ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO008

OBTAINING HIGH DEGREE OF CIRCULAR POLARIZATION AT X-RAY FELS VIA A REVERSE UNDULATOR TAPER

E. A. Schneidmiller and M.V. Yurkov, DESY, Hamburg, Germany

Abstract

Baseline design of a typical X-ray FEL undulator assumes a planar configuration which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from using a circularly polarized radiation. As a cheap upgrade one can consider an installation of a short helical (or cross-planar) afterburner, but then one should have an efficient method to suppress powerful linearly polarized background from the main undulator. In this paper we propose a new method for such a suppression: an application of the reverse taper in the main undulator. We discover that in a certain range of the taper strength, the density modulation (bunching) at saturation is practically the same as in the case of non-tapered undulator while the power of linearly polarized radiation is suppressed by orders of magnitude. Then strongly modulated electron beam radiates at full power in the afterburner. Considering SASE3 undulator of the European XFEL as a practical example, we demonstrate that soft X-ray radiation pulses with peak power in excess of 100 GW and an ultimately high degree of circular polarization can be produced. The proposed method is rather universal, i.e. it can be used at SASE FELs and seeded (self-seeded) FELs, with any wavelength of interest, in a wide range of electron beam parameters, and with any repetition rate. It can be used at different X-ray FEL facilities, in particular at LCLS after installation of the helical afterburner in the near future.

INTRODUCTION

Successful operation of X-ray free electron lasers (FELs) [1–3], based on self-amplified spontaneous emission (SASE) principle [4], opens up new horizons for photon science. One of the important requirements of FEL users in the near future will be polarization control of X-ray radiation. Baseline design of a typical X-ray FEL undulator assumes a planar configuration which results in a linear polarization of the FEL radiation. However, many experiments at X-ray FEL user facilities would profit from using a circularly polarized radiation. There are different ideas [5–12] for possible upgrades of the existing (or planned) planar undulator beamlines.

As a cheap upgrade one can consider an installation of a short helical afterburner. In particular, an electromagnetic helical afterburner will be installed behind the soft X-ray planar undulator SASE3 of the European XFEL. However, to obtain high degree of circular polarization one needs to suppress (or separate) powerful linearly polarized radiation from the main undulator. Different options for such a suppression (separation) are considered: using achromatic bend between planar undulator and helical afterburner [7]; tuning resonance frequency of the afterburner to the second harmonic of the planar undulator [8]; separating source positions and using slits for spatial filtering [12].

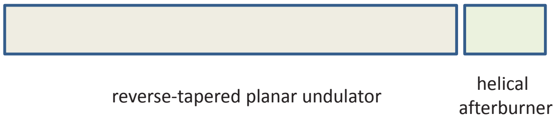

Figure 1: Conceptual scheme for obtaining circular polarization at X-ray FELs.

In this paper we propose a new method for suppression of the linearly polarized background from the main undulator: application of the reverse undulator taper. In a short-wavelength SASE FEL the undulator tapering is used for two purposes: to compensate an electron beam energy loss in the undulator due to the wakefields and spontaneous undulator radiation; and to increase FEL power (post-saturation taper). In both cases the undulator parameter K decreases along the undulator length. The essence of our method is that we use the opposite way of tapering: parameter K increases what is usually called reverse (or negative) taper. We discover that in some range of the taper strength the bunching factor at saturation is practically the same as in the reference case of the non-tapered undulator, the saturation length increases slightly while the saturation power is suppressed by orders of magnitude. Therefore, our scheme is conceptually very simple (see Fig. 1): in a tapered main (planar) undulator the saturation is achieved with a strong microbunching and a suppressed radiation power, then the modulated beam radiates at full power in a helical afterburner, tuned to the resonance.

Detailed explanation of the suppression effect can be found in [13], here we only present the results of numerical simulations for the European XFEL [14].

NUMERICAL SIMULATIONS FOR THE EUROPEAN XFEL

We consider the parameters of the soft X-ray SASE3 undulator of the European XFEL [14]. Main parameters used in our simulations are presented in Table 1. The electron beam parameters are taken from the table provided by the European XFEL beam dynamics group [15] for the bunch charge of 0.5 nC. We consider operation of SASE3 in "fresh bunch" mode [16] when the energy spread of electron bunches is not spoiled by the FEL interaction in the upstream SASE1 undulator. The simulations were performed with 3-D version of the code FAST [17].

Table 1: Main Parameters used in Simulations

Electron beam	
Energy	14 GeV
Charge	0.5 nC
Peak current	5 kA
Rms normalized slice emittance	0.7 μm
Rms slice energy spread	2.2 MeV
Planar undulator	
Period	6.8 cm
K_{rms}	5.7
Beta-function	15 m
Active magnetic length	55 m
Taper $\Delta K_{\mathrm{rms}}/K_{\mathrm{rms}}(0)$	2.1 %
Helical afterburner	
Period	16 cm
K	3.6
Beta-function	15 m
Magnetic length	10 m
Radiation	
Wavelength	1.5 nm
Power from planar undulator, P_{lin}	0.4 GW
Power from helical undulator, P_{cir}	155 GW
$1 - P_{\mathrm{lin}}/(2P_{\mathrm{cir}})$	99.9 %

A gap-tunable permanent-magnet SASE3 undulator consists of 21 undulator modules, each of them is 5 m long. One can easily control active part of the undulator by opening the gaps of the modules which are not needed. In our case we use only 11 last modules to adapt the saturation length to the given wavelength (1.5 nm) and electron beam parameters. A long-period electromagnetic helical afterburner is being developed [18] for installation behind SASE3 undulator. The choice of technology is driven by the request of users to quickly change (between the macropulses, i.e. with the frequency of 5 Hz) the polarization of the output radiation between left and right.

We optimized the taper strength in the main undulator such that the radiation power is sufficiently suppressed, on the one hand, and the bunching factor is still close to that in the case of untapered undulator, on the other hand. We ended up with 2.1 % increase of K parameter over the undulator length of 55 m.

Evolution of the bunching factor along the planar undulator and the helical afterburner is shown in Fig. 2, and the time dependence of bunching factor at the exit of the planar undulator - in Fig. 3. One can see that the bunching factor reaches a pretty high level and becomes even larger in the helical afterburner.

Radiation power as a function of position in the planar main undulator and in the helical afterburner is shown in Fig. 4. One can see that, indeed, linearly polarized radiation from the main undulator is strongly suppressed (it is about 0.4 GW), and the powerful circularly polarized radiation quickly builds up in the afterburner. This happens because the bunching is strongly detuned from the resonance with the last part of the planar undulator, but the K value of the afterburner is optimized in such a way that it is close to the resonance, and maximum power is achieved at the end of the afterburner. A part of the radiation pulse is shown in Fig. 5 for illustration; ensemble averaged peak power reaches 155 GW. Now we can calculate the degree of circular polarization due to contamination from the planar undulator: $1 - P_{\mathrm{lin}}/(2P_{\mathrm{cir}}) \simeq 0.999$.

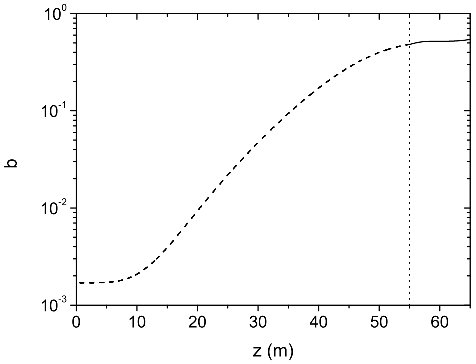

Figure 2: Evolution of the ensemble averaged rms bunching factor along the planar undulator SASE3 (dash) and the helical afterburner (solid).

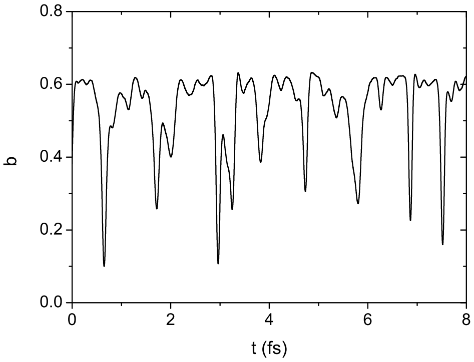

Figure 3: Modulus of bunching factor versus time at the exit of the planar undulator SASE3 (position 55 m on Fig. 2). A central part of the electron bunch is shown.

Parameters of the helically polarized radiation are shown in Table 1. The pulse duration and the pulse energy are defined by the chosen bunch charge (set of charges from 20 pC to 1 nC with different parameters will be available at the European XFEL). For example, the pulse duration can be chosen between few femtoseconds and 100 femtoseconds. In all cases the peak power and the degree of circular polarization will be comparable to those shown in Table 1. Let us also notice that our method will work in a wide range of photon energies so that one can easily cover not only L-edges but also M-edges of all interesting elements. Indeed, in the considered case of lasing at 1.5 nm the active length of the undulator is 55 m (to be compared to the saturation length of 45 m for the untapered case, i.e. we have only 20% increase in length). The total magnetic length of the SASE3 undulator is 105 m so that there is a big reserve for going

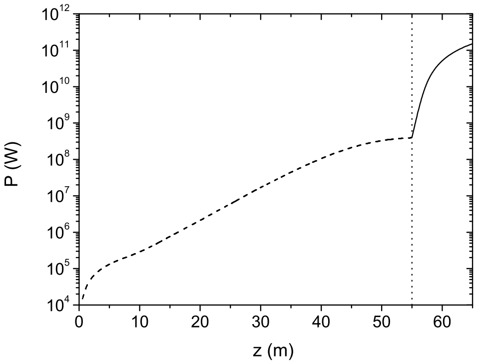

Figure 4: FEL power versus the length of the planar main undulator SASE3 (dash) and the helical afterburner (solid).

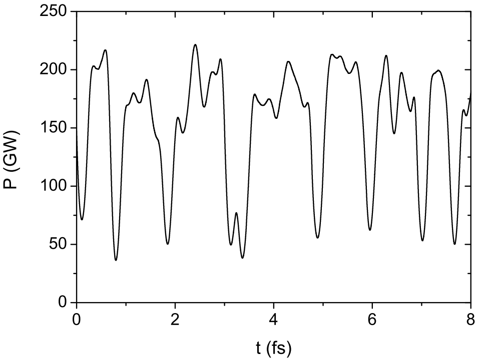

Figure 5: Peak power of circularly polarized radiation at the exit of the afterburner (position 65 m on Fig. 4). A central part of the X-ray pulse is shown.

to shorter wavelength. Generally speaking, our method can also work at hard X-ray beamlines if this is requested by users.

Finally, let us note that in the case of energy loss along the undulator due to the wakefields and spontaneous undulator radiation at high energies, the strength of the reverse taper can be decreased accordingly. In our case both effects are small corrections, each of them is on the order of 0.1% in the active part of the SASE3 undulator - to be compared with about 2% of the K change.

A POSSIBLE OPERATION AT LCLS

A gap-fixed planar undulator is used to generate hard- and soft- X-ray radiation at the Linac Coherent Light Source (LCLS) [2]. A helical afterburner is going to be installed soon in order to provide a circular polarization for user operation at LCLS [19].

Design of the planar undulator allows for a mild tapering by making use of canted poles. This option is normally used for compensation of the beam energy loss along the undulator length, and for the post-saturation taper - in both cases a standard (positive) sign of taper is needed. We propose here to use a reverse taper to obtain powerful X-ray radiation (in soft- and hard- X-ray regimes) with a high degree of circular polarization, in excess of 99%. Our estimates suggest that the strength of the reverse taper should typically be on the order of 1% over active undulator length. After optimizing the taper strength and active length of the main undulator, the K-value of the helical afterburner should be scanned in order to obtain maximum power. Such an experiment can be performed in the near future.

REFERENCES

[1] W. Ackermann et al., Nature Photonics **1**(2007)336.

[2] P. Emma et al., Nature Photonics **4**(2010)641.

[3] T. Ishikawa et al., Nature Photonics **6**(2012)540.

[4] A.M. Kondratenko and E.L. Saldin, Part. Accelerators **10**(1980)207.

[5] K.-J. Kim, Nucl. Instrum. and Methods **A 445**(2000)329.

[6] Y. Ding and Z. Huang, Phys. Rev. ST Accel. Beams 11(2008)030702.

[7] Y. Li et al., Phys. Rev. ST-AB **13**(2010)080705.

[8] E.A. Schneidmiller and M.V. Yurkov, Proc. of the FEL2010 Conference, Malmö, Sweden, p. 123, [http://www.jacow.org].

[9] E.A. Schneidmiller and M.V. Yurkov, Proc. of the FEL2010 Conference, Malmö, Sweden, p. 115, [http://www.jacow.org].

[10] T. Tanaka and H. Kitamura, AIP Conference Proceedings 705 (2004)231.

[11] G. Geloni, V. Kocharyan and E. Saldin, preprint DESY-11-009, January 2011.

[12] G. Geloni, V. Kocharyan and E. Saldin, preprint DESY-11-096, June 2011.

[13] E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 16(2013)110702.

[14] M. Altarelli et al. (Eds.), XFEL: The European X-Ray Free-Electron Laser. Technical Design Report, Preprint DESY 2006-097, DESY, Hamburg, 2006 (see also http://xfel.desy.de).

[15] W. Decking, M. Dohlus, T. Limberg, and I. Zagorodnov, Baseline beam parameters for the European XFEL, private communication, December 2010.

[16] R. Brinkmann, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Meth. **A 616**(2010)81.

[17] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods **A 429**(1999)233.

[18] N. Vinokurov et al., private communication.

[19] E. Allaria et al., Proc. of the FEL2011 Conference, Shanghai, China, August 2011, p. 31, [http://www.jacow.org].