BETATRON SWITCHER FOR A MULTI-COLOR OPERATION OF AN X-RAY FEL

R. Brinkmann, E.A. Schneidmiller, and M.V. Yurkov
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

With bright electron beams the full length of gap-tunable X-ray FEL undulators can be efficiently used to generate multiple x-ray beams with different independent wavelengths for simultaneous multi-user operation. We propose a betatron switcher and show that one only needs to install a compact fast kicker in front of an undulator without any modifications of the undulator itself. Different groups of bunches get different angular kicks, and for every group a kick is compensated statically (by corrections coils or moving quadrupoles) in a part of the undulator, tuned to the wavelength designated to the given group. As a generalization of the method of the betatron switcher, we briefly describe a scheme for pump-probe experiments.

INTRODUCTION

Free-electron lasing at wavelengths shorter than the ultraviolet can be achieved with a single-pass, high-gain FEL amplifier. Due to lack of powerful, coherent seeding sources, short-wavelength FEL amplifiers work in the so called Self-Amplified Spontaneous Emission (SASE) mode, where the amplification process starts from shot noise in the electron beam [1, 2, 3]. Present acceleration and FEL techniques allow to generate powerful, coherent femtosecond pulses in wavelength range from vacuum ultraviolet (VUV) [4, 5, 6] through soft X-ray [7, 8] to hard X-ray [9].

Recent successful lasing of the Linac Coherent Light Source (LCLS) in the hard x-ray regime [9] has lead to the discussions on optimistic scenarios of operation of the European XFEL [10]. In this paper we consider an option that makes use of low-emittance beams, a gap-tunable undulator, and multi-bunch capability of this facility.

If the undulator is long enough and/or the electron beam is bright enough, a few different colors can be produced within a given undulator length (see also [11, 12]). In this paper we propose a simple, cheap and reliable method for a production of several independent colors. Although the description of the method, as well as numerical examples, are connected with the layout and parameters of the European XFEL, the method can also be used at other X-ray FEL facilities.

LAYOUT OF THE EUROPEAN XFEL

Basic concept of the European XFEL facility assumes to cover continuously wavelength range from 0.1 to 1.6 nm at a fixed energy of the electron beam of 17.5 GeV (at the

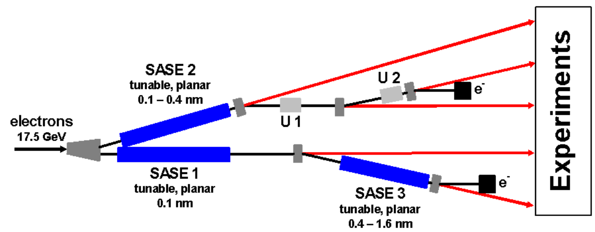

Figure 1: Layout of the European XFEL.

moment the reduction of energy and extension of wavelength range are being discussed). This is achieved with installation of three FEL radiators. Taking into account that many of planned user experiments require wavelength around 0.1 nm, two FEL beamlines are foreseen to operate simultaneously in this wavelength range. The first FEL beamline (SASE1) is optimized for operation at the wavelength of 0.1 nm. The second FEL beamline (SASE2) is designed to provide tunable radiation from 0.1 to 0.4 nm, and the third FEL beamline (SASE3) covers wavelength range of 0.4 -1.6 nm. All undulators utilize planar, variable-gap undulators with a similar mechanical design. SASE3 will be installed after SASE1 and will operate in a ”parasitic” mode using spent electron beam passed through SASE1 undulator.

SCHEME DESCRIPTION

A long undulator with tunable gap (to be specific, in the following we mainly consider SASE2, although the method can also be applied to SASE1) may be used for generation of several wavelengths. We propose to install a fast kicker in front of the undulator (or using the feedback kicker [10]) and to give different angular kicks (with a shift between kicks on the order of 10 μrad or less, depending on requested wavelengths) to different groups of bunches (a bunch pattern for each group is defined by users requests). For every group a kick is compensated statically at one location in the undulator by moving transversely a quadrupole, i.e. by using it as a steerer. After that location the bunches of this group go straight and lase to saturation in a part of an undulator (sub-undulator), of which magnetic field is tuned to a desired wavelength (see Fig. 2 for illustration). In other sub-undulators the trajectory of this group strongly deviates from the straight path, and bunches of this group do not lase. In a given sub-undulator only one group of bunches lases to saturation, orbits of other groups are strongly disturbed. So, every group lases in its own sub-undulator, of which magnetic field is tuned to a requested wavelength. A length of a sub-undulator is chosen such that a betatron phase advance per its length is π (or multiple of π) on the one hand, and the length is multiple of a length of an elementary cell on the other hand.

The elementary cell of SASE2 consists of an undulator module and a focusing (defocusing) quadrupole (we do not describe here elements that are not relevant to the operation of the scheme). The length of an elementary cell is $L_{cell} = 6.1$ m, FODO period is equal to $2L_{cell}$. Beta-function for a given beam energy is defined by the strength of quadrupoles and can be varied remotely. In the following we assume for simplicity that the strength is the same for all quadrupoles in the undulator, so that periodicity is not perturbed. Optimal beta-function depends on the wavelength as well as on beam and undulator parameters [13]:

$$\beta_{\rm opt} \simeq 11.2 \left(\frac{I_A}{I}\right)^{1/2} \frac{\epsilon_n^{3/2}\lambda_{\rm w}^{1/2}}{\lambda K A_{JJ}} (1+8\delta)^{-1/3} \quad (1)$$

Here I is the beam current, $I_A = 17$ kA is Alfven current, ϵ_n is the normalized emittance, λ is resonant wavelength, δ is a parameter depending on energy spread [13] (usually a small correction), $\lambda_{\rm w}$ is the undulator period, K is the rms undulator parameter, $A_{JJ} = 1$ for a helical undulator and $A_{JJ} = J_0(K^2/2(1+K^2)) - J_1(K^2/2(1+K^2))$ for a planar undulator, J_0 and J_1 are the Bessel functions of the first kind. The expression (1) was obtained in [13] under an assumption of small betatron phase advance per FODO period, $2L_{cell} \ll \beta$. If this condition is not satisfied, this expression is still a good first guess for an average beta-function. Also note that this condition is not necessary for operation of the proposed scheme.

As one can see from (1), optimal beta function is the largest for the shortest wavelength. We choose an optimal beta-function for a shortest wavelength from a requested set because FEL saturation length is the largest for the shortest wavelength. Note, however that deviations at 10-20 % level are tolerable (since a function changes slowly near an optimum)[1], so that one has some freedom to adjust β. Then we define a length of a shortest possible sub-undulator as[2]

$$\int_0^{L^0_{sub}} \frac{dz}{\beta} = \pi$$

$$L^0_{sub} = nL_{cell}$$

Under these conditions the integrated kick from upstream quadrupoles and a current quadrupole (all located at zero crossings of electron orbit) can compensate exactly a kick from fast kicker for a given group of bunches. Then these bunches go straight and lase in a given sub-undulator. A length of a sub-undulator, depending on a wavelength, can be a multiple of the elementary sub-undulator length, $L_{sub} = mL^0_{sub}$.

[1] If the undulator length allows, one can even use β that deviates significantly from the optimum for the shortest wavelength.

[2] For simplicity we assume here that a kick is localized just in front of the undulator. In a general case one might think of a (tunable) phase advance between the kicker and the undulator, which is multiple of a phase advance per cell. In that case the length of the first sub-undulator is reduced, what might be tolerable for the longest requested wavelength

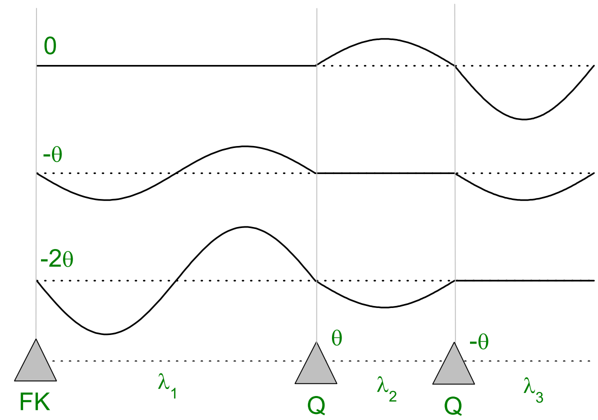

Figure 2: A schematic illustration of the betatron switcher for multi-color operation of a SASE undulator. Here "FK" stands for a fast kicker (giving different kicks to different bunches) and "Q" for a quadrupole (giving the same static kick to all bunches). Betatron phase advance is 2π in the first sub-undulator, and π in each of the last two sub-undulators. Lasing to saturation takes place only on straight sections of beam orbit.

NUMERICAL EXAMPLES

Let us consider numerical examples, using the formulas of Ref. [13]. Consider an electron beam with the following parameters: $I = 5$ kA, $\epsilon_n = 0.4$ mm mrad, energy spread is 1 MeV at the entrance of SASE2, beam energy is 17.5 GeV. The length of SASE2 undulator is 256 m (42 cells). Imagine that users request three different wavelengths (see Fig. 2 for illustration): 0.5 Å, 1.6 Å, and 2.3 Å. Optimal beta-function for 0.5 Å is about 20 m, we adjust it such that the above mentioned conditions are met. As a result, we choose an elementary sub-undulator to be equal to 10 cells (61 m). In order to have FEL saturation at 0.5 Å, we use two elementary sub-undulators, i.e. the magnetic field of first 20 cells is tuned for this wavelength ($K = 1.2$). The next 10 cells are tuned to 1.7 Å ($K = 2.7$), and the 10 cells after that operate at 2.3 Å ($K = 3.2$). Although beta-function is significantly larger than the optimal ones in the last two cases, the wavelengths are long enough for saturation within given sub-undulators. In this case the group of bunches, lasing at 0.5 Å, is undisturbed by a kicker, the second group (1.7 Å) gets a kick of -10 μrad, and the third one -20 μrad.[3] After 20 cells (full period of betatron oscillations) the quadrupole gives the kick of 10 μrad to all

[3] Kicks to the one direction are considered here for simplicity. Note that in this specific example the symmetric kicks of ± 10 μrad are also possible.

bunches, so that now the second group goes straight, but the first and the third have ± 10 μrad and do not lase. After 30 cells the quadrupole compensates the kick for the third group, then the first and the second groupes have -20 and -10 μrad, respectively. The last two cells are not used. Also note that in the case when unspoiled bunches for the recently suggested [14] ultra-hard FEL SASE-U1 (spontaneous radiator U1 in Fig. 1, operated in SASE mode) are needed, in the considered case this would be the fourth group that gets a kick of -30 μrad, and the kick is compensated, for instance, after 40 cells. Thus, in SASE-U1 only this unspoiled group lases but the other groups do not. A number of possible colors is mainly defined by the shortest wavelength. It can be increased to 4-5 in SASE2 if the shortest wavelength is about 1.5 Å or larger. Alternatively, it can be increased for a smaller emittance.

Let us now consider an example for SASE1 undulator for the same parameters of the electron beam as in the example with SASE2. SASE1 consists of 33 cells (total length is 201 m). At the nominal operating energy of 17.5 GeV the longest possible wavelength (with closed undulator gap of 10 mm) is 1 Å. Operation at shorter wavelengths is possible by opening the gap. In our example the first part of the undulator (16 cells with net magnetic length 80 m and total length about 98 m) is tuned to a resonance with 0.5 Å, beta-function is close to 16 m (phase advance per 16 cells is 2π). The second part of the undulator can be used for generation of another x-ray beam with any wavelength between 0.5 Å and 1 Å. The number of colors can be increased for a smaller emittance. Also note that fresh (unspoiled by FEL interaction in SASE1) bunches for operation of SASE3 can be also obtained by using a fast kicker.

It is worth to note that the proposed scheme is very simple and robust. A fast kicker is compact (about 1 m long) and not expensive, one can use the same type as that used in a separation system upstream of SASE undulators. High accuracy of kicks is not required, a per cent level of amplitude stability is tolerable.

DISTRIBUTION OF X-RAY BEAMS

Distribution of x-ray beams with different wavelengths can be based on multilayer movable mirrors [15]. A disadvantage of such a scheme is that an entire macropulse goes to a single user, so that, for instance, for 5-color operation of the undulator, each user station gets macropulses with the repetition rate of 2 Hz instead of possible 10 Hz. In addition, multilayer mirrors must be exchanged when a given user station is supposed to run with a new wavelength. Here we would like to attract an attention to another option of distribution of photon beams. Namely, one can make use of a recently developed x-ray prism (see [16] and references therein), which is made of high-quality diamond and can operate in the range from 2-4 keV to 100 keV. A resolution of $10^3 - 10^4$ is claimed [16] so that, in principle, even very near colors can be separated. A long transport line of the European XFEL should be sufficient for spatial separation of dispersed x-ray beams of different colors - and, of course, an actual geometry would define how near the colors could be. In case of using such kind of prism every user gets a required pulse pattern with the repetition rate of 10 Hz. This option, however, requires further studies.

SCHEME FOR PUMP-PROBE EXPERIMENTS

Using the principle of the betatron switcher, we can also propose a scheme for pump-probe experiments. A long flat-top laser pulse (20-25 ps) in the XFEL injector is formed from many short pulses (about 2 ps). One can program the laser operation such that, for instance, only two of such pulses with variable separation between them are produced. Two low-charge electron bunches are then produced in photoinjector, and compressed with the help of linearized bunch compression system. The distance between bunches is compressed proportionally, so that finally one can vary the separation on the scale of tens (or hundreds) of femtoseconds. In front of an undulator one of these two bunches gets a small angular kick from a transverse deflecting cavity [17], while the other one is not kicked. The kick is compensated statically at some position in the undulator as described above for the scheme, based on fast kicker (so the deflecting cavity in this scheme is just an ultrafast kicker). Two bunches produce then two different colors. In principle, the scheme can be generalized for the case of several bunches as described above.

REFERENCES

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

[2] Ya.S. Derbenev, A.M. Kondratenko and E.L. Saldin, Nucl. Instrum. and Methods **193**(1982)415.

[3] J.B. Murphy and C. Pellegrini, Nucl. Instrum. and Methods A **237**(1985)159.

[4] V. Ayvazyan et al., Phys. Rev. Lett. **88**(2002)104802

[5] V. Ayvazyan et al., Eur. Phys. J. **D37**(2006)297

[6] T. Shintake et al., Nature Photonics **2**(2008)555

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

[8] K. Tiedtke et al., New Journal of Physics **11**(2009)023029

[9] P. Emma, "First lasing of the LCLS X-ray FEL at 1.5 A", presented at the Particle Accelerator Conf., Vancouver, May 2009

[10] 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).

[11] G. Geloni, V. Kocharyan, and E. Saldin, DESY Report DESY 10-006 (2010)

[12] G. Geloni, V. Kocharyan, and E. Saldin, DESY Report DESY 10-010 (2010)

[13] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Opt. Commun. **235**(2004)415

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

[15] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, DESY Report TESLA-FEL 2004-02 (2004)

[16] A.G. Tur'yanskii, Instruments and Experimental Techniques **52**(2009)587

[17] R. Akre et al., Proc. of the 2001 Particle Accelerator Conf. (Chicago), p. 2353