STUDIES FOR POLARIZATION CONTROL AT LCLS*

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Abstract

In order to improve the capabilities of LCLS to meet more of the user requirements it has been proposed to implement a method to produce circularly polarized coherent radiation in the LCLS free electron laser.

In this work we will present the results of a new set of studies and simulations that have been done for adding polarization control to LCLS using circularly polarizing undulators. Attention has been focused mainly on the use of variable gap APPLE-II undulators to be used at the end of a long SASE radiator that is based on the standard planar LCLS undulators. Issues like polarization contamination from the planar polarized light, polarization fluctuation and the choice of undulator configuration have been studied.

INTRODUCTION

Polarization control is an important property for light sources that can allow performing experiments that aim at exploring the symmetry of the sample. Polarization control is crucial for determine the an atomic magnetic moment, the lattice geometry of a crystal and the chirality of a molecule,

In the shortest wavelength range of LCLS circular polarization can be created by the use of special x-ray optics that convert planar polarization into circular polarization [1]. Such a method cannot be used for the soft x ray spectral range from 1.5 to 0.6 nm. In this range it is necessary that circular polarization be generated directly by the FEL.

PARAMETERS CHOISE FOR THE STUDIED CASE

LCLS Parameters

The wavelength range of interest for the polarization control is covered by LCLS with an electron beam energy ranging from about 4.3GeV to about 6.8 GeV. On this work we focus on the 0.6 nm wavelength case (~2keV photon energy and 6.8GeV e-beam energy) that is the most challenging due to the longer gain length. The used electron beam parameters are reported in Table 1 and are a conservative extrapolation from the parameters commonly measured during the last period of operation of LCLS [2].

The standard LCLS undulators [3] with the usual electron beam optics have been used for the main SASE; the same electron beam optics with 3.3 meter undulator sections and short and long breaks accommodating quadrupoles and diagnostics has been used also for the circularly polarized undulators.

Table 1: Used Electron Beam Parameters

Parameter	Value	Units
Energy	6.8	GeV
Current	2000	A
Normalized slice emittance	0.6	mm mrad
Energy spread	1.4	MeV
Average beta function	10-15	m

Presently at LCLS after the main SASE undulators are installed few modified undulators that have been tuned at the second harmonic of the main radiator. These undulators have been recently used for generating Second Harmonic After Burn coherent emission and are generally called SHABs [4]. In order to keep the compatibility with the SHAB option in our studies we placed the circularly polarized undulators after a set of four SHABs that are used as a simple drift. The effects of this options and the possibility to use the SHAB undulators to improve the efficiency for generating circularly polarized light have been also studied [5].

APPLE Undulators

An efficient undulator design that has been demonstrated to be very efficient for providing variable polarization is the APPLE-II (Advanced Planar Polarized Light Emitter) [6]. In addition to be largely used in synchrotron radiation beam lines, APPLE-II undulators have been recently considered for some of the next generation light sources based on high gain Free Electron Lasers [7, 8] and has been also already used on some FEL experiments [9]. For APPLE-II it has been shown that the on axis magnetic field B_0 can be obtained by a semi-empirical formula [10, 11].

$$B_0 = a \cdot \exp\left[-b \cdot \left(\frac{g}{\lambda_0}\right) + c \cdot \left(\frac{g}{\lambda_0}\right)^2\right] \qquad (1)$$

where a, b, c are fitting parameters (Table 2), g and λ_0 stay for the undulator gap and period.

The required undulator parameters for LCLS can be estimated using Eq. 1 with the coefficients used for FERMI [11] and reported in Table 2. The critical point for LCLS is that APPLE-II undulators are used for produce coherent circularly polarized light from a prebunched electron beam taking advantage of the bunching that has been created in the main LCLS SASE radiator. Two possible configurations are possible.

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Table 2: Coefficient used in Equation (1) Gives the Magnetic Field Intensity as a Function of Undulator Gap (g) and Period (λ_0)[11]

Polarization	Fitting coefficients		
	a	**b**	**c**
Horizontal	1.76	2.77	-0.37
Circular	1.54	4.46	0.43
Vertical	2.22	5.19	0.88

The first one is to tune the APPLE-II undulators at the same wavelength than the SASE radiator, the second possibility is to tune the APPLE-II undulators at the second harmonic of the wavelength produced in the SASE radiator.

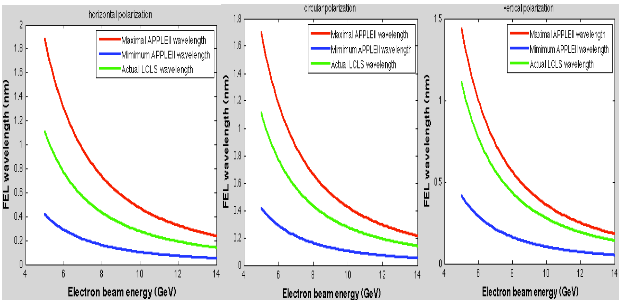

Figure 1: Estimated tuning range for an APPLE-II undulator with *40 mm* undulator period and *7 mm* minimum gap. The maximum (red) and minimum (blue) APPLE-II wavelengths are compared to the LCLS resonant wavelength (green). The tuning ranges for Horizontal, Circular and Vertical polarization are plotted as a function of the electron beam energy.

Using Eq. 1 and assuming a minimum gap of *7 mm* we can chose the best undulator period that match the APPLE-II undulators with the LCLS SASE undulators. Figure 1 shows the resonance curves for a 40 mm period APPLE-II and the SASE undulator. Results indicate that in this case the APPLE-II undulator can be tuned at the fundamental and at the second harmonic of the LCLS planar undulator in all the polarization configurations.

An undulator period of about 40mm has been used in our studies and simulations with the use of APPLE-II undulators.

THEORETICAL BACKGROUND

For evaluating the FEL performances of LCLS in circularly polarized we calculated the produced power and the stability, also in term of degree of polarization, of the circularly polarized light. Moreover, in the case where the circular polarization is produced in an undulator that follow the main radiator which is horizontally polarized, an important parameter that characterize the produced radiation is the degree of polarization.

Polarization Quality

The most accurate way to measure the degree of polarization is to calculate the Stokes parameters of the produced radiation [12]. For the studied case, even in the ideal case of a perfect circularly polarized light produced in the APPLE-II undulator we expect the polarization of the final output radiation not to be perfect due to the perturbation of the radiation coming from the SASE undulator that is horizontally polarized.

The whole process can be approximated considering that the SASE intensity (I_{SASE}) is perfectly horizontally polarized and at the entrance of the APPLE-II unduator can be decomposed in left and right circular polarized $\left(\frac{I_{SASE}}{2}\right)_R$ and $\left(\frac{I_{SASE}}{2}\right)_L$. The left polarized light will be coupled to the electron beam into the APPLE-II undulator and amplified becoming $(I_{APPLE})_L$ at the radiator exit, while the right polarized light will freely propagate and become $\left(\frac{I^{out}_{SASE}}{2}\right)_R$. With the approximation that relative phases between the left polarized APPLE-II field and the propagated right polarized SASE field are constant and the two fields have same temporal and spatial distribution, we immediately have a measure of the degree of circular polarization [12]:

$$Q_C = \left|\frac{S3}{S0}\right| = \left|\frac{I_L - I_R}{I_L + I_R}\right| = \frac{(I_{APPLE})_L - \left(\frac{I^{out}_{SASE}}{2}\right)_R}{(I_{APPLE})_L + \left(\frac{I^{out}_{SASE}}{2}\right)_R}. \qquad (2)$$

Due to the diffraction that affect the non-amplified right polarized light and the gain guiding of the left polarized the two fields are quite different in terms of spatial and temporal profiles and also on phase, nevertheless we have seen [5] that Equation (2) is a good approximation for the degree of polarization quality that can be used for a quicker estimation of the quality of the circular polarization. Equation (2) has been used for on this work. The use of more detailed measurements using the Stokes parameters of the produced light from both the SASE and APPLE-II undulators will be presented elsewhere [5] and can be used to exploit the advantage of the different position of the source point for the two different polarization as proposed in Ref. [13].

Exponential Regime

In case the FEL is operated in the exponential regime far from saturation the degree of polarization can be estimated with a simple formula. As already anticipated 50% of the SASE radiation is interacting with the electron beam on the APPLE-II undulator. This radiation can be considered perfectly coupled with the FEL gain mode of the electron beam in the APPLE-II undulator since it is the same electron that produced it. In these conditions the power evolution of the radiation in the APPLE-II undulator can be described by:

$$I_{APPLE} = \frac{I_{SASE}}{2} e^{\frac{l_A}{l_g}} \qquad (3)$$

where l_A is the length of the APPLE-II undulator and l_g is the FEL gain length in the APPLE-II undulator.

By using Eq,s (3) and (2) we can then estimate the degree of circular polarization produced in APPLE-II undulators as a function of the undulator length.

$$Q_C = \frac{e^{\frac{l_A}{l_g}} - 1}{e^{\frac{l_A}{l_g}} + 1} \qquad (4)$$

By using Eq. (4) in combination with the M. Xie formula [14] for calculating the gain length it is possible to immediately predict the FEL performance for a particular undulator setup. In particular in Figure 2 we show the predicted degree of polarization for LCLS at 0.6 nm as a function of the APPLE-II undulator length. Equation (4) is also useful to give a first estimation of possible shot to shot fluctuations of the polarization quality due to variation of the FEL gain length caused by the jitter on the electron beam parameters, a detailed study on this important topic has been done in Ref. [5].

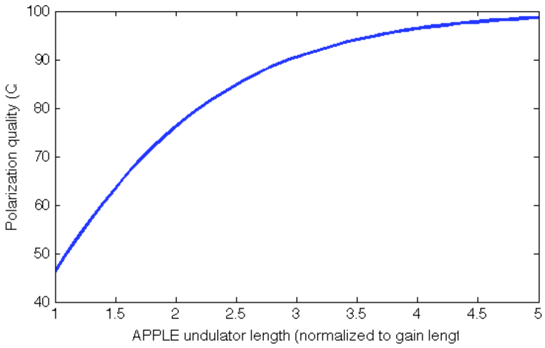

Figure 2: Expected polarization quality (Q) as a function of the length of the APPLE-II radiator in case of simple exponential growth.

Eq. (4) can give only a rough estimation of the polarization quality since does not take into account some process that may affect both the SASE radiation and the APPLE-II radiation. Indeed in order to optimize according to the desiderata the output radiation it is possible to use the detuning and/or the bunching to affect the FEL evolution and improve the output FEL power or the degree of polarization. Such a detailed studies have been done with FEL simulations with GINGER [15] and are presented in forthcoming sections.

NUMERICAL SIMULATIONS

Numerical simulations have been done for characterize FEL performance in circular polarization. Most of the studies are with single slice time independent simulations that we saw to be in good agreement with both time dependent and start to end FEL simulations [5].

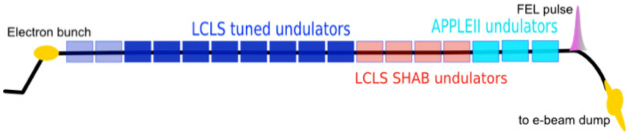

Figure 3: Undulator setup used for the simulations. The number of LCLS undulators has been varied to optimize the FEL output. For these studies 4 SHABs have been considered. The number of APPLE-II undulators studied has been varied from 1, 3 and 5.

One APPLE-II Undulator

In order to have a better control of the power and the bunching entering into the APPLE-II undulator the last of the SASE undulator can be slightly detuned (the detuned undulator is plotted in green). By detuning the last undulator we are able to control the power growth but also the energy spread and the bunching. This is very useful when the FEL gain length is shorter than the undulator segment length in order to set the FEL to operate close to saturation, but not too close.

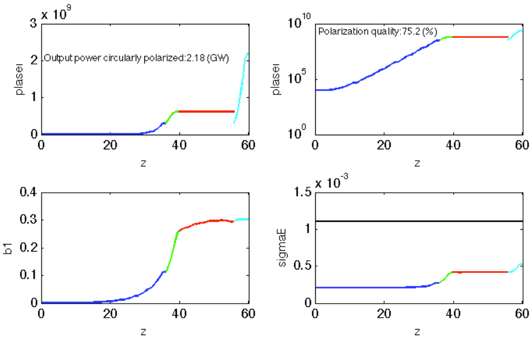

Figure 4: Predicted FEL power at 0.6 nm (a, b), bunching (c) and relative energy spread (d) as a function of the undulator length in the SASE radiator (blue and green) and in the final APPLE-II undulator (cyan). The SHABs undulators (red) are only used as a drift and interaction between electron beam and radiation is suppressed by suing a very small k.

Depending on the chosen length of the SASE radiator and on the optimization done with the detuned undulator the FEL can be set to maximize the output power or the degree of polarization. In figure 4 is reported the result for the best compromise where about 2.2GW of radiation circularly polarized are extracted from one single APPLE-II undulator. The predicted degree of polarization is 75%.

Three APPLE-II Undulators

The same optimization has been done for the case with three undulators in the circularly polarized radiator. In this case since there are several gain lengths available in the APPLE-II undulator both the FEL power and the degree of circular polarization are improved.

The chosen configuration for this case show that about 8GW can be extracted from the APPLE-II radiator in circular polarization with a degree of polarization of about 97%.

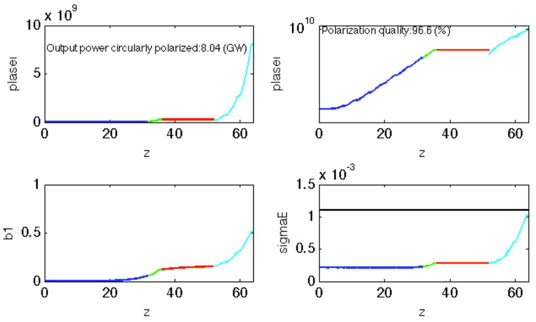

Figure 5: Predicted FEL power at 0.6 nm (a, b), bunching (c) and relative energy spread (d) as a function of the undulator length in the SASE radiator (blue and green) and in the final APPLE-II undulator (cyan).

Five APPLE-II Undulators

In the case of five APPLE-II undulators there are about 9 gain lengths in the circularly polarized radiator this allow to operate the FEL almost in saturation without affecting the degree of polarization.

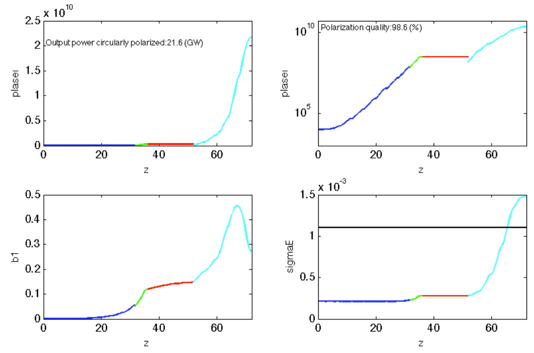

Figure 6: Predicted FEL power at 0.6 nm (a, b), bunching (c) and relative energy spread (d) as a function of the undulator length in the SASE radiator (blue and green) and in the final APPLE-II undulator (cyan).

In the case of a long APPLE-II radiator about 20GW are produced in circular polarization with a degree of polarization close to 1.

Time Dependent Simulations

The same optimization has been done for the case with three undulators performing time dependent simulations. Simulations have been done both using an ideal electron beam with constant electron beam parameters and also a start to end electron beam file that has the electron beam properties expected for the LCLS. Results confirm the time independent predictions and will be presented elsewhere [5].

Time dependent simulations are also useful to estimate the polarization quality evolution along the FEL pulse and the polarization stability from shot to shot due to the SASE process and e-beam parameters fluctuations. As expected simulations indicate that both kind of polarization fluctuations depend on the length of the polarized undulators and are generally of the order of 1%.

CONCLUSIONS

We have investigated the possibility to produce circularly polarized light on the LCLS FEL by adding few APPLE-II undulators after the long SASE radiator horizontally polarized. Performances in terms of produced FEL power and degree of polarization have been calculated by using FEL simulations. Further analysis on the stability of the degree of polarization and on the effect of start to end files have been started [5]. Results of numerical simulations show a good agreement with theoretical predictions introduced in Eq. (4), that can be used independently of the particular undulator used for produce circular polarization. It is important to point out that better performances are expected for the longer wavelength range. Although the study has been focused on APPLE-II undulators, the possibility to adopt other schemes or different kind of polarized undulator are still under consideration. In particular, cross-polarized undulators [16] are still one of the possible solutions for LCLS. Expected performance from other circularly polarized undulators like DELTA [17] or superconducting helical undulator can easily be done by simply calculating the gain length [5].

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