AN OPTION OF FREQUENCY DOUBLER AT THE EUROPEAN XFEL FOR GENERATION OF CIRCULARLY POLARIZED RADIATION IN THE WAVELENGTH RANGE 1–2.5 nm*

E.A. Schneidmiller and M.V. Yurkov

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

Wavelength range of high scientific interest refers to K- and L- absorption edges of magnetic elements which spans from 2.5 nm to 1.4 nm (500 - 900 eV). This wavelength range can be partially covered by SASE3 at the European XFEL, from 1.6 nm and down when operating at the nominal energy of 17.5 GeV. Operation at the reduced energy would allow to cover complete wavelength range of interest. Currently SASE3 is a planar device producing linearly polarized radiation. On the other hand, it is important to have circular polarization for experiments with magnetic samples. Solution of the problem of polarization is installation of an afterburner generating circularly polarized radiation. This can be helical afterburner or crossed-planar afterburner operating at the fundamental or double frequency.

INTRODUCTION

The first stage of SASE3 FEL will be based on a planar undulator, and there is a demand to produce circularly polarized radiation after corresponding upgrade of the undulator [1]. Relevant roadmap for studying different options have been formulated in the framework of the European XFEL project [2]. These options include full-length helical undulator, helical afterburner and cross-planar afterburner operating at the fundamental or double frequency, and self-seeding scheme. Recently options operating at the fundamental frequency (based on helical undulator and cross-planar undulator) have been analyzed in details [3–6]. Option of a full-length helical undulator [6] is considered as the most attractive in terms of quality of the output radiation (power and coherence properties). However, its realization is not foreseen at the first stage of the realization of the project mainly due to technical challenges of long helical undulators. An option of a (short) helical afterburner could be reasonable compromise at the first stage, but its technical realization need more studies related to separation of the powerful radiation from the main undulator (having linear polarization) and low-power radiation from an afterburner. This problem is common for both, helical and cross-planar afterburner [3, 4].

Solution for generation of clean circularly polarized radiation is provided by a concept of an afterburner operating at the second harmonic of the main undulator [7–10]. Afterburner is installed downstream of the main undulator.

_____
* FEL 2010 Conference

Electron beam current brings rich harmonic content when FEL process enters nonlinear stage (saturation) in the main undulator. An important feature of the nonlinear mode of the FEL operation is that even harmonic of the FEL radiation are significantly suppressed, while it is not the case for the harmonics of the beam density modulation [11, 12]. Thus, radiation power from an afterburner tuned to the second harmonic of the main undulator significantly exceeds radiation power of the second harmonic from the main undulator. Separation of the second harmonic radiation is performed by means of dispersive optical elements. In this paper we present studies of two afterburner options: with helical and cross-planar undulator. Numerical results illustrate wavelength range around 1.6 nm.

HELICAL FREQUENCY DOUBLER

SASE3 undulator is a planar device with period of 6.8 cm. Tunability of the radiation is provided by variable undulator gap. With minimum undulator gap of 10 mm maximum wavelength is 1.6 nm and 4.9 nm for the energy of electrons of 17.5 GeV and 10 GeV, respectively. Minimum wavelength is defined by the quality of the electron beam (peak current, emittance and energy spread), and the undulator length (100 meters). In this paper we consider operation of SASE3 with 1 nC bunch charge, peak current 5000 A, normalized rms emittance 1.05 π mm-mrad, and rms energy spread 2 MeV [13]. Operating energy of electrons is 10 GeV.
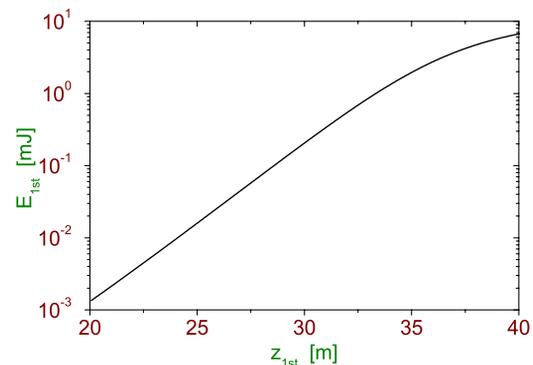

Figure 1: Energy in the radiation pulse versus undulator length in the main undulator SASE3. The radiation wavelength is equal to 3.2 nm. Driving accelerator operates at the energy of 10 GeV.
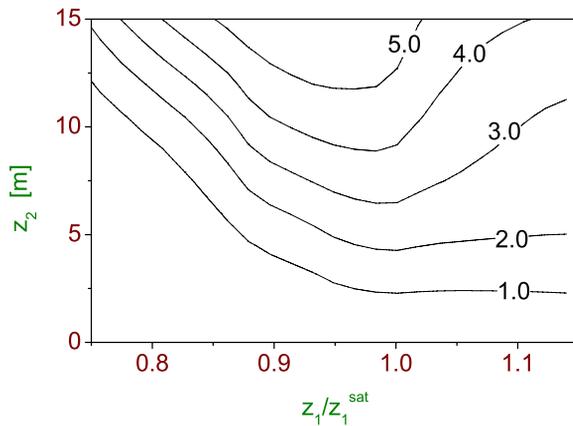
Figure 2: Contour plot for the energy in the radiation pulse (mJ) in the helical frequency doubler. Horizontal coordinate is the length of the main undulator normalized to saturation length. Vertical coordinate is the length of the helical frequency doubler. The radiation wavelength is equal to 1.6 nm. Driving accelerator operates at the energy of 10 GeV.
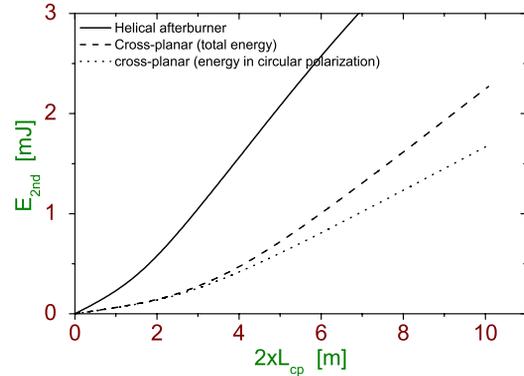

Figure 3: Energy in the radiation pulse in the helical (solid line) and cross-planar frequency doubler (dashed line). Dotted line shows radiation energy with circular polarization from the cross-planar undulator. Frequency doubler operates at 1.6 nm wavelength. Driving accelerator operates at the energy of 10 GeV.

Table 1: Parameters of the Frequency Doubler at SASE3

Undulator (2nd harmonic, 10 GeV)	
Type	helical, PPM
Wavelength range	0.8 - 2.5 nm
Period	6.8 cm
Gap	10 - 20 mm
Peak magnetic field	0.82 - 0.45 T
Undulator length	5 m
Coherent radiation at $\lambda = 1.6$ nm	
Energy per pulse	2 mJ
Peak power	20 GW
Bandwidth (FWHM)	0.3%
Pulse duration (FWHM)	100 fs

Here we present the results of numerical simulations of an afterburner with helical undulator for production of the 2nd harmonic at SASE3. Simulations have been performed with time-dependent FEL simulation code FAST [14]. The parameters of the undulator and the output radiation are presented in Table 1. Parameters of the helical permanent magnet undulator are close to those of described in the XFEL TDR [1]. In the afterburner scheme the spent electron beam leaving the main X-ray undulator passes an undulator tuned to the second harmonic. Figure 1 shows evolution of the energy in the radiation pulse in the main undulator. For given parameter set saturation occurs at the undulator length of 37 meters. At the exit of the main undulator the electron beam has a pronounced amplitude of density modulation at the second harmonic which serves as input signal for the second harmonic afterburner. When the electron beam enters the afterburner radiator, it readily starts to produce radiation. Figure 2 shows contour plot of the radiation pulse energy for the helical afterburner as a function of the lengths of the main undulator and the afterburner. For each length of the afterburner we can optimally tune main undulator to have maximum power in the afterburner. For the given parameter space optimum case is an interrupt of the amplification process in the main undulator near the saturation point. Plot for maximum pulse energy in the 2nd harmonic afterburner is shown in Fig. 3. The pulse energy rapidly reaches a mJ level at 2 meters. The FWHM pulse duration is about 100 fs. The spectral width is about 0.3%, and is defined mainly by the energy spread in the electron beam induced by the FEL process in the main undulator. The level of output radiation energy (2 mJ at 5 meters long undulator) is about 20% of the power of the fundamental frequency of the main undulator.

CROSS-PLANAR FREQUENCY DOUBLER

A concept of cross-planar undulators has been introduced by K.-J. Kim [15]. The system consists of two planar undulators (long and short) separated by phase shifter. Short undulator is rotated by 90 degrees with respect to a long one. SASE process develops in the long (main) undulator, the beam is modulated by the FEL process in the first undulator, and then radiates in the second (short) undulator. Wavepackets with crossed polarization are phased such that output radiation has high contribution of circular polarization. Here the problem is to produce (nearly) identical wavepackets from the main (long) and the crossed (short) undulator. Recent studies have shown that relatively high degree of polarization can be obtained only when the main undulator operates in the linear regime [16]. As a result, radiation power is small, and the radiation intensity is subjected to strong fluctuations.

Another scheme with cross-planar undulators has been proposed in refs. [3, 4]. Main SASE undulator is a planar one and operates in the saturation regime. Cross-planar afterburner is placed after the main undulator and consists
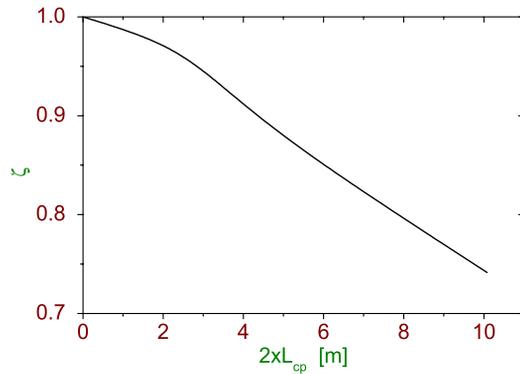
Figure 4: Degree of circular polarization of the radiation from cross-planar 2nd harmonic afterburner. Frequency doubler operates at 1.6 nm wavelength. Driving accelerator operates at the energy of 10 GeV.
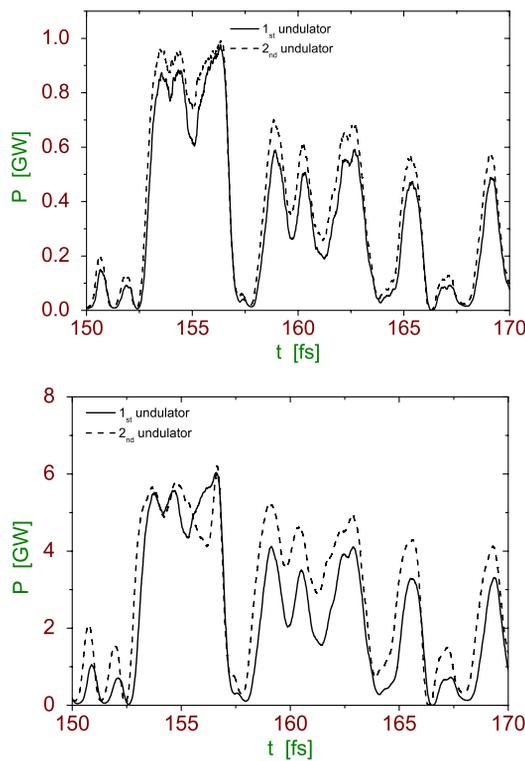

Figure 6: Intensity distributions of the radiation at the exit of the cross-planar undulator for different lengths of the undulators: 2×1 meters (top plot) and 2×2.5 meters (bottom plot). Solid and dashed lines refer to the first and the second undulator, respectively. Frequency doubler operates at 1.6 nm wavelength. Driving accelerator operates at the energy of 10 GeV.

Figure 5: Temporal structure of the radiation pulse for different lengths of cross-planar undulators: 2×1 meters (top plot) and 2×2.5 meters (bottom plot). Solid and dashed lines refer to the first and the second undulator, respectively. Frequency doubler operates at 1.6 nm wavelength. Driving accelerator operates at the energy of 10 GeV.

of two short pieces of planar undulator rotated by 90 degrees with respect to each other and separated by phase shifter. "Short" means undulators operate as radiators only not disturbing density modulation gained in the main SASE undulator, and slippage of the radiation is much less than coherence length. Thus, radiated wavepackets are nearly identical, but have crossed polarization. An appropriate tuning of the phase shifter allows to prepare helical polar-
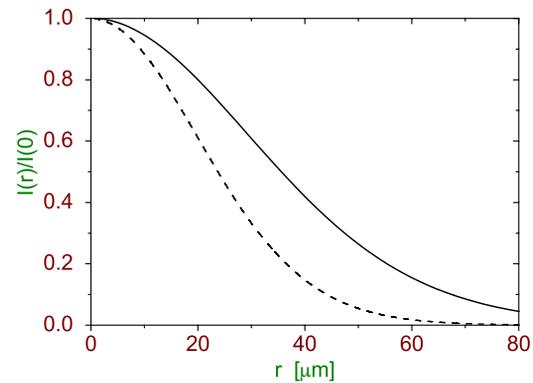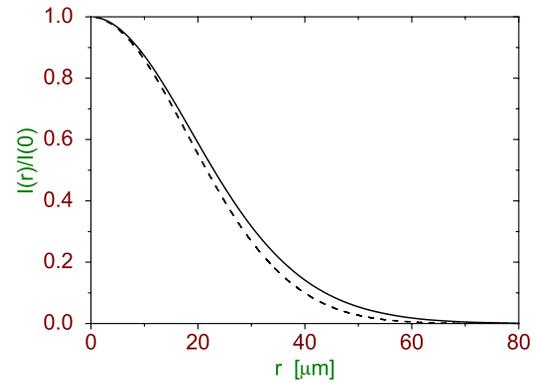
ization. This scheme holds potential of providing relatively high degree of circular polarization, but at a relatively small level output power. Positive feature of this scheme is small shot-to shot fluctuations of the radiation intensity. This happens because the main undulator operates in the saturation. Realization of this scheme operating at the fundamental harmonic requires spatial separation of powerful radiation from the main undulator, and relatively weak radiation from the cross-planar afterburner. Matching section to the cross-planar afterburner should preserve bunching induced in the main undulator which is rather challenging [5].

On the other hand, undulators of a cross-planar afterburner can be tuned to any harmonic of the main undulator. As we mentioned above, tuning to the second harmonic provides clean circularly polarized radiation. High power radiation from the main undulator and the cross-planar afterburner have different frequencies and can be easily separated with dispersive optical elements. Here we illustrate operation of a cross-planar second harmonic afterburner for specific case of European XFEL. Operating wavelength of the main SASE undulator is 3.2 nm, and operating wavelength of the afterburner is 1.6 nm, the 2nd harmonic of the main undulator. SASE process in the main undulator is tuned to the saturation, and then electron beam passes

second harmonic afterburner. Figure 3 shows evolution of the radiation energy as a function of the length of the afterburner. We notice that cross-planar afterburner produces visibly less radiation power than helical afterburner of the same length. This result reflects well known feature of more effective coupling factor for the helical undulator. More essential difference relates to the degree of circular polarization. Radiation from helical undulator is always completely circularly polarized, but it is not the case for the cross-planar scheme as we can see from Fig. 4. There are several effects leading to degradation of the degree of circular polarization. The most strong effect is different bunching in the undulators. Bunching changes due to the longitudinal velocity spread induced by the FEL process in the main undulator (debunching), or FEL process in the afterburner itself. Another effect is slippage of the radiation which becomes more pronounced with the undulator length. These effects are illustrated with Fig. 5. Another effect refers to diffraction expansion of the radiation. Radiation produced in the first undulator does not interact with the electron beam in the second undulator, and just expands as in the free space to the end of the cross-planar system. Electromagnetic wave with crossed polarization is radiated when electron beam propagates to the second undulator. As a result, spot sizes of the radiation from the first and the second undulator are different, and this difference grows with the undulator length as one can see from Fig. 6).

DISCUSSION

In this paper we presented comparative analysis of a helical and cross-planar after burner operating at the second harmonic. Installation of a helical afterburner allows to produce radiation with high peak power and high pulse energy (20 GW and 2 mJ, respectively), and with nearly complete circular polarization. Helical magnetic field can be realized with permanent magnet technology, or electromagnetic winding (superconducting or pulsed) [19–21]. Helicity of the radiation (left or right) is defined by the helicity (left or right) of the magnetic field rotation in the undulator. Many user experiment require fast change of the helicity [22]. For a helical undulator based on permanent magnet technology changing the helicity of the field is possible on a scale of several minutes (limited by the speed of mechanical motion of poles). Another solution of the problem can be realized with electromagnetic undulators: one can install two of helical afterburners with opposite helicity, and power on that with required helicity.

Polarization properties of the cross-planar system degrade with the increase of the undulator length (and hence, of the radiation power). For relatively short cross-planar afterburner (2×1 meter long) it is possible to have degree of circular polarization about 95%. Peak radiation power and pulse energy are about 0.8 GW and 80 microjoles, respectively. However, an attractive feature of the cross-planar system is the possibility of a fast change of the helicity of the radiation by means of fast tuning of the phase shifter.

REFERENCES

[1] Altarelli, M. 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).

[2] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, SASE-3: options for variable polarization. Report at the European XFEL WPG3 Metteting, November 6, 2007. Available by request.

[3] Y. Li et al., Proc. EPAC 2008 Conference, WEPC118.

[4] Y. Li et al., Proc. FEL 2008 Conference, TUPPH004.

[5] Y. Li et al., Proc. FEL 2009 Conference, WEPC03.

[6] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Proc. FEL2009 Conference, WEPC51.

[7] J. Feldhaus et al., Preprint DESY 03-092, Hamburg, 2003, 16pp.

[8] J. Feldhaus et al., Nucl. Instrum. and Methods A 528(2004)471.

[9] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, DESY Print TESLA-FEL 2004-02, Hamburg, 2004.

[10] Z. Huang and S. Reiche, Proc. FEL2004 Conference, MO-POS63.

[11] G. Geloni, E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Optics Communications, 271(2007)207.

[12] W. Ackermann et al., Nature Photonics, 1 (2007)336-342.

[13] W. Decking and T. Limberg, Baseline parameters for the European XFEL. Available by request.

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

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

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

[17] E. L. Saldin, E. A. Schneidmiller, M. V. Yurkov, The Physics of Free Electron Laser. Springer, Berlin-Heidelberg-New York, 1999.

[18] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 9(2006)030702.

[19] S. Sasaki et al., Nucl. Instrum. and Methods 347(1994)87.

[20] J.A. Clarke et al., Proc. EPAC08, MOPP070.

[21] A.A. Kaminsky et al., Nucl. Instrum. and Methods 375(1996)215.

[22] C. Gutt et al., Phys. Rev. B 79 (2009) 212406.