POLARIZATION ANALYSIS FOR SEEDED FELS IN A CROSSED-PLANAR UNDULATOR

H. Geng[*1,2], R. Bartolini[3], Y. Ding[2], D. Dunning[4], Z. Huang[2], N. Thompson[4]
[1]National Synchrotron Radiation Laboratory, USTC, Hefei, Anhui 230029, PRC
[2]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[3]Diamond Light Source Ltd, Oxfordshire, OX11 0DE, UK
[4]STFC Daresbury Laboratory, Warrington, UK

Abstract

The crossed-planar undulator is a promising scheme for full polarization control in x-ray FELs. For SASE FELs, it has been shown a maximum degree of circular polarization of about 80% is achievable at fundamental wavelength just before saturation. In this paper, we study the effectiveness of a crossed undulator for a seeded x-ray FEL. The degree of circular polarization for both the fundamental and the harmonic radiation are considered. Simulations with realistic beam distributions show that a degree of circular polarization of over 90% and 80% is obtainable at the fundamental and 2nd harmonic frequencies, respectively.

INTRODUCTION

Seeded FELs have the advantages of narrower bandwidth, better temporal coherence, and more stable central wavelength over SASE FELs. Several soft x-ray FELs based on various seeding schemes have been proposed [1, 2]. In this wavelength range, controlling the polarization state of the radiation has broad applications for probing ultrafast magnetic phenomena and material science [3].

Although polarization control can be provided by the APPLE-type undulator, the undulator tolerance may be very tight for lasing at ~ 1 nm radiation wavelength, and the slow mechanical movement of APPLE device prevents any fast-switching of polarization states. An alternative method is the so-called "crossed undulator" (or "crossed-planar undulator"), first proposed by K.J. Kim [4]. In this method circularly polarized light is obtained by interfering the radiation fields from two adjacent planar undulators in a crossed configuration (see Fig. 1). The first undulator is normally polarized in x and the second in y, and a phase shifter between them is used to delay the electron beam and thus control the final polarization state. The phase shifter can be designed to control the polarization state with a very fast rate (> 100 Hz).

The effectiveness of this method for controlling polarization at the fundamental wavelength in a SASE FEL was studied in [5]; it was found that over 80% circular polarization could be achieved at the end of the exponential gain regime, just before saturation. A modified crossed undulator scheme has also been proposed for the second harmonic radiation when the FEL reaches saturation [6]. The

maximum degree of circular polarization is $\sim 90\%$ and is insensitive to the length of the first undulator.
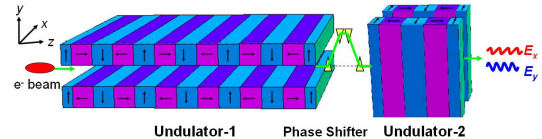

Figure 1: Schematic of the crossed undulator for polarization control at the fundamental wavelength.

In this paper, we study the effectiveness of a crossed undulator for a seeded x-ray FEL. The degree of circular polarization for both the fundamental and the harmonic radiation with the normal and modified crossed undulator schemes will be considered.

DEGREE OF POLARIZATION

The state of polarization can be described by the coherency matrix [7]

$$\mathbf{J} = \left[\begin{array}{cc} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{array} \right] = \left[\begin{array}{cc} \langle E_x(t)E_x^*(t)\rangle & \langle E_x(t)E_y^*(t)\rangle \\ \langle E_y(t)E_x^*(t)\rangle & \langle E_y(t)E_y^*(t)\rangle \end{array} \right],$$

(1)

where $E_x(t)$ and $E_y(t)$ are the two components of the light, $*$ means complex conjugate, and the angular bracket refers to the ensemble average. Stokes parameters are generally used to describe the state of partially polarized light. They are related to the coherency matrix by [7]:

$$\begin{aligned} S_0 &= J_{xx} + J_{yy}, \\ S_1 &= J_{xx} - J_{yy}, \\ S_2 &= J_{xy} + J_{yx} = 2\langle A_x(t)A_y(t)\cos[\theta(t)]\rangle, \\ S_3 &= i(J_{yx} - J_{xy}) = 2\langle A_x(t)A_y(t)\sin[\theta(t)]\rangle. \end{aligned}$$

(2)

Here $A_x(t)$ and $A_y(t)$ are the amplitudes of the field components $E_x(t)$ and $E_y(t)$, and $\theta(t)$ is the phase difference between $E_x(t)$ and $E_y(t)$ (controllable through the phase shifter in the crossed undulator scheme). The degree of total polarization can be defined as:

$$P = \sqrt{S_1^2 + S_2^2 + S_3^3}/S_0.$$

(3)

The degree of circular polarization P_c is defined as

$$P_c = |S_3|/S_0.$$

(4)

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In the following analysis, we use the time average to replace the ensemble average for the far-field radiation in both x and y directions.

START-TO-END SIMULATIONS AT THE FUNDAMENTAL WAVELENGTH

The New Light Source (NLS) project [2] is used for this study. In FEL-3, a HHG seed at $\lambda_{HHG} = 12.4$ nm and a two stage up-conversion are used to generate final radiation at $\lambda_s = 1.24$ nm . The schematic layout of FEL-3 is shown in Fig. 2. FEL-3 consists of two modulators, two dispersion sections and one radiator. The first modulator(modulator-1) has a period of $\lambda_{u1} = 4.4$ cm and it is resonant at λ_{HHG}. The second modulator (modulator-2) has a period of $\lambda_{u2} = \lambda_{u1} = 4.4$ cm and is resonant at the second harmonic of the seed laser, *e.g.* $\lambda_{HHG}/2$. The radiator has a period of $\lambda_u = 3.22$ cm and is resonant at $\lambda_{HHG}/10 = 1.24$ nm. In the latest optimization study for FEL-3, the scheme with the second modulator length twice that of the first modulator yields the best performance [8]. Thus, this latest optimal FEL-3 configuration will be used for our start-to-end simulations.
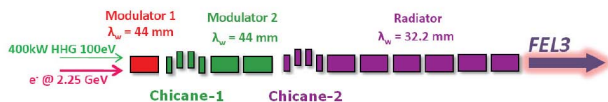

Figure 2: Schematic layout of the NLS FEL-3 at 1.24 nm FEL wavelength.

The simulated S2E beam parameters for the NLS projects are $E_0 = 2.25$ GeV , $I_{pk} = 1200$ A , $\sigma_\gamma = 0.7 \times 10^{-4}$ and $\epsilon_n = 0.3$ mm-mrad. The undulator is separated into 2.5 m sections, and a distance of 1 m is reserved between adjacent sections for the installation of phase shifters, focusing quads, and diagnostic components. FODO lattice is chosen for focusing the beam in the undulator with the average $\beta = 8$ m [9].

For polarization control at the fundamental wavelength, the radiator in FEL-3 will be used as the first main undulator (undulator-1). The crossed undulator can be formed by adding a phase shifter and a vertical-polarized undulator (undulator-2) as in Fig. 1. Undulator-2 has the same period and strength as the radiator.

We use the 3D time dependent FEL simulation code GENESIS [10] to calculate the radiation fields. The S2E beam with realistic distributions are read into GENESIS at the beginning of modulator-1. The numbers of macroparticles $npart = 147$ k and particle bins in particle loading $nbins = 24$ are chosen to effectively suppress numerical noise in the frequency up-conversion[11]. The seed laser is assumed to be a gaussian beam with a peak power of 400 kW and a fwhm pulse duration of 20 fs. After undulator-1, the electron beam file is dumped and is imported in undulator-2 to generate E_y, while the radiation field E_x from undulator-1 is allowed to propagate freely to the end of undulator-2. The polarization analysis is performed with the on-axis far field intensity and phase of the
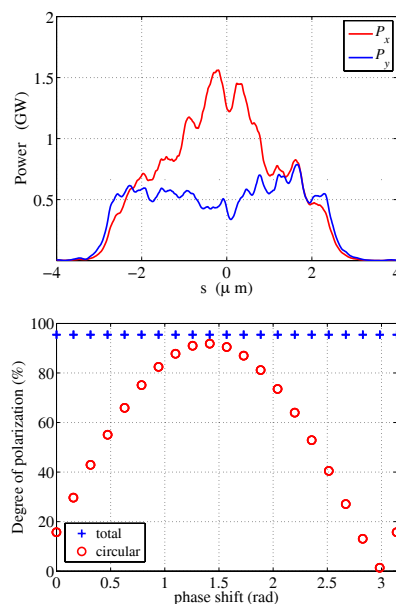
Figure 3: Power profiles from horizontal and vertical undulators (upper plot), and degree of polarization vs. phase shift (lower plot) at the fundamental wavelength.

two radiation components.

After optimization studies, we choose $L_1 = 14$ m for undulator-1 (4 sections), and $L_2 = 2.5$ m for undulator-2 (1 section). The average FEL power is about 3 m before saturation. Power profiles of the two radiation components are shown in the top plot of Fig. 3, while both the total and the circular degree of polarization at the fundamental wavelength as a function of the phase shift are shown in the lower plot. We see that the power of the horizontal component (P_x) is higher than that of the vertical component (P_y) at the center part of the pulse, while the duration of P_y is wider than that of P_x. This tendency in the pulse shape development can be explained by the gaussian shape of the seed laser. The electrons at the bunch center interacts with the maximum laser intensity and hence reaches saturation faster than the head/tail part of the bunch. For a longer undulator length, the FEL microbunching at the bunch center starts to decrease after saturation, but the microbunching of the head/tail part of the bunch still increases. This nonuniform bunching profile leads to a more flat radiation profile for the vertical component in undulator-2. In the lower plot we see that the optimal degree of circular polarization is $\sim 93\%$ with a radiation phase close to π for the phase shifter. Note that there is an intrinsic phase shift between E_x and E_y. Therefore, the optimal phase for the circular degree of polarization is nowhere near $\pi/2$.

In passing we note that the proposed cross undulator configuration can be easily realized with APPLE undulators. Suppose that the radiator consists of several 2.5-m APPLE undulators. The first four sections can be tuned to the horizontal polarization for undulator-1, and the fifth section can be tuned to the vertical polarization

for undulator-2. Thus, the phase shifter between the fourth and the fifth sections can be used for polarization control.

START-TO-END SIMULATIONS AT THE SECOND HARMONIC WAVELENGTH

For polarization control at the second harmonic wavelength we use the modified crossed undulator scheme as proposed in [6]. It consists of three undulators: a first (main) undulator of length L_1 that reaches saturation and generates microbunching at the fundamental and harmonic frequencies; two short undulators of equal length $L_2 = L_3$ with the crossed configuration as shown in Fig.4. The resonant wavelength of the two short undulators is chosen to be the second harmonic of the first undulator ($\lambda_2 = \lambda_3 = \lambda_1/2$). The radiator in FEL-3 will again be used as the first undulator. An important feature of this method is its capability to generate a high level of circular polarization when the first undulator operates in saturation. To demonstrate this feature, we choose the length of undulator-1 to be at saturation, *e.g.*, $L_1 = 17$ m.
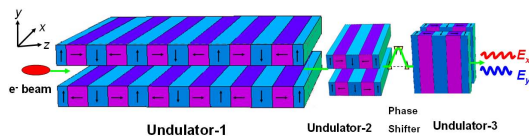

Figure 4: Schematic of the crossed undulator for polarization control at the 2nd harmonic wavelength.

Similar to the previous section, the S2E beam with realistic distributions are read into Genesis at the beginning of modulator-1. The same seed laser is used in the simulations. The beam file is dumped at the exit of undulator-1 and then used for the generation of E_x and E_y in undulator-2 and 3. The radiation field E_x from undulator-2 is allowed to propagate freely to the end of undulator-3. The polarization analysis will be performed with the on-axis far field intensity and phase of the two field components.

When we choose $L_2 = L_3 = 1$ m with an undulator period $\lambda_u/2 = 1.61$ cm, the simulation results are shown in Fig. 5. The upper plot shows the radiation power profiles P_x and P_y at 0.62 nm, and the lower plot shows the total and the circular degree of polarization at this wavelength as a function of the phase shift. We see that P_x and P_y both have spikes at the head/tail part of the pulse due to the intrinsic evolution of the FEL microbunching after saturation. The maximum degree of circular polarization is shown to be 86% with a proper phase shift, again close to π.

DISCUSSION

In this paper we have studied the generation of circularly polarized radiation in a seeded soft x-ray FEL using the crossed undulator scheme. We have shown that arbitrarily polarized radiation can be achieved at both the fundamental
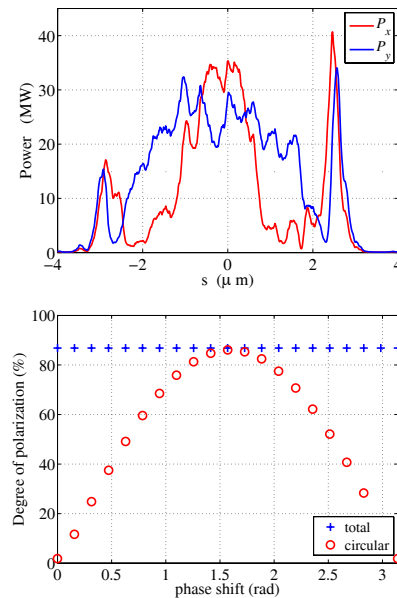

Figure 5: Power profiles from horizontal and vertical undulators (upper plot), and degree of polarization vs. phase shift (lower plot) at the fundamental wavelength (1.24 nm).

and the 2nd harmonic wavelengths. For the fundamental radiation, a maximum degree of $\sim 93\%$ is obtainable just before FEL saturation. For the second harmonic radiation, the modified scheme can work well in the saturation regime with over 80% of circular polarization.

Compared to the SASE FEL, the synchrotron oscillation for the FEL microbunching is more pronounced for a seeded FEL. Thus, the microbunching decreases quickly once the part of the bunch reaches saturation. This effect limits the vertical radiation power and also the uniformity of the radiation profile, especially for polarization control at the fundamental wavelength. Therefore, the lengths of the undulators should be designed properly in order to use the crossed undulator scheme.

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