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RESEARCH ON BUNCH-BY-BUNCH POLARIZATION SWITCH MECHANISMS OF HIGH-REPETITION-RATE X-RAY FELs

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Abstract

X-ray free electron laser (FEL) is one of the latest generation of high-quality accelerator-based light sources in the world. With the continuous development and improvement of magnetic dichroism, in order to meet the needs of various users, many mainstream X-ray FEL facilities in the world have been equipped with elliptically polarized undulators (EPUs) to realize polarization control. These schemes cannot switch the FEL polarization at a high speed, so it is difficult to meet the needs of high-frequency hard X-ray FEL facilities. This study aims to generate FEL radiation with different polarization states pulse by pulse on the first superconducting hard X-ray FEL facility under construction in China (SHINE), whose repetition rate will be up to 1 MHz. A new scheme is proposed combining a bunch-by-bunch phase shifter and several EPUs. Based on the parameters of FEL-II, the simulation results show that it is possible to produce X-ray pulses with higher than 85% circular polarization under SASE mode.

INTRODUCTION

Nowadays, several XFEL facilities around the world exploit circular polarization by employing Apple-type or Delta undulators as afterburner, such as Linac Coherent Light Source (LCLS), European XFEL, etc. [1, 2]. It's easy to reach as high as over 90% polarization degree for these EPU afterburner, but can hardly switch the polarization state at a high repetition rate, e.g more than 1 kHz. Another way to generate circularly polarized X-ray FEL is proposed by K.-J. Kim by using crossed-planar undulators (CPUs) as shown in Fig. 1 [3, 4]. In this case, the FEL polarization is significantly determined by the phase difference between horizontal and vertical radiation, which contributes to the possibility of fast arbitrary polarization switching. However, the circular polarization degree of the CPU radiation is theoretically limited to under 80% under SASE mode, much lower than EPU afterburner [5].

The scheme is based on the interference of horizontal and vertical radiation from two planar undulators in a crossed configuration. The CPUs serve as the afterburner, and a special bunch-by-bunch phase shifter is designed to change the phase difference rapidly. There will be 4 Apple-type undulators on FEL-II, 2 for horizontal radiation and 2 for vertical radiation, but only part of them will work meanwhile at a certain wavelength so as to reach a higher polarization degree. The phase shifter will be set between the horizontal undulators and vertical ones. It's also possible to make those Apple-type undulators generate left-handed and right-handed radiation, finally obtaining linear polarized radiation with different polarization directions.

BUNCH-BY-BUNCH PHASE SHIFTER

The bunch-by-bunch phase shifter consists of 4 kickers as shown in Fig. 2, with similar structure to normal phase shifters, usually called a chicane. The main parameters of the kickers are shown in Table 1, and the frequency and amplitude are adjustable continuously. It's apparently more difficult for kickers to achieve strong magnetic fields than normal dipoles, so the length of such a phase shifter is also much larger. In order to reduce the possible influence on the bunched electron beam, the whole length is limited under 2.5 m. The kickers operate on the 1 MHz continuous-wave (CW) electron beam, deflecting half of the bunches while allowing the rest of the beams to pass smoothly through the original trajectory. On the one hand, the parameters of the kickers make sure that the path length difference will offer enough phase difference (more than π) during the whole wavelength range. On the other hand, based on the existing conditions, these demands are not too high to be reached.

Table 1: Kicker Parameters

Parameter	Value	Unit
Beam energy	8	GeV
Max frequency	500	kHz
Working mode	bunch by bunch	
Effective length	300	mm
Deflection angle	25 – 60	μrad

SASE FEL WITH THE PHASE SHIFTER

SASE starts from electron density shot noise and produces X-ray pulses with spiky temporal and spectrum profile, which leads to poor polarization purity [6, 7]. It can be improved by working under self-seeding mode, HGHG mode, or EEHG mode instead. Up to now, since seeded FEL is still much more complicated and difficult than SASE FEL in terms of high repetition, it's essential to generate FEL pulses with high polarization degree under SASE mode. Slight reverse tapering is used in the scheme to preserve the electron beam micro-bunching. Fewer planar undulators are on work than usual to prevent saturation, thus reducing the impact of phase difference.

As a numerical example, the three-dimensional FEL simulation is conducted by Genesis 1.3 using parameters of SHINE [8]. The main parameters of SHINE are listed in Table 2. The electron beams are chosen to be Gaussian profile and the radiation field file is obtained 100 m downstream of the last EPU.

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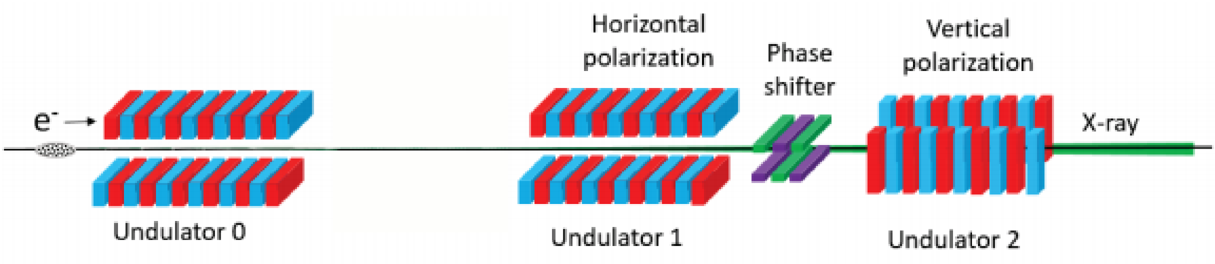


Figure 1: Layout of the scheme with CPU afterburner.

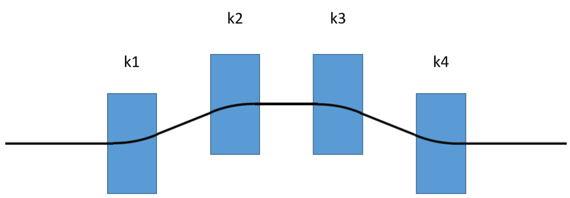


Figure 2: Layout of the bunch-by-bunch phase shifter.

As implied by the Stokes parameters, the vertically polarized laser should be matched to the horizontally polarized one in both intensity and phase in order to increase the polarization degree. So besides light intensity, it's also necessary to make both divergence angles similar. The first two EPUs are used to generate horizontal radiation, while the third EPU serves as the vertical radiation generator at 1 nm. As shown in Fig. 4, the polarization degree can be over 90%, with relatively similar light spots in both directions. The result is close to this when the radiation wavelength is set to 2.4 nm,, with 85% polarization degree. However, '2+1' mode is not suitable for 0.4 nm wavelength due to too large phase and intensity differences between horizontal and vertical radiation, and the polarization degree is under 80% as a result. It can be increased to 89% by adding the 4th EPU as a vertical radiator, as shown in Fig. 5.

Similarly, if the EPUs generate left-handed and right-handed FEL pulses, linearly polarized FEL radiation with almost the same polarization purity will be obtained, whose polarization direction rotates with the change of the phase shifter, just as shown in Fig. 3. The results seem not sensitive to different shot noise, only with a slight difference around 3%. The observation point has little impact on the results either, as long as it's 60-100 m downstream of the last EPU. The total length of the phase shifter determines the drift section between the 2nd and 3rd EPU, thus affecting the bunching factor of the electron beam as well as the beam trajectory in the downstream EPUs. If the length is limited between 2.1 m and 2.7 m, the polarization degree will remain over 80%.

CONCLUSION

In this paper, we propose to generate FEL radiation with different polarization states pulse by pulse, by means of a bunch-by-bunch phase shifter. A set of feasible parameters for the kickers have been put forward. Then, the parameters of SHINE FEL-II are used in the FEL simulations by means of Genesis 1.3. Based on the scheme of CPU afterburner, a series of simulations have been performed to obtain FEL radiation with polarization degree over 85%, even over 90% under certain circumstances. These simulations are all performed under SASE mode. Furthermore, the influence of different shot noise and observation point has also been evaluated, which makes little sense to the result. All these simulation results indicate that it's possible to realize high-repetition-rate polarization switch on an XFEL facility. The results will be even better under the seeding mode.

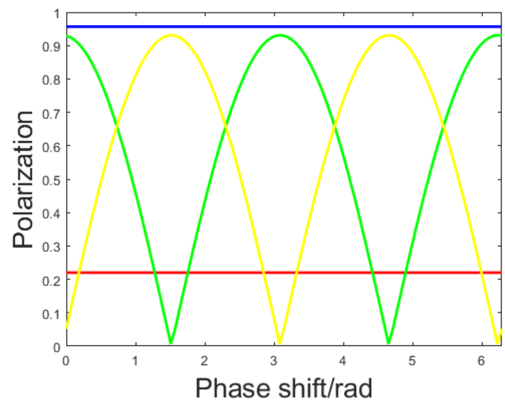
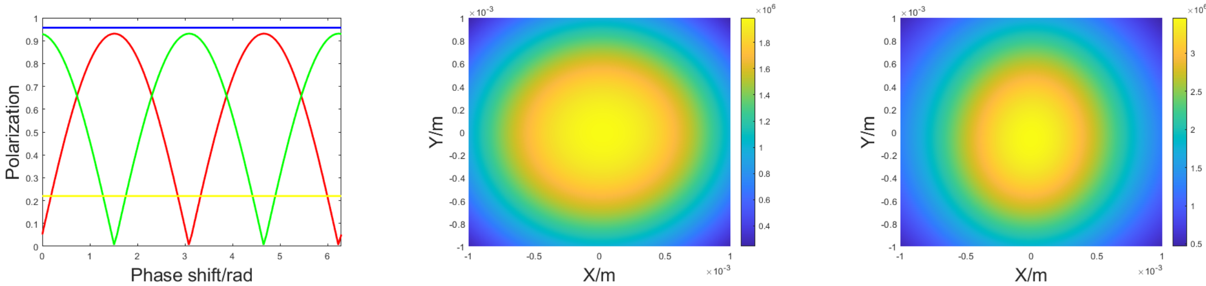


Figure 3: The polarization degree at 1 nm. Blue:total polarization, green:45°/135° linear polarization, red:circular polarization, yellow: 0°/90° linear polarization.

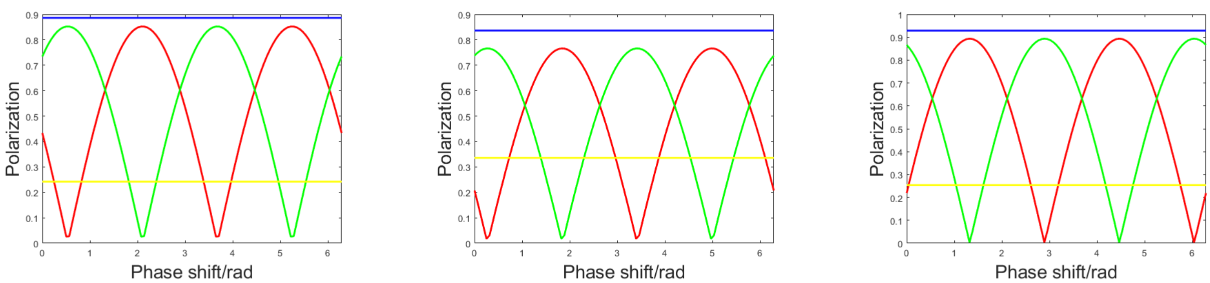
Table 2: SHINE Parameters

Parameter	Value	Unit
Beam energy	8	GeV
Repetition rate	1	MHz
Slice relative energy spread	0.01	%
Normalized emittance	0.45	mm · mrad
Peak current	1.5	kA
Bunch charge	100	pC
Undulator period	0.055	m
Undulator length per section	4	m



(a) (b) (c)

Figure 4: The polarization degree (a) and the radiation spots at 1 nm, (b) for horizontal radiation and (c) for vertical radiation. Blue:total polarization, green:45°/135° linear polarization, red:circular polarization, yellow: 0°/90° linear polarization.



(a) (b) (c)

Figure 5: The polarization degree at 2.4 nm (a) and 0.4 nm, (b) for '2+1' mode and (c) for '2+2' mode. Blue:total polarization, green:45°/135° linear polarization, red:circular polarization, yellow: 0°/90° linear polarization.

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REFERENCES

[1] A. A. Lutman, J. P. MacArthur, M. Ilchen, A. O. Lindahl, *et al.*, "Polarization control in an X-ray free-electron laser", *Nat. Photonics*, vol. 10, pp. 468–-472, 2016. doi:10.1038/nphoton.2016.79

[2] P. Li, T. Wei, Y. Li, and J. Pflueger, "Magnetic design of an Apple-X afterburner for the SASE3 undulator of the European XFEL", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 870, pp. 103–109, 2017. 5 doi:10.1016/j.nima.2017.07.023

[3] K. J. Kim, "Polarization characteristics of synchrotron radiation sources and a new two undulator system", *Nucl. Instrum. Methods Phys. Res.*, vol. 222, nos. 1–2, pp. 11–13, 1984. doi:10.1016/0167-5087(84)90497-6

[4] L. Feng *et al.*, "Single-shot measurement of free-electron laser polarization at SDUV-FEL", *Chin. Phys. C*, vol. 39, no. 2, p. 028101, 2015. doi:10.1088/1674-1137/39/2/028101

[5] Y. Ding and Z. Huang, "Statistical analysis of crossed undulator for polarization control in a self-amplified spontaneous emission free electron laser", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 11, no. 3, p. 030702, 2008. doi:10.1103/PhysRevSTAB.11.030702

[6] A. M. Kondratenko and E. L. Saldin, "Generation of coherent radiation by a relativistic electron beam in an ondulator", *Part. Accel.*, vol. 10, nos. 3–4, pp. 207–216, 1980.

[7] R. Bonifacio, C. Pellegrini, and L. M. Narducci, "Collective instabilities and high-gain regime free electron laser", *Opt. Commun.*, vol. 50, no. 6, pp. 373–378, 1984. doi:10.1016/0030-4018(84)90105-6

[8] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, nos. 1–3, pp. 243–248, 1999. doi:10.1016/S0168-9002(99)00114-X