ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMK068

HIGH-DEGREE CIRCULAR POLARIZATION AT X-RAY SELF-SEEDING FELS WITH CROSSED-PLANAR UNDULATORS

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Abstract

The crossed-planar undulator (CPU) configuration for a high-gain free-electron laser is well-known for the ability of versatile polarization control. However, the degree of polarization is very sensitive to power and phase between two stages of undulator. In this paper, we investigate the generation of high circular polarization degree X-ray in self-seeding FELs with CPU. Three-dimensional simulations using Shanghai Coherent Light Facility parameters show that it is possible to produce 0.1 nm hard X-ray with higher than 90% circular polarization.

INTRODUCTION

With the ability of generating high-brightness light pulse at short wavelength regimes, as well as controlling the spectral bandwidth and temporal duration, free-electron laser (FEL) opens frontiers in research fields like chemistry, biology and material science [1]. Some experiments aiming at exploring the local symmetry of sample, e.g., magnetic materials and biologic molecular systems with chirality, would also greatly benefit from a high-degree and variable light polarization. The X-ray FELs around the world are normally linearly polarized based on planar undulators. Some exploit circular polarization by employing helical or Apple-type undulator. Polarization switching mechanically at Hz level between linear and circular could be achieved by elliptically polarized undulator (EPU) or Delta undulator as demonstrated at Linac Coherent Light Source [2].

An alternative way of generating polarized X-ray FEL is proposed by K.-J. Kim by using crossed-planar undulators (CPU) [3, 4]. It circumvents the large cost of EPU construction. And its characteristic of fast arbitrary polarization switching might enable some special applications. Among several X-ray FEL schemes, the most successful one is based on self-amplified spontaneous emission (SASE) [5, 6]. The optimized point to implement crossed undulator in SASE scheme would be near the FEL saturation regime, where electron beam has developed maximum density modulation and remains constant inside CPU. However, SASE starts from electron density shot noise and produces X-ray pulses with spiky temporal and spectrum profile, which theoretically limits the circular polarization degree to under 80% [7].

The CPU scheme is based on the interference of horizontal and vertical radiation from two planar undulators in a crossed configuration as shown in Fig. 1. For increasing the polarization degree of CPU, one solution would be to imprint electron bunch with coherent density modulation by seeded FEL. The proof-of-principle experiment demonstrated a 80% polarization with switching rate of 2 Hz in seeded FEL [8]. In this paper, we have investigated the scheme of generating highly polarized X-ray by self-seeding FEL [9–11] with CPU. The schematic is shown in Fig. 1, which exploits the enhanced longitudinal coherence of a self-seeding scheme to generate coherent electron bunch density modulation and to increase the polarization degree of CPU.

SELF-SEEDING FEL WITH CROSSED-PLANAR UNDULATORS

Self-seeding schemes are proposed for improving the longitudinal coherence of SASE. In hard X-ray regime, the crystal is employed as a monochromator to obtain a coherent seed from upstream SASE, and then it is amplified at downstream undulators. The narrow-spectral-bandwidth X-ray pulse from the self-seeding scheme reflects a coherent density modulation of electron bunch which is suitable for CPU. Also, slight reverse tapering is used in the self-seeding scheme to preserve the electron beam micro-bunching. The length of vertical undulator is adjusted for generating identical X-ray including power and phase. The phase shifter is able to switch the X-ray polarization by change the relative phase between horizontally and vertically polarized radiation.

Table 1: The Main Parameters of SCLF

Parameter	Value	Unit
Beam energy	8	GeV
Slice relative energy spread	0.01	%
Normalized emittance	0.4	μm·rad
Repetition rate	1	MHz
Peak current	1.5	kA
Bunch charge	100	pC
Undulator period	26	mm
Undulator length per section	5	m
Total undulator length	200	m

As a numerical example, we conduct the three-dimensional FEL simulation by Genesis 1.3 using parameters of Shanghai Coherent Light Source (SCLF) [12]. SCLF is going to be the first hard X-ray FEL facility in China, which is now under construction. The main parameters of SCLF are listed in Table. 1. The electron beams are chosen to be Gaussian profile with the peak current of 1.5 kA. Thousands of slices are used in time-dependent simulations. The

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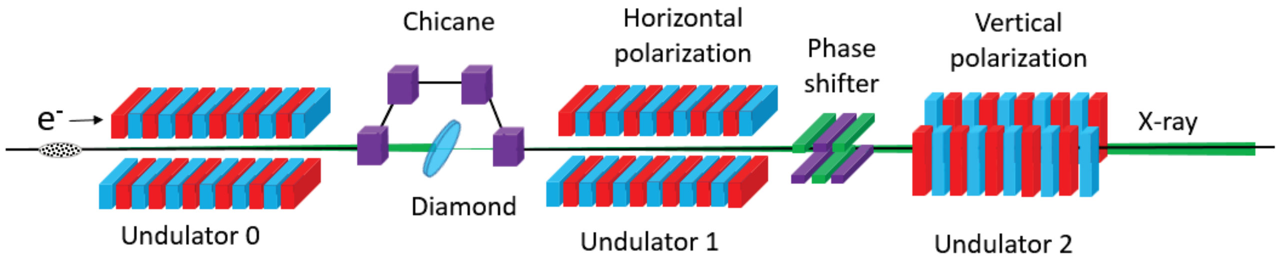

Figure 1: Layout of self-seeding FEL with CPU.

self-seeding part is calculated by the methods in Ref. [13]. With incident angle equals to 34.1, the photon energy is chosen to be 12.4 keV which matches the Bragg energy of diamond crystal (4 0 0) atomic plan. The thickness of crystal is assumed to be 100 µm.

As implied by the Stokes parameters [14], we should match the vertically polarized light to the horizontally polarized one in both intensity and phase so as to increase the polarization degree. To maximize the beam bunching factor, the undulator1 is optimized to contain nine undulator segments, which is around 51.48 m (with nearly 1 m break section between undulators). Then different reverse tapering is applied to suppress the saturation of light in undulator1, which leads to the beam bunch factor increasing even more. The length of vertical undulator2 L is adjusted in order to reach the best power matching. With the reverse tapering intensity k being 0.2%, the degree of circular polarization is as high as 95.83% when the one segment of vertical undulator is implemented. However, the pulse energy is only 16.12 µJ, which leaves room for improvement. For pursuing higher pulse energy, the reverse tapering factor is decreased slowly, and the length of the vertical undulator increases at the same time to keep the matching while the polarization degree remaining over 95%.

Figure 2 shows the power profile of seeding laser ,which is due to Bragg diffraction. It also illustrates the power and phase profiles of the horizontally and vertically polarized light respectively, as well as the spectrum of the circularly polarized laser, with k being 0.14% and L equaling 7.02 m. The pulse energy grows up to 30.5 µJ with the polarization degree remaining 95.42%. Thanks to the self-seeding scheme, the horizontal and vertical spectrums are narrow and almost the same, with their power and phases also being similar. The circularly polarized laser is highly longitudinal coherent, with 0.1 eV (FWHM) bandwidth, or 8.1×10^{-6}. The power is not so high due to such a short wavelength with a relatively short undulator1 and 2. Although the difference between their power profiles may be larger than the former results, the pretty similar phases of those slices generating high-power lasers help to keep excellent circular polarization. Moreover, the polarization degree can be even higher, up to over 97%, at the sacrifice of pulse energy, proving the benefits of the seeding laser for CPU.

Furthermore, the undulators are tuned in simulations to lase at the wavelength of 0.2 nm, which leads to a different gain length, resulting in a different value of L. One solution to this problem is the afterburner scheme. However, we find it possible to make CPU work at different wavelengths by tuning the FODO lattice. This easier scheme may contribute to a simpler design. In order to meet the needs for variable wavelengths with a length-fixed vertical undulator, the lattices are redesigned so that the gain length can be similar to the former one. The intensity of the quadrupole magnets are weakened, from 16 T/m down to 3.5 T/m, and the circular polarization degree is still as high as 93.42%, with the pulse energy of 23 µJ. Since in many situations the polarization degree of 90% is well enough, the reverse tapering factor and the intensity of the quadrupole magnets are modulated to maximize pulse energy. As is shown in the simulation, a different k does little benefits to circular polarization, while slightly intensified quadrupole magnets do help to strengthen the pulse energy at little expense of polarization degree. The pulse energy is 52 µJ, more than twice the former result, with the polarization degree being around 90% when the intensity of the quadrupole magnets is 4.6 T/m.

The simulation results of self-seeding FEL using the same parameter demonstrates a 172 µJ X-ray output. The optical power in the simulations may be too low for hard X-ray FEL, but the length of the CPU undulators used in our scheme is less than 60 m, which means that higher power is possible as long as better parameters are applied to restrain saturation in undulator1. Also, there is no need to separate the electron beams from the laser as in the afterburner scheme, thus preventing possible spoilage of beam bunch factor.

CONCLUSION

In this paper, we propose to generate highly circularly polarized light by a self-seeding scheme with the crossed-planar undulator. The parameters of SCLF self-seeding is used in the simulations. At first we tune the undulators to lase at the wavelength of 0.1 nm. A number of simulations have been performed to obtain a laser with polarization degree over 95% and pulse energy over 30 µJ. These results demonstrated that the self-seeding scheme indeed improves the longitudinal coherence as well as the circular polarization. Then we change the resonant wavelength to 0.2 nm with the same length of the vertical undulator. The simulations illustrate the possibility of meeting the needs for different wavelengths as long as a proper lattice design is

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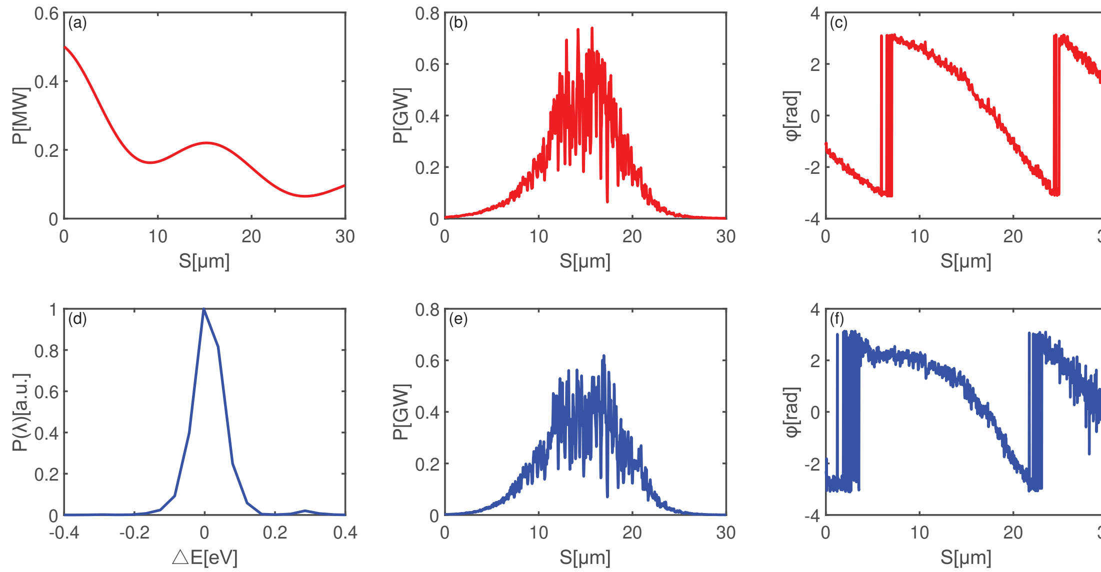

Figure 2: The X-ray power profile after self-seeding(a), the power(b) and phase(c) of the horizontal radiation field, the spectrum of the circularly polarized laser(d), and the power(e) and phase(f) of the vertical radiation field.

performed. The laser with polarization around 90% and pulse energy over 50 μJ is acceptable compared with the former one. Moreover, variable polarizations are available by means of the phase shifter.

ACKNOWLEDGEMENTS

The author would like to thank Z. Zhao for helpful discussions on the SCLF project; K. J. Kim, Y. Shvyd'ko and R. Lindberg for providing information and related parameters of the crystal. This work was partially supported by the National Natural Science Foundation of China (11775293), the National Key Research and Development Program of China (2016YFA0401900), the Young Elite Scientist Sponsorship Program by CAST (2015QNRC001), and the Ten Thousand Talent Program.

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