



Polarization properties of a crossed planar undulator

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ABSTRACT

Instead of using a helical undulator, another method to generate circularly polarized radiation in an FEL is to utilize two crossed planar undulators. The main benefit of the crossed undulator over the helical option is that its structure is simpler so that it is technically and economically more convenient. Unlike a helical undulator, two orthogonal polarizations are respectively generated from two crossed undulators and their combination comprises circularly polarized radiation. Therefore, the overlap and resemblance of the two polarizations determine the quality of the composed radiation field. The 3D simulations have been performed with parameters from the European XFEL. Polarization has been studied in detail and optimization of the crossed undulator length has also been done.

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1. Introduction

The European XFEL facility will generate radiation wavelength down to 0.1 nm with a 17.5 GeV electron beam, using self-amplified spontaneous emission (SASE) [1–3]. Currently there are three undulator beam lines foreseen: SASE1, SASE2 and SASE3. For 17.5 GeV, SASE1 generates 0.1 nm radiation, SASE2 can generate different wavelengths in the range between 0.1 and 0.4 nm by adjusting the undulator gap, SASE3 supplies long wavelengths from 0.4 to 1.6 nm. In the start-up scenario, these three undulator lines consist of planar devices so that only linearly polarized radiation can be generated. While at short wavelengths the linear polarization can be changed into circular radiation by other means, e.g. quarter wave plates, this is not the case for SASE3. Therefore, beyond this start-up scenario, there is a strong wish that SASE3 can also supply circularly polarized light.

To generate circularly polarized light, a natural choice is to use a helical undulator such as an APPLE II. There are practical examples that they can be used for synchrotron radiation [4] or long wavelength FELs. However, there is no example showing how it works for an X-ray FEL. Because the Pierce parameter of an X-ray FEL is very small ($\rho < 10^{-3}$), the undulator tolerance can be expected to be very tight. Whether the technical challenges can be met is still unclear. In addition, helical undulators are much more expensive than planar ones.

An alternative approach is to generate circularly polarized radiation using two crossed planar undulators. It is originally proposed in Refs. [5,6]. Because the coherence length in SASE FELs is much longer than the coherence length of spontaneous

emission, the longitudinal shift between the two fields from two crossed undulators can be made shorter than the coherent length. Thus the combination of the two orthogonal fields results in circular polarization without requiring a complex monochromator. With a phase shifter between these two undulators, the polarization can be varied between linear and circular.

Fig. 1 shows the layout of this proposal. In this configuration, electrons successively pass through two crossed planar undulators. The first one is quite long to generate powerful FEL radiation as well as micro-bunch electrons with a periodicity of the radiation wavelength. Because the micro-bunches are already formed in the first undulator, the second undulator emits coherently. Therefore, even for a short length of the second undulator powerful FEL radiation comparable in intensity to the radiation by the first long undulator is generated. High degree of circular polarization requires that the radiation powers from two undulators are equal. In Ref. [7] it is shown that if the length of the second undulator equals 1.3 gain lengths, the radiation power from the second undulator is equal to the first one. Unfortunately, the gain length is influenced by many parameters such as radiation wavelength, beam current, emittance and β -function. Therefore, this scheme can be optimized for one wavelength with given beam parameters only. For other parameters, the degree of polarization will drop. In addition, the power at the end of the first undulator is not saturated, which causes intrinsic shot-to-shot fluctuation of the intensity. This in turn automatically translates into variation of degree of polarization.

To improve the stability of polarization, a modified scheme has been proposed in Ref. [8]. The long planar undulator is only used as a buncher. It is followed by a system to separate the micro-bunched electron beam and the linear polarized light. Then it is followed by two equal-length crossed undulators. If the micro-bunched structure can be preserved in the separation system,

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both undulators will coherently radiate and emit the same amount of power as long as the beam parameters do not differ significantly in the two crossed undulators, i.e. if the beam is frozen in phase space. In this case, the two fields should be quite similar so that their combination can be circularly polarized for all wavelengths. Compared to the original scheme, this modification has higher flexibility with respect to undulator length. Fig. 2 shows this modified configuration.

Although the modified scheme in principle can improve the quality of polarization, it is still based on the strategy of combining two separated fields and therefore the polarization can not be perfect. Several points which can decrease its circular polarization can be summarized:

1. The bunching is not frozen in phase space and as consequence, the radiation properties of the two radiators differ slightly.
2. The β -function in this two crossed undulators is not exactly the same, resulting in a different beam size and opening angle.
3. Because of the slippage between electrons and light wave, there is an unavoidable longitudinal shift between the two orthogonal polarized waves generated by two undulators.
4. Because of the different position at which the waves are generated, the two fields' transverse distribution of phase and intensity cannot be exactly the same. This difference increases as the two undulators become longer.

The first two points decrease the circular polarization through reducing the resemblance of two orthogonal field components, the last two reduce the overlap.

To include all the points above and calculate the polarization, it is necessary to perform numerical simulations. A 3D FEL simulation code such as Genesis 1.3 can calculate transverse and longitudinal intensity and phase. The simulation can be divided into several steps:

1. Do time dependent simulation of the buncher, dumping the particle distribution file.

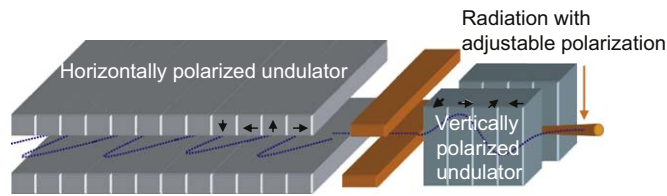


Fig. 1. Crossed planar undulator system proposed for high-gain FEL radiation in Refs. [5,6].

2. Directly load the particle file dumped by the buncher to the simulations for crossed undulators. This means the impact of bending system is neglected.
3. Do simulations for the two crossed undulators respectively and dump the field files from each of them.
4. Propagate both fields a certain distance in free space (far zone), combine them and calculate the polarization.

The first three steps can be done by a 3D FEL simulation code. For the fourth step we have tested three different methods to numerically calculate optical field propagation in free space: the spectral method based on FFT, the Fresnel integral method and the straight forward numerical integration of the fields [11]. Here, we will use the Fresnel method to transport the field to far zone.

In this paper, Stokes parameters are used to describe the polarization properties [10]. In the second section, the polarization versus different longitudinal shifts is studied in detail. In the third section, the polarization dependence on undulator length for different radiation wavelengths is investigated. The electron beam current is assumed to be homogeneous instead of Gaussian. It should be stressed again that the beam dynamics of the system separating the electron beam from the linearly polarized radiation is not included here and is assumed to have no influence on the performance. As such, numbers quoted here for the polarization should be considered upper limits.

2. Circular polarization properties

2.1. Getting 1D Stokes parameters from 3D simulation

The electric field of a plane wave can be written as

$$E_x = a_1 \cos(kz - \omega t + \phi_1)$$

$$E_y = a_2 \cos(kz - \omega t + \phi_2) \quad (1)$$

where a_1 and a_2 are field amplitudes in x - and y -directions, respectively, ϕ_1 and ϕ_2 are their phases. Hence, the Stokes parameters, which include four real elements S_0, S_1, S_2, S_3 can be defined as

$$S_0 = \langle a_1^2 \rangle + \langle a_2^2 \rangle$$

$$S_1 = \langle a_1^2 \rangle - \langle a_2^2 \rangle$$

$$S_2 = 2 \langle a_1 a_2 \cos(\phi_1 - \phi_2) \rangle$$

$$S_3 = 2 \langle a_1 a_2 \sin(\phi_1 - \phi_2) \rangle \quad (2)$$

where the angle brackets $\langle \dots \rangle$ means averaging over time.

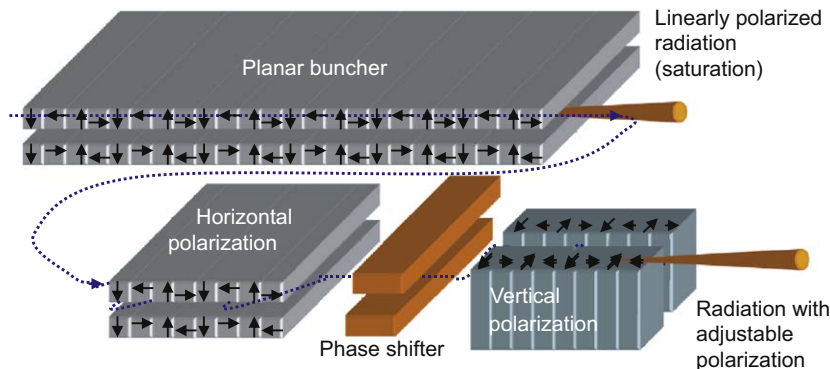


Fig. 2. Modified crossed planar undulator system for high-gain FEL generation.

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