STUDY OF CONTROLLABLE POLARIZATION SASE FEL BY A CROSSED-PLANAR UNDULATOR

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Abstract

Several methods to produce variable polarization have been under discussion for the European XFEL facility. One such method is to utilize a crossed-undulator scheme. In this paper, the polarization of X-ray radiation for longer wavelengths (0.4 nm and longer) of the XFEL is investigated. The degree of polarization and the Stokes parameters are calculated for different configurations. A first attempt at optimization of the configuration for XFEL parameters is presented.

INTRODUCTION

The European XFEL will generate photons in the X-ray range of 0.8 keV to 12.4 keV (1.6 to 0.1 nm) at its maximum beam energy of 17.5 GeV [1]. It uses the principle of Self-Amplified Spontaneous Emission (SASE) [2, 3]. Three undulator systems will be used to cover this wavelength range, two planar devices for the short wavelengths between 0.1 and 0.4 nm and one device called SASE3 for the longer wavelengths of 0.4 to 1.6 nm. For the long wavelengths, there is a strong demand on delivering light with variable polarization. Therefore APPLE type undulators would be an obvious choice for SASE3 [4, 5, 6]. However, because the length of the device will be about 100 m, it would be a rather expensive solution. In addition, the tolerances are more stringent than for planar devices.

An alternative method is first using planar undulators to bunch the electrons and then use the bunched electrons in shorter APPLE undulator to generate variable polarized light. An other alternative is to use crossed-planar undulators to generate variable polarized radiation. The Duke storage ring FEL reported their experiment of controllable polarization by crossed undulators with a nearly 100 % degree of polarization [7]. The concept of crossed undulators used for synchrotron radiation or FELs is first proposed in Ref. [8, 9]. It consists of two planar undulators whose magnet field direction is orthogonal. A phase shifter, an adjustable magnetic chicane, installed between them is used to delay the electron beam and consequently the phase difference between the two fields. If the amplitudes of the two fields are equal and their phases are consistent, arbitrary polarized light can be achieved. For LCLS parameters, over 80 % helical polarization can be achieved at the end of exponential gain regime before saturation [10]. However, at the end of exponential gain regime the fluctuations in SASE intensity are also highest. To avoid these large intensity fluctuations, a modified version of the crossed-undulator system has been proposed by including three undulators in the system. The first one is long enough to reach saturation. After separation of the electrons from the light generated in the first undulator, the bunched electrons pass through two short but equal length crossed-undulators. A phase shifter is also installed between them to control the polarization. Fig. 1 shows this configuration. One benefit of this scheme is that, because the polarized light is generated by these two equal length undulators, there is no special limitation to the undulator length. Therefore after optimizing the crossed undulator length, high polarized light can be achieved at various wavelengths.

In this paper, simulations have been performed based on this modified configuration to estimate the polarization and power level for SASE3 at different wavelengths. An optimizing for crossed-undulator length is also done. Furthermore, first simulations of separation of the linearly polarized light generated in the main undulator from the variably polarized light from the two short undulators is presented.

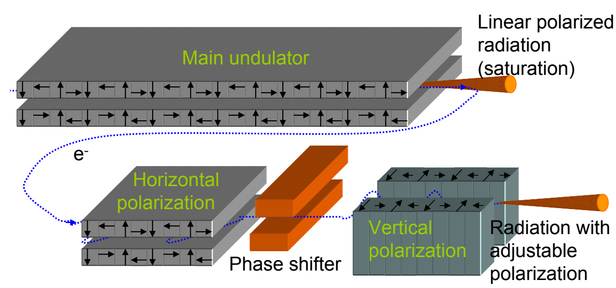

Figure 1: Modified crossed-planar undulator system for high-gain FEL generation.

BASIC RELATIONS

To describe polarization properties of light, Stokes parameters are generally used [11]. It includes four elements $S_0,\ S_1,\ S_2,\ S_3$. The Stokes parameters are defined as:

$$\begin{aligned} S_0 &= \left\langle E_x^2(t) \right\rangle + \left\langle E_y^2(t) \right\rangle \\ S_1 &= \left\langle E_x^2(t) \right\rangle - \left\langle E_y^2(t) \right\rangle \\ S_2 &= 2\left\langle E_x(t)E_y(t)cos(\phi_x(t)-\phi_y(t)) \right\rangle \\ S_3 &= 2\left\langle E_x(t)E_y(t)sin(\phi_x(t)-\phi_y(t)) \right\rangle , \end{aligned} \tag{1}$$

where $E_x(t)$ and $E_y(t)$ donate to two field's amplitude in x and y direction, $\phi_x(t)$ and $\phi_y(t)$ are their phases. For a partially polarized light, which can be deemed as superposition of unpolarized light and completely polarized light, its degree of polarization P is defined by:

$$P = \frac{\sqrt{S_1^2+S_2^2+S_3^2}}{S_0} \qquad (0 \leq P \leq 1). \tag{2}$$

S_0 represents the total intensity. After normalizing Stokes parameters to unit intensity, $S = (1, \pm1, 0, 0)$ represents horizontal/vertical linear polarization, $S = (1, 0, \pm1, 0)$ denotes to the $\pm 45°$ linear polarization and $S = (1, 0, 0, \pm1)$ represents right/left circle polarization. Because SASE3 aims at production of arbitrary polarized light, we maximum the value of $|S_3/S_0|$ to evaluate the fraction of circular polarization of SASE3 in addition to the value of total polarization P.

The 3D time dependent FEL code GENESIS 1.3 is used for simulations. To express the distribution of field and electron bunch in time domain, GENESIS 1.3 splits the optical field and electron bunch into many slices. Each slice denotes to a certain position along the electron bunch or light pulse [12]. During the FEL process, slices of field and electron bunch longitudinally slip with respect to each other by one radiation wavelength per undulator period. In order to speed up the simulations, we choose the distance between slices equal to several tens of wavelengths. We calculate the two fields, E_x and E_y, separately from two crossed planar undulators. Because the velocity of E_x and E_y is different inside the second crossed undulator, they shift longitudinally. Because the shift length can not always be an integer times of the distance between two slices simulated, the error bars shown in Fig. 2 indicate the simulated slippage closest to the optimum value.

On the other hand, for each slice, GENESIS 1.3 expresses the field distribution across a transverse plane by normally hundreds of points which are homogeneous on a square grid in $x-$ and y-direction. Each point holds a local electric field component $\tilde{E}_i$. For every slice we first integrate the field across the transverse plane, i.e. $\tilde{E} = \sum \tilde{E}_i$, then average them in time domain based on Eq. (1) to calculate the Stokes parameters. We use Fresnel's method to do the calculation [13]. By this method the calculation for field propagation can be performed in one step and a long distance for example more than 100 m transport can be calculated [14].

SIMULATION OF THE FEL PROCESS

SASE3 is gap adjustable. Therefore, for simplification we choose $K_{rms} = 3.58,\ 5.16,\ 6.36,\ 7.36$, respectively, corresponding to the foreseen wavelength change by gap variation from 0.4 nm to 6.4 nm. For each wavelength, five different crossed undulator lengths from 1 m to 5 m are simulated. The longest 5 m is approximately one gain length at 0.4 nm. The length of first long undulator (bunching undulator) is chosen such that the electron bunch factor $| < \exp(i\theta) > |$ is most close to the maximum value, where θ denotes to the ponderomotive phase. Because in practice, the undulator is divided into 5 m long structures, whose gap can be opened and closed independently its length is adjusted in 5 m steps. As already mentioned, before combining the two optical fields to calculate the polarization, they are simulated to transport a long distance in free space from the source point (end of undulator) to the observer point. The propagated length is long enough that the beam size expands linearly with distance (far field approximation), 30 m is enough in our case. Due to the field expansion, we set the aperture up to nearly 4 mm at the observer point to permit all radiation power to pass through. Because the phase shifter value is adjustable, to achieve a maximum value of $|S_3/S_0|$, we always optimize it such that $|S_2|$ has its smallest value. If the two fields are exactly the same when they are combined, the optimized value should be $\pi/2$ (See definition Eq. (1)). Since the amplitudes of the fields generated by the two undulators is different and they have a different propagation distance by at least one undulator length, the actual value of the phase shift differs from $\pi/2$. Finally, a SASE FEL shows random spikes distributed in time domain. In order to include more spikes and thus get more statistics, we take a 150 μm long bunch with homogeneous current distribution instead of a 25 μm long Gaussian bunch.

Table. 1 lists the main parameters used in our simulations.

Table 1: Parameters for SASE3 used in simulation

Parameter	Value	Unit
Undulator period λ_u	68	mm
Undulator parameter K_{rms}	3.58-7.36	
Segment length	5	m
Electron beam energy	17.5	GeV
Radiation wavelength	0.4-1.6	nm
Energy spread	8.0	MeV
Bunch current (flat top)	5	kA
Bunch length	150	μm
Normalized emittance	1.4	mm mrad

Fig. 2 illustrates the total degree of polarization (top left), the polarization $|S_3/S_0|$ (top right), the radiation power of circularly polarized light $|S_3|$ (bottom left) and the radiation power (bottom right) and the polarization ellipse. It can be seen that as the crossed undulator length increases, both of the degree of polarization and $|S_3/S_0|$ go down, while the latter one decreases more. This can be understood as follows. Because of the increased undulator length, the slippage between both fields becomes larger as well and hence the longitudinal overlap of different spikes decreases both the degree of polarization and of its circular polarization fraction. The fraction of circularly polarized light decreases even more because at longer undulator length beam dynamics plays a more prominent role and therefore also the increased energy spread (and therefore the difference in power level in the second undulator) diminishes the circular fraction in addition. We can see that if the crossed undulators have the shortest length of 1 m, more than 95 % total degree of polarization and circle polarization $|S_3/S_0|$ can be expected. On the other hand, however, we also noticed that the radiation power increases for longer undulators. Therefore, the polarized power $|S_3|$ should be used as an alternative figure of merit to be defined by an experiment. From Fig. 2, only a crossed undulator length of up to

4 m gives a significant increase in cirular polarized power $|S_3|$.

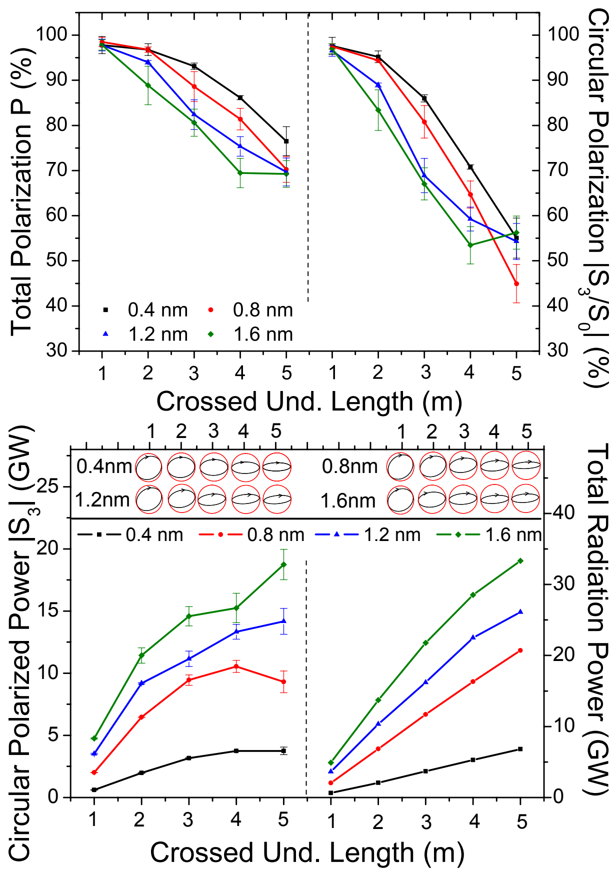

Figure 2: Top: Circular polarization (right) and total polarization (left). Bottom: power (right), circular polarized power (left). The polarization ellipses are shown for illustration.

From the left bottom plot, for example for the shortest wavelength of 0.4 nm and an undulator length of 3 m, the radiation power is nearly 4 GW. We know that at the end of long bunching undulator, the power is about 49 GW. Using this value to estimate the power level of the scheme completely constructed by helical APPLE type undulators, we can say that with the crossed undulator scheme one achieves 10% of the maximum achievable power.

SEPARATION OF LINEAR AND CIRCULAR LIGHT

The FEL simulations in the previous section have assumed that the electron bunching has exactly the same value as that of the electron beam leaving the long undulator. In addition, it is assumed that the radiation from the first undulator is diverted and no longer interacts with the electrons. A simple way to achieve this is by putting the two short undulators under an angle with respect to the main undulator.

For a Gaussian beam, the $1/e$ spot size $\omega(z)$ for the field amplitude in the far field is:

$$\omega(z) \approx \frac{\omega_0 z}{z_R} = \frac{\lambda_s z}{\pi \omega_0} \qquad (z >> z_R), \tag{3}$$

where z_R denotes to the Rayleigh length and ω_0 denotes to the waist size, which is comparable with the electron beam size, about 25 μm for SASE3 and λ_s denotes to the wavelength. Therefore for 0.4 nm to 1.6 nm FEL, the opening angle of the radiation varies roughly between $5 - 20$ μrad. The deflecting angle has to be much larger than this in order to avoid overlap.

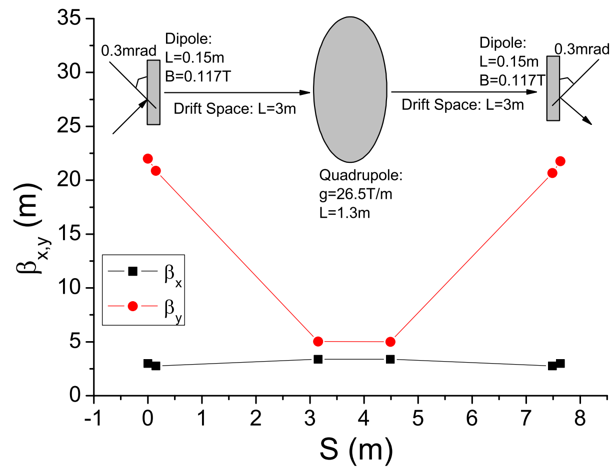

Figure 3: Schematic overview as well as the beta function of the simplest geometry of the separation area.

Kicking the beam to achieve the angle is not sufficient because the bunching is still in the original forward direction and has to be rotated as well. Therefore, an 0.6 mrad deflecting angle is induced by two dipoles with a quadrupole in the middle to rotate the bunching as shown in Fig. 3. This is a simplified version of the deflecting dispersive chicane for the BESSY FEL [15]. Taking into account the linear terms of the transfer matrix only, making R_{51}, R_{52} and R_{56} equal to zero keeps the beam quality to large extent intact. However, taking into account the second order terms, a typical bunching factor $| < exp(i\theta) > |$ for SASE3 of 0.57 is reduced to 0.2 for the worst case of 0.4 nm radiation wavelength. The electron beam at different positions between the main undulator and the crossed undulators is shown in Fig. 4. These results have been obtained with Elegant [16]. As can be seen, the electron beam clearly shows an asymmetry due to higher order terms. Fig. 5 shows the loss of bunching for different wavelengths of interest for SASE3. Down to a wavelength of 1 nm the reduction in bunching is 25%. For shorter wavelengths, a more complicated scheme is under study.

CONCLUSION

In this paper, we propose to generate variable polarized light by means of a scheme using crossed-undulators for the long wavelength range of the XFEL, called the SASE3

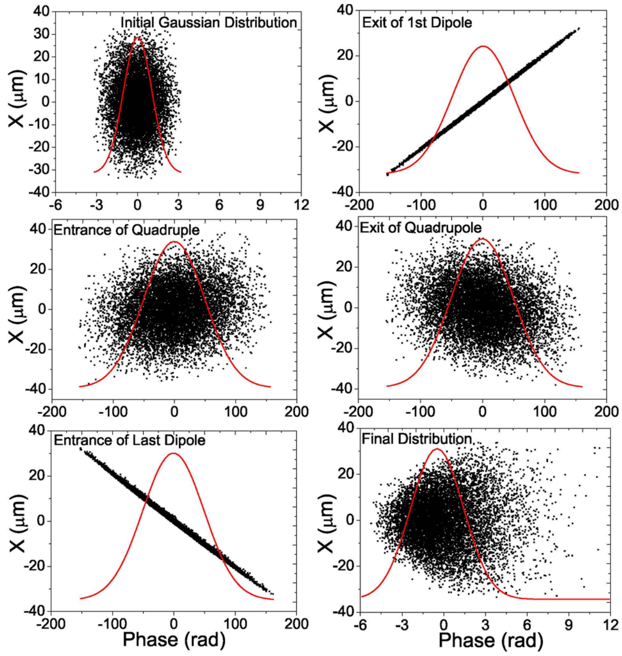

Figure 4: Bunch distribution during the deflection at the entrance and exit of each of the three elements taking into account second order terms. The beam shape is assumed to be Gaussian for these simulations.

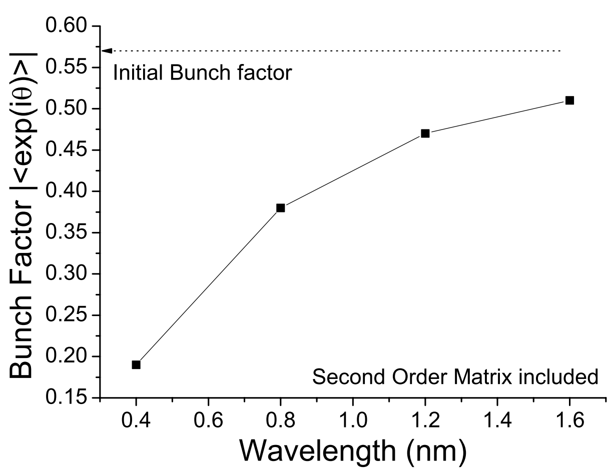

Figure 5: Bunching factor for different wavelengths at the entrance of the crossed undulator, including the second order matrix. The bunching at the exit of the planar undulator is approximately 0.57.

undulator line. To estimate its degree of polarization as well as to optimize crossed undulators' length, a number of simulations have been performed. Simulation of the FEL process, optical field propagation in free space and calculation of Stokes parameters are included. From the simulation results, it can be seen that as the crossed undulator length increases, the polarization drops, especially its circular polarized content $|S_3/S_0|$. For example, if the crossed undulator has a length of 1 m, over 95 % of $|S_3/S_0|$ and total polarization can be expected for all wavelengths. Nevertheless, the radiation power is higher for a longer undulator. Therefore maximizing the product of circular polarization fraction, $|S_3/S_0|$, and the power can be a criterion for the optimum undulator length. For the simulations performed, around 4 m undulator length maximizes this product for all wavelengths at 17.5 GeV. Considering the result of lower electron energy of 8.75 GeV, which is not shown in this paper, if the length is longer than 3 m, $|S_3|$ drops.

Finally, the separation scheme presented here only works for the longer wavelengths, reducing the bunching by some 20% or less for wavelengths longer than 1 nm. For the short wavelength part, further study is ongoing. Furthermore, a complete set of simulations has to be performed, including a more realistic particle distribution.

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