IMPROVEMENT OF THE CROSSED UNDULATOR DESIGN FOR EFFECTIVE CIRCULAR POLARIZATION

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Abstract

The production of X-ray radiation with a high degree of circular polarization constitutes an important goal at XFEL facilities. A simple scheme to obtain circular polarization control with crossed undulators has been proposed so far. In its simplest configuration the crossed undulators consist of pair of short planar undulators in crossed position separated by an electromagnetic phase shifter. An advantage of this configuration is a fast helicity switching. A drawback is that a high degree of circular polarization (over 90%) can only be achieved for lengths of the insertion devices significantly shorter than the gain length, i.e. at output power significantly lower than the saturation power level. Here we propose to use a setup with two or more crossed undulators separated by phase shifters. This cascade crossed undulator scheme is distinguished, in performance, by a fast helicity switching, a high degree of circular polarization (over 95%) and a high output power level, comparable with the saturation power level in the baseline undulator at fundamental wavelength. We present feasibility study and exemplifications for the LCLS baseline in the soft X-ray regime. **These proceedings are based on the article [1], to which we address the interested reader for further information and references. Simulations have been modified to account for the novel proposed arrangement in [2].**

INTRODUCTION

There is an always increasing demand by the LCLS users for circularly polarized X-ray pulses with fast switching of helicity. An APPLE-type undulator can provide variable polarization, but it is difficult to quickly change the polarity due to the magnet motion mechanism. One possible solution is to use crossed undulators. The concept of crossed undulators was devised by Kim in order to produce various polarization states with planar undulators. The configuration is based on a pair of planar undulators in a crossed position with a phase shifter in between. A fast switching of the polarization direction can be achieved by using electromagnetic phase shifters. For synchrotron radiation sources a monochromator after the crossed undulator is required to temporally stretch both pulses and to achieve interference. The degree of polarization is limited, in practice, by the finite beam emittance, energy spread and resolution of the monochromator (40% − 45% at BESSY). In particular, the angular divergence of the electron beam is responsible for a blurring of the phase between the radiation field components, which is a cause of depolarization. A remarkable

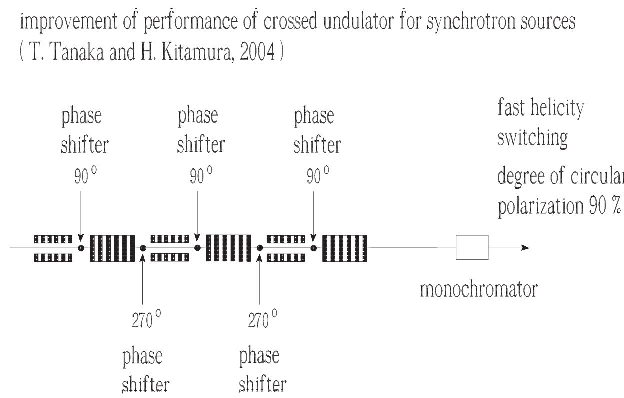

Figure 1: Schematic of the cascade crossed undulator proposed for effective polarization control at synchrotron radiation sources

feature of an XFEL device is a narrow bandwidth in the order of 0.1% of the output radiation. It follows that the monochromator, which is needed for the operation of the crossed undulator scheme at synchrotron radiation sources, can be avoided. In addition, due to the high quality of the electron beam at XFELs, emittance and energy spread effects play no significant roles in the determination of the degree of polarization for crossed undulators.

The drawback of crossed undulator XFEL schemes is that, in order to reach a circular degree of polarization larger than 80% − 90%, undulators need to be significantly shorter than the FEL gain length. This is due to the need for equal intensities in the two linearly polarized components separately generated in the different undulators. As a result, the performance of the output radiation is significantly lower than that of the light produced by the baseline undulator, meaning that the intensity is reduced by more than an order of magnitude.

The cascade crossed undulator scheme proposed by Tanaka and Kitamura, Fig. 1 for synchrotron radiation sources is a candidate to overcome this difficulty. In this paper, we study the use of this scheme at XFEL facilities as a mean to generate circularly polarized radiation at the fundamental frequency. The undulator is composed of several cascades, each of which forms a crossed undulator. We present exemplifications for the LCLS baseline case. The radiation from the proposed device is investigated numerically, and shows that a high degree (over 98%) of circular polarization and, simultaneously, a high output power level (GW-level) can be obtained if a sufficiently large number of cascades (up to four) is considered.

The applicability of the cascade crossed undulator

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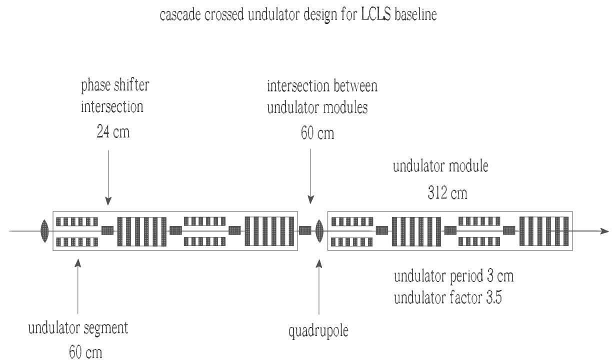

Figure 2: Schematic of the cascade crossed undulator proposed for effective polarization control at the LCLS baseline.

scheme is obviously not restricted to the LCLS baseline. Other facilities, e.g. the LCLS-II and the European XFEL, may benefit from this scheme as well.

CASCADE CROSSED UNDULATORS FOR THE LCLS BASELINE

We propose an undulator configuration for X-ray FELs allowing for high and stable degree of circular polarization, high output power and fast helicity switching. Although it is based on the short crossed undulator configuration, it can achieve much higher output power. With reference to Fig. 2, the undulator is composed of several cascades, each of which forms a crossed undulator. The helicity switching can be performed very quickly. In fact, a fast switching of the polarization direction can be achieved by using electromagnetic phase shifters.

Here we describe a particular realization of our proposal, a polarization control scheme that may be easily developed at the LCLS. It combines the cascade crossed undulator arrangement with the filtering method proposed in [2]. The electron beam first goes through the baseline undulator, producing SASE radiation. This induces energy and density modulation on the electron beam. We assume that the five second harmonic afterburner (SHAB) modules are rolled away from the beamline. At the end of the 20 m-long SHAB section we install a cascade crossed undulator, instead of an APPLE-type undulator as in [1], followed by slits. The electron beam bypasses the slits through a chicane. When the radiation pass through the slits, the linearly-polarized soft X-ray radiation from the LCLS baseline undulator is suppressed, because it is characterized by a much larger spot size compared with the circularly polarized radiation, and the background radiation power can therefore be diminished of orders of magnitude.

We performed FEL simulations with the help of the FEL code GENESIS 1.3 running on a parallel machine. We present a statistical analysis consisting of 100 runs. Parameters used in the simulations for the low-charge mode of operation in the crossed undulators are presented in Table 1. The choice of the low-charge mode of operation is motivated by simplicity.

First, the LCLS baseline is simulated. As discussed before, the baseline LCLS undulator should work in the linear regime. An optimum is found when only the last 5 cells upstream of the SHAB are used. In other words we assume

Table 1: Parameters for the Low-charge Mode of Operation at LCLS used in this Paper

	Units	
Undulator period	mm	30
K parameter (rms)	-	3.5
Wavelength	nm	1.5
Energy	GeV	4.3
Charge	nC	0.02
Bunch length (rms)	μm	1
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

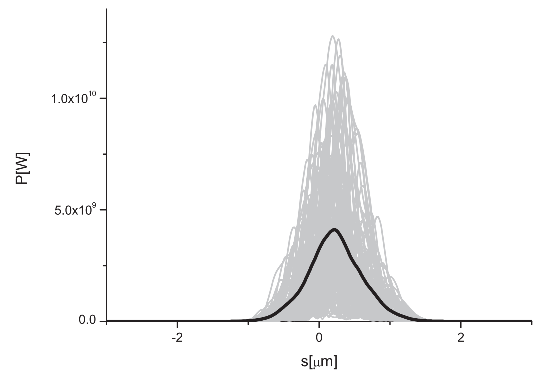

Figure 3: Power distribution after the first SASE undulator (5 cells). Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations.

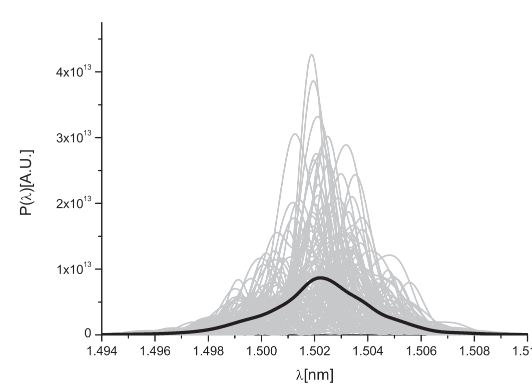

Figure 4: Spectrum after the first SASE undulator (5 cells). Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations.

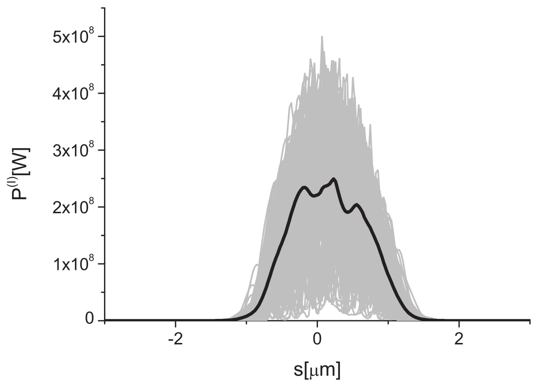

Figure 5: Power after the first crossed-undulator cascade, composed by the first crossed undulator. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations.

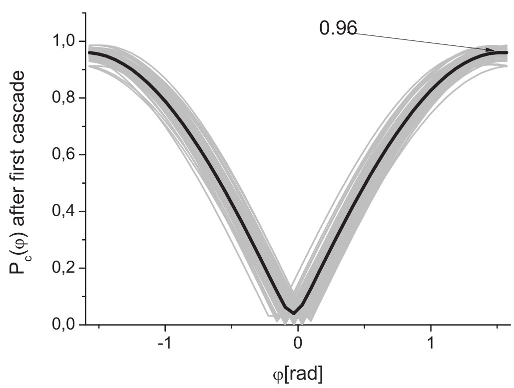

Figure 6: Circular degree of polarization as a function of the phase shift, after the first crossed-undulator cascade. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations. An average 98% degree of polarization can be obtained when the right phase is chosen.

that the first 23 baseline undulator modules are detuned. The power and spectrum after the baseline undulator are shown in Fig. 3 and Fig. 4. Simulations procedures follow reference [2]: the only difference is that now the APPLE II undulator is substituted by the crossed undulator system.

Following the 20 m drift, the electron beam enters the crossed-undulator cascade. We propose to fill two undulator modules of about 3.5 m of length each with crossed-undulator cascades as sketched in Fig. 2. We assume that each undulator segment is 60 cm-long, with a period of 3 cm. This allows for the installation of phase shifters between one segment and the following one. Two cascades fit in a single module. Finally, the filtering section, composed of slits and chicane for electron beam bypass follows.

The particle file is used to simulate the radiation output from the first undulator in the cascade. In particular, both a field file and a new particle file are produced by Genesis. The intersection between the first and the second undulator is modeled as a straight section. The correct phase shift is simulated by properly adjusting the length of this straight section. The horizontally polarized radiation should be further propagated through the second undulator and through the second phase shifter. To this purpose we still used Genesis after switching off the interaction with the electron bunch[1]. Then, the particle file at the entrance of the second undulator is used as an input for Genesis to calculate the vertically polarized field from the second undulator. The total output power from the first cascade, composed by the first crossed undulator is shown in Fig. 5.

Concerning the calculation of the average degree of polarization, following the LCLS approach we reduce the 3D averaging procedure to a one-dimensional calculation by, first, taking the Fourier transform of the horizontal and vertical radiation field at this position down the setup. This yields the far-zone radiation field. The on-axis far-zone field is then used to calculate the Stokes parameters and yields the circular polarization degree as a function of time for a given pulse, $P_{1c}(t)$. We subsequently weight $P_{1c}(t)$ over the on-axis power density of the pulse, $I(t)$, and we make an ensemble average over many pulses according to

$$P_c = \frac{1}{N_p} \sum_{n=1}^{N_p} \frac{\int_{-\infty}^{\infty} I(t) P_{1c}(t) dt}{\int_{-\infty}^{\infty} I(t) dt} , \qquad (1)$$

$N_p = 100$ being the number of pulses in our statistical run. The degree of polarization is obviously a function of the phase between the two polarization components. A plot of the circular degree of polarization as a function of the phase shift, after the first crossed-undulator cascade is shown in Fig. 6. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations. An average 96% degree of polarization can be obtained when the right phase is chosen.

The particle file resulting from the propagation at nominal current and the field file for the horizontally and vertically polarized radiation are used as input files for the following cascade, and the process is repeated up to the last cascade. The total output power is shown in Fig. 7, while the degree of polarization as a function of the phase is shown in Fig. 8. An average degree of polarization in excess of 98% can be obtained when the right phase is chosen, and high-power pulses can be produced in the GW-level.

CONCLUSIONS

In this paper we exploit the cross-undulator cascade scheme developed by Tanaka and Kitamura in order to achieve ultimate performance in polarization control, yielding high-power pulses of X-ray radiation with arbitrary state of polarization, very high degree of polarization, and

[1] This is done by decreasing the electron bunch current to 1A.

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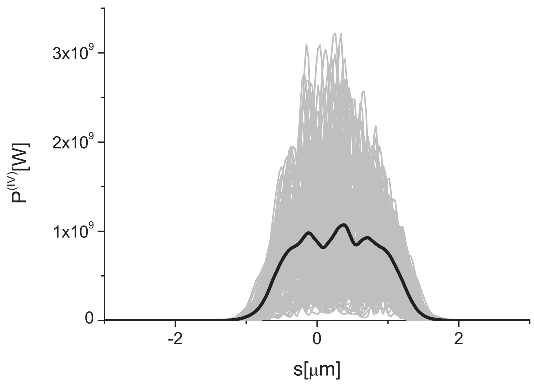

Figure 7: Power after the fourth crossed-undulator cascade. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations.

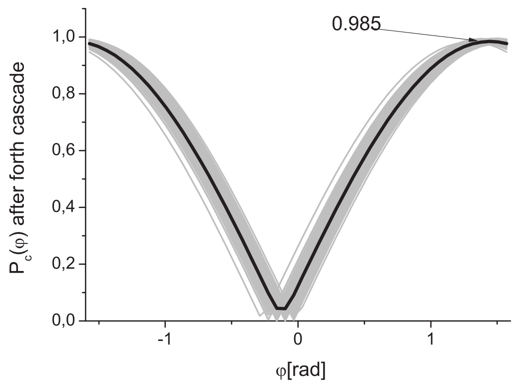

Figure 8: Circular degree of polarization as a function of the phase shift, after the fourth crossed-undulator cascade. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations. An average 98% degree of polarization can be obtained when the right phase is chosen.

fast switching of helicity. The proposed setup can be composed of an unlimited number of cascades, up to the full scale of the baseline undulator, the degree of polarization being independent of the length of the setup. This hints to possible future designs for baseline XFEL undulators where, for example, one half of the total length can be taken by a long cross-undulator cascade. In this case one may achieve circular polarization for soft and hard X-rays using the same scheme, and without problems of linearly polarized radiation background from the first part of the undulator.

We presented an illustration of the scheme for the LCLS, although other facilities like the LCLS-II and the European XFEL may also benefit from it, limiting ourselves to the soft x-ray range. We combined this method with the filtering concept considered in [2]. The main advantage achieved consists in obtaining fast helicity-switching up the the KHz level and, simultaneously, a high power level typical of APPLE-type undulators. In fact, by increasing the number of cascades from one to four we increase the output power by up to the GW and with very high ($> 95\%$) degree of polarization. Moreover, the use of planar devices is much less expensive compared to the APPLE-type. The exploitation of the filtering concept presented, in the case of an APPLE-type radiator [2], solves the issue of separating planar from circular polarization radiation components. The setup can be installed at the LCLS in a little time. It constitutes a cost-effective, risk-free alternative to currently available methods for polarization control.

REFERENCES

[1] G. Geloni, V. Kocharyan and E. Saldin, "Improvement of the crossed undulator design for effective circular polarization control in X-ray FELs", DESY 11-009 (2011), `http://arxiv.org/abs/1101.4085`.

[2] G. Geloni, V. Kocharyan and E. Saldin, "Microbunch preserving in-line system for an APPLE II helical radiator at the LCLS baseline", DESY 11-083 (2011), `http://arxiv.org/abs/1105.4783` and G. Geloni, V. Kocharyan and E. Saldin, "Circular polarization control for the European XFEL in the soft X-ray regime", DESY 11-096 (2011), `http://arxiv.org/abs/1106.1776`, concerning the idea of bypassing the slits with a magnetic chicane.

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