, such a short drift length may fail to meet the requirements of the bunch-by-bunch phase shifter, posing a challenge to clari- fying the impact of drift length on polarization purity. As noted earlier, electron beams with ultra-high energy are min- imally affected by the space charge effect; for the sake of simplicity, this effect is neglected in the present study. To investigate the drift length dependence, the drift length was scanned over a range of 3 m to 7 m, and the resulting varia- tion in final polarization is illustrated in Fig. 5. Throughout the scanning process, the transverse beam size remained un- changed in the pre-bunching section and was essentially con- stant in the afterburner. This stability eliminates any influ- ence arising from differences in gain length, thereby enhanc- ing the accuracy of the scanning results. For a FEL wave- length of 1 nm, the circular polarization exhibited negligible degradation as the drift length increased, while the total po- larization decreased slowly but steadily. The stability of these two polarization metrics in this regime indicates that neither the electron beam bunching factor nor the beam phase under- goes significant changes during the drift process. This con- firms that there is sufficient spatial margin for integrating the new phase shifter. On the other hand, a less favorable out- come was observed when the FEL wavelength was increased to 2.344 nm. Here, the total polarization exhibited a signifi- cantly more rapid decline overall, and this decline ultimately propagated to the circular polarization as the drift length in- creased. Specifically, both the total and circular polar- ization degrees dropped below 0.8 when the drift length exceeded 0246Phase shift/rad00.20.40.60.81Polarization050100150Time/fs01234Power/GW34567Drift length/m0.70.750.80.850.90.951Polarization degree

1 pronounced. This discrepancy may arise from inconsistent ra- diation diver- gences generated by different EPUs due to insuf- ficient beam matching; how- ever, it also suggests a strategy to narrow the gap between circular and total polarizations. With the pre-bunching section beam size fixed, modest adjust- ments to the beam size in the afterburner can lead to a significant in- crease in circular polarization at the cost of a relatively small reduction in total polariza- tion. For example, with a beam size of 65.6 µm, the circular polarization degree increases from 0.865 to 0.89, while the total polarization degree decreases only slightly from 0.926 to 0.918. In general, a larger beam size for efficient bunching,

combined with an appropriately sized beam for radiation generation, is beneficial for optimiz- ing polarization purity. Beyond manipulating beam size, another potential approach to enhance polarization is selecting a smaller receiving surface. Since divergent radiation nega- tively impacts polarization, higher purity might be achieved by discarding more off-axis radiation—though this would en- tail a significant loss in radiation intensity. To explore this trade-off, Fig. 6(b) displays the pulse energy and circular po- larization degree for different receiving surface sizes with a 57.4 μm beam size. However, the results exhibit only mono- tonic changes, with no optimal balance point for FEL perfor- mance: pulse energy decreases almost linearly with decreas- ing receiving surface side length (by over 70% in extreme cases), while polarization purity shows negligible improve- ment (at most < 0.1). Similar trends are observed for other 2.344 nm wavelength cases, indicating that improving polar- ization by truncating the radiation spot is of limited practical utility. However, Fig. 6(b) also shows that the polarization purity may grow up more greatly with the reduction of the receiving surface if the FODO of afterburner is not well opti- mized.

Even when all EPUs operate in the same mode and the phase shifter is deactivated, the intensity of circularly polar- ized radiation is significantly affected by the long drift section required for the fast phase shifter. In the context of polariza- tion switching—where only 1 EPU functions as the second radiator—the "3+1" EPU distribution (3 EPUs in one group, 1 in the other) might initially seem preferable, given the con- ventional mode discussed earlier. However, this configuration is impractical due to two critical challenges: First, polariza- tion switching only requires 2 EPUs (one for each polariza- tion state), which means the first EPU would need a reverse taper to enable pre-bunching. Currently, implementing a re- verse taper on the APPLE-III undulator carries substantial operational risks, primarily due to insufficient gap clearance for such modifications. Second, while the third EPU can act as a more powerful radiator than the first two at longer wave- lengths, it fails to match their power output at shorter wavelengths (e.g., 0.414 nm). Beyond generating circularly polar- ized radiation, linearly polarized radiation with adjustable ori- entation can also be produced by superimposing left-handed and right-handed circularly polarized FEL signals using a similar approach. Fig. 7 [Figure 7: see original paper] presents the gain curves of EPU- generated radiation after optimizing both circular and linear polarization configurations as described above. For two cases with comparable beam sizes, circularly polarized FELs ex- Fig. 6. (a) Polarization degree varies with the beam size at 2.344 nm.

Blue: total polarization, red: circular polarization. (b) Circular po- larization and pulse energy vary separately with the receiving area, solid: optimized FODO, dashed: unoptimized FODO.

Fig. 7. Gain curves of the afterburner at 0.414 nm. Red: the first 2 EPUs, green: the last 2 EPUs, solid: horizontal and vertical, dashed: left-handed and right-handed. hibit faster gain dynamics and achieve comparable polariza-5560657075800.80.850.90.95Polarization degree11.21.41.61.82Side length of the

receiving area/m10-30.50.60.70.80.91Circular polarization1020304050600246810Undulator length/m01020304050

tion purity (exceeding 0.9). The drift length was set to 4.5 m for these simulations. Additional simulation results con- firm that highly polarized FEL radiation—with a polarization purity of 0.9 or higher—can be achieved across the entire op- erational wavelength range, with a minimum pulse energy of approximately several tens of microjoules. Based on these findings, the bunch-by-bunch phase shifter will be installed in a 4.5-meter-long drift section, which constrains the maxi- mum mechanical length of the phase shifter to approximately FEL simulations were also conducted to examine the im- pact of other parameters on polarization, with key findings summarized as follows. First, although the bunching factor at the end of the planar undulators is critical for determin- ing FEL radiation intensity, it does not exhibit a significant influence on polarization, provided that the afterburner ra- diation remains below saturation. As the reverse taper pa- rameters are adjusted, the pulse energy of the radiation varies over a wide range (from less than 1 µJ to more than 80 µJ), yet the polarization degree remains stable between 0.85 and

0.92. Second, precise tuning of the EPUs effectively min-

imizes the phase deviation between the FELs generated by different EPUs. When combined with a well-designed beam focusing configuration, this precise tuning results in satisfac- tory polarization performance.

Fig. 8 [Figure 8: see original paper]. Current(a), energy(b) as well as horizontal(c) and vertical(d) FEL power profiles of the S2E electron beam.

After preliminary parameter determination, a series of S2E simulations were conducted. Recent optimizations of the electron beam have enabled significantly lower slice emit- tance for FEL-II; however, achieving improved slice emit- tance at the expense of beam current distribution and en- ergy chirp is unacceptable for polarization switching perfor- mance. This trade-off would likely introduce substantially larger phase errors. Even when beam sizes were fully opti- mized as described earlier, it remained extremely challeng- ing to improve polarization purity in simulations using such an electron beam. For relatively long wavelengths, the maxi- mum polarization degree consistently ranged between 0.7 and

0.8. As illustrated in Fig. 8, significant distortion persisted be-

tween the FEL power profiles, which is attributed to the de- graded current distribution and energy chirp of the beam, even when the actual beam sizes were considerably larger than the values mentioned previously.

Since such a well-designed electron beam is not suitbale for polarization switching, more simulations were conducted to find out appropriate beam conditions.

While optimizing the current and energy distributions of the beam, the polarization purity was significantly improved. The slice emittance, on the other hand, shows little impact on polarization. By featureing a slice emittance stabilized at approximately 0.45 µrad, along with significantly improved current distribution and energy chirp, a new beam is optimized for polarization It must be noted that this is not the S2E beam, switching. but rather obtained through reasonable phase space transfor- mation based on the S2E beam. The inhomogeneities of the beam current and energy distribution can be reduced by fac- tors of 4 and 2 respectively, at the cost of the slice emittance increasing to around 2.5 times its original value. The meth- ods for enhancing polarization using ideal Gaussian beams, as discussed earlier, remain highly effective. Compared to the profiles obtained with the previously mentioned suboptimal beam, these profiles exhibit significantly greater similarity across all cases. In every scenario, the polarization purity ap- proaches or exceeds 0.9, and the pulse energy is comparable to the results achieved with ideal Gaussian beams. Beyond the wavelengths tested here, FEL performance shows mini- mal variation across different operating conditions in terms of high polarization purity. Finally, the main factors mentioned above affecting polarization or pulse energy are concluded in Table. 2.

TABLE 2 . Main factors affecting polarization or pulse energy Factor Larger drift length Larger beam size Larger receiving area Worse slice emittance Larger energy chirp Worse current distribution Circularly polarized afterburner Polarization Lower Higher Lower/Unobvious Unobvious Lower Lower Unobvious Pulse energy Unobvious Lower Higher Lower Unobvious Unobvious Higher IV. BUNCH-BY-BUNCH PHASE SHIFTER As shown in Fig. 10 Figure 10: see original paper, the bunch-by-bunch phase shifter can change the delay between the electron beam and the radi- ation through several kickers with ultra-high repetition rate, just like a chicane, thus affecting the phase difference be- tween FELs. These kickers, with a similar design to[35], operate on the continuous-wave (CW) electron beam, deflect- ing half of the bunches while allowing the rest of the beams to pass smoothly through the original trajectory. The pulse power supply provides excitation current for these kickers. It 6080100120Time/fs05001000150020002500Current/A6080100120Time/fs7970798079908000801080208030Energ

8 Fig. 9 [Figure 9: see original paper]. FEL power profiles of the S2E beam at 2.344 nm(a), 1 nm(b) and 0.414 nm(c). Red: horizontal, green: vertical.

Fig. 10. Layout of the bunch-by-bunch phase shifter and the scheme of the pulse power supply. adopts a hybrid circuit configuration, where a resistor (R1) and a capacitor (C2) are connected in parallel first, and then this parallel combination is connected in series with the kicker magnet (L), as presented in Fig. 10(b). A negative polarity DC power source(-V) is used for charging the capacitor bank (C1), A SIC MOSFET switching transistor (NMOS) is used to control the turning on and off of the circuit, thereby gen- erating required pulse current. At the moment the switch is turned on, the hybrid circuit produces a step response. In or- der to achieve a faster pulse front edge and high peak current, the second-order circuit should operate in an underdamped state by adjusting the value of

capacitance(C2). When the switch is turned off, a RD (resistor R2 and diode D) snubber circuit is essential to avoid over-voltages due to the recov- ery current from the kicker magnet (L)[36]. Assuming that all the kickers have the same length and magnetic field, it is evident that the field intensity, the length of the kickers, and the distance between k1 and k2 (or k3 and k4) determine the delay of such a phase shifter together. Since it' s apparently more difficult for kickers to achieve strong magnetic fields than normal dipoles and the total length is strictly limited, the demand of delay as well as the parameters of the phase shifter are supposed to be determined more prudently.

To achieve a longer time delay with a shorter overall length, it is imperative to minimize the distance between kickers K2 and K3 ideally, even integrating them into a single magnet if technically feasible. However, this approach lacks practicality when considering magnetic field quality, owing to the edge-field effects of the kickers. Both unduly elongated mag- nets and excessively reduced inter-magnet spacing would in- duce edge-field interference, which in turn distorts the elec- tron beam trajectory and thus cannot be tolerated. For 8 GeV electron beams, the deflection strength of these kickers is capped at 0.17 µrad/mm, and the minimum recommended gap between K2 and K3 is 0.3 m. For a wavelength of 2.344 nm, both the drift length between K1 and K2 and the total system length are contingent on the kicker length. On the premise of eliminating edge-field interference, the kickers should be extended to their maximum feasible length, with a recommended value of 0.3 m. Under this configuration, the resultant delay corresponds to slightly over half a wave- length, or a phase shift of 1.1π, rather than a full wavelength.

By leveraging a standard phase shifter to optimize the ini- tial polarization superposition scheme, a half-wavelength de- lay can fully meet all rapid-switching requirements, thereby significantly lowering the system implementation difficulty.

The total system length under this design is 2.15 m, which is well within the allowable limit. To accommodate a maximum wavelength of 2.75 nm, the total length can be extended to 2.5 m.

Fig. 11 [Figure 11: see original paper]. The structural diagram of the kickers. As noted previously, the kickers incorporated in the fast 6080100120Time/fs00.511.522.53Power/GW6080100120Time/fs00.511.522.53Power/GW6080100120Time/fs00.511.522.53Power/GW6080100120Time/fs00

553 phase shifter are capable of deflecting electron beams by up to 50 µrad. However, given the constraints imposed by mag- netic field homogeneity and stability, it is impractical for these kickers to achieve a continuous deflection range span- ning from zero to the maximum angle. In addition to the up- per limit, a recommended minimum effective deflection an- gle of 25 µrad—equivalent to half of the maximum value—is proposed for reliable operation. Regrettably, a straightfor- ward calculation reveals that this phase shifter cannot gen- erate a π-phase delay at the shortest wavelength of 0.414 nm.

Consequently, a 3π-phase delay is required to cover shorter wavelength regimes.

The π delay mode together with the 3π delay mode need to collectively accommodate the full radi- ation wavelength range. The phase shifter' s delay exhibits a quadratic dependence on the kicker deflection angle, and both delay modes can be simultaneously realized at a wavelength of approximately 1 nm. The kicker parameters are tailored to ensure that the induced path length difference delivers the required phase delays (π or 3π) across the entire operational wavelength spectrum of 0.414 nm to 2.75 nm, enabling po- larization switching at a maximum frequency of 500 kHz. In summary for 8 GeV electron beams at SHINE, these 4 kick- ers are required to stably deflect the beam by 25 to 50 µrad at a repetition frequency of 250 kHz. Each magnet has an effective length of approximately 300 mm and a maximum mechanical length of 450 mm, so as to satisfy the constraint that the total mechanical length does not exceed 2650 mm.

Notably, the magnetic field frequency and amplitude can be tuned in a continuous manner. Since the wavelength and phase delay exhibit identical scaling behaviors with respect to electron beam energy, the phase shifter is also compatible with low-energy operation scenarios. The structural diagram of the kickers is displayed in Fig. 11, mainly consisting of a vacuum chamber, feedthrough, as well as magnetic cores and coils for generating magnetic fields. At last, the key design parameters of the pulsed power supply are ultimately sum- marized as follows. The resistor R1 and R2 are 25 Ω and 50 Ω respectively, while the capacitor C1 and C2 are 8 nF and 5 mF separately. The SIC MOSFET switching transistor con- sists of 16 MSC080SMA330B4, and the Diode D includes 8 MSC030SDA330B. The negative polarity DC power source is 2000 V, and the kicker inductance L is 1.2 µH. [1] Huang N, Deng H, Liu B, et al., Features and futures of X-ray free-electron lasers. The Innovation 2, 2 (2021). doi: 10.1016/j.xinn.2021.100097 [2] Emma P, Akre R, Arthur J, et al., First lasing and operation of an ˚angstrom-wavelength free-electron laser. Nature Photon 83, 641-647 (2010). doi: 10.1038/nphoton.2010.176 [3] Ackermann, W., Asova, G., Ayvazyan, V. et al., Operation of a free-electron laser from the extreme ultraviolet to the water window. Nature Photon 1, 336-342 (2007). doi: 10.1038/npho- ton.2007.76 V. CONCLUSIONS AND OUTLOOK In this paper, a hybrid approach that integrates crossed- planar/circular undulators with a bunch-by-bunch phase shifter is implemented in simulations to realize rapid polariza- tion switching of the FEL for FEL-II at SHINE. Leveraging ultrahigh-repetition-rate kickers, this study for the first time enables polarization modulation within the undulator section at a frequency of hundreds of kilohertz via the afterburner scheme. To minimize discrepancies in the power and phase of individual FEL pulses—factors that exert a critical im- pact on the final polarization state following pulse superpo- sition—simulations are performed to evaluate the effects of diverse parameters, including the drift length and beam size in the radiation section, as well as the beam size and bunch- ing factor in the pre-bunching section. For an 8 GeV electron beam spanning the full wavelength range of 0.414 nm to 2.75 nm, the generated FEL pulses achieve an energy of no less than tens of microjoules with a polarization purity exceeding

0.9. To ensure optimal matching of FEL intensity, different

numbers of EPUs are configured as the secondary radiator for distinct wavelength regimes. The optimization rules de- rived from these simulations are applicable to both numerical modeling and experimental polarization tuning. Furthermore, although S2E simulations have not meet the need of polariza- tion purity at present, a reasonably optimized electron beam partially verifies that a polarization purity of approximately 0.9 can still be attained when employing realistic electron beam parameters.

To streamline the computational process, a numerical method is adopted in this work to characterize the beam phase space evolution throughout the phase shifter section, with the space charge effect deliberately neglected. This approxima- tion proves valid and reliable for electron beams at an energy as high as 8 GeV. Nevertheless, for beam energies reduced to 4 GeV or lower, comprehensive simulations utilizing the ELEGANT code are deemed more credible and rigorous.

Based on the aforementioned findings, dedicated experi- ments are scheduled to be conducted within the next two years, aiming to validate the predicted polarization purity and switching frequency. Moreover, this proposed scheme can be extended to other high-repetition-rate hard X-ray FEL facili- ties, provided that these facilities are equipped with multiple EPUs serving as the afterburner and possess sufficient free space for the installation of a fast phase shifter. [4] Pile, D., First light from SACLA. Nature Photon 5, 456–457 (2011). doi: 10.1038/nphoton.2011.178 [5] Feng C, Deng H X., Review of fully coherent free-electron lasers. Nuclear Science and Techniques 29, 11(2018). doi: 10.1007/s41365-018-0490-1 [6] Allaria, E., Castronovo, D., Cinquegrana, P. et al., Two- stage seeded soft-X-ray free-electron laser. Nature Photon 7, 913-918 (2013). doi: 10.1038/nphoton.2013.277 [7] Feng C, Liu T, Chen S, et al., Coherent and ultrashort soft x-ray pulses from echo-enabled harmonic cascade free- electron lasers. Optica 9, 785-791 (2022). doi: 10.1364/OP- TICA.466064 [8] Rebernik Ribiˇc, P., Abrami, A., Badano, L. et al., Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser. Nature Photon 13, 555–561 (2019). doi: 10.1038/s41566-019-0427-1 [9] Longhi E C, Bencok P, Dobrynin A, et al., Developments in Polarization and Energy Control of APPLE-II Undulators at Diamond Light Source. Journal of Physics Conference 425, 032011 (2013). doi: 10.1088/1742-6596/425/3/032011 [10] Yu C, Zhu Y, Zhang W, et al., Development of an APPLE III undulator prototype with three-dimensional force compensa- tion for SHINE. Frontiers in Physics 11, 1174620 (2023). doi: 10.3389/fphy.2023.1174620 [11] Li P, Wei T, Li Y, et al., Magnetic design of an Apple-X after- burner for the SASE3 undulator of the European XFEL. Nu- clear Instruments and Methods in Physics Research Section A:

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Note: Figure translations are in progress. See original paper for figures.