AN OVERVIEW OF THE RADIATION PROPERTIES OF THE EUROPEAN XFEL

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Abstract

We present an overview of the radiation properties of the European XFEL based on recently accepted strategy of operation at the fixed set of electron energies (8.5 GeV, 12 GeV, 14 GeV, and 17.5 GeV), baseline parameters if the electron beam, and new set undulator parameters. We also discuss potential extension of the parameter space which does not require new hardware and can be realized at a very early stage of the European XFEL operation.

INTRODUCTION

Construction of the European XFEL [1] entered final stage: underground tunnels and infrastructure are ready, and first pieces of the equipment has been already installed [2]. Superconducting accelerator will provide energy of electrons up to 17.5 GeV. It operates in the burst mode with 10 Hz repetition rate of 0.6 ms pulse duration. Each pulse brings train of up to 2700 electron bunches (4.5 MHz repetition rate). Three undulators will be installed at the first stage: SASE1, SASE2, and SASE3. SASE3 undulator is placed sequentially after SASE1 undulator in the same electron beamline. All undulators have similar mechanical design. Length of the undulator module is equal to 5 meters. Length of undulator intersection is equal to 1.1 m. undulators SASE1 and SASE2 are identical: period length is 40 mm, number of modules is 35, range of gap variation is 10 to 20 mm. Undulator SASE3 has period of 68 mm, 10 to 25 mm gap tunability range, and consists of 21 module. Most portion of the undulator modules has been manufactured, and magnetic measurements and tuning are going on [3]. Design and construction of user's end station (instruments) is on track as well. Requirements by users are summarized and analyzed in a proper way to provide maximum opportunities for every instrument and experiment [4].

BASELINE PARAMETERS

Baseline parameters of the European XFEL passed two major corrections: in 2006 [1] and 2010 [4–6]. Operating range for bunch charge is from 20 pC to 1 nC, peak current is 5 kA, and normalized rms emittance is between 0.3 mm-mrad and 1 mm-mrad depending on bunch charge [5]. There are two changes in the baseline option since last update in 2010. Tunability range of undulators has been corrected on the base of magnetic measurements [3], and in terms of undulator parameter is 1.65 - 4 and 4 - 9 for SASE1/2 and SASE3, respectively. Tunability range in terms of $\lambda_{max}/\lambda_{min}$ is 3.5 for SASE1/2 and 4.6 for SASE3. Reduction of tunability range caused the change of operating energies providing required flexibility for simultaneous operation of different beamlines and instruments. Now four operating points in the electron energy are fixed: 17.5 GeV, 14 GeV, 12 GeV, and 8.5 GeV [7]. Figures 1 and 2 show an overview of the main photon beam properties of the European XFEL for two values of the baseline parameters for the bunch charge of 0.1 nC and 1 nC. Calculations have been performed with FEL simulation code FAST [8]. Left and right columns in these plots correspond SASE1/2 and SASE3 undulator, and allow visual tracing of the operating wavelength bands, pulse energy, and brilliance as function of the electron energy. General tendencies are that operation with higher charges provides higher pulse energy and higher average brilliance. Qualitative difference in the behavior of the brilliance at 0.1 nC and 1 nC for SASE1/2 requires some clarification. It originates from two reasons. The first reason relates to optimization procedure which corresponds to the choice of optimum focusing beta function providing maximum power gain [9, 10]. Optimization procedure suggests smaller values of focusing beta function for smaller emittances. However, there is always technical limitation on the minimum focusing beta function (15 m in our case). As a result, SASE3 and 0.1 nC option of SASE1 operate with beta function defined by technical limit of 15 m, while optimum beta function for high charge (1 nC) option of SASE1 is above 15 m, and its values depend on operating point in the radiation wavelength and in the electron energy. Another factor defining peculiar behavior of brilliance at high charge and small wavelength relates to degradation of coherence properties of the radiation due to large value of the emittance [10]. This effect is responsible for the reduction of the brilliance for 1 nC case at short wavelengths.

Detailed parameters of the radiation together with 3D field maps are being compiled in the photon data base of the European XFEL [11, 12]. Currently this data base is used in the test mode for optimization of the photon beam transport and imaging experiment [13,14]. When user interface will be finally settled, photon data base will be open for free external access, and can be used by users for planning experiments.

Operation of SASE3

Properties of the radiation from SASE3 presented in Figs. 1 and 2 assume that electron beam is not disturbed by FEL interaction in the SASE1 undulator. Decoupling of SASE3 and SASE1 operation can be performed with an application of betatron switcher [6, 15] (see Fig. 3). Feedback kickers can be used to test and operate this option at the initial stage. In case of positive results dedicated kickers need to be installed [5].

Operation of SASE3 as an afterburner of SASE1 is also possible, but with reduced range of accessible wavelengths, and reduced power (see Fig. 4). General problem is that

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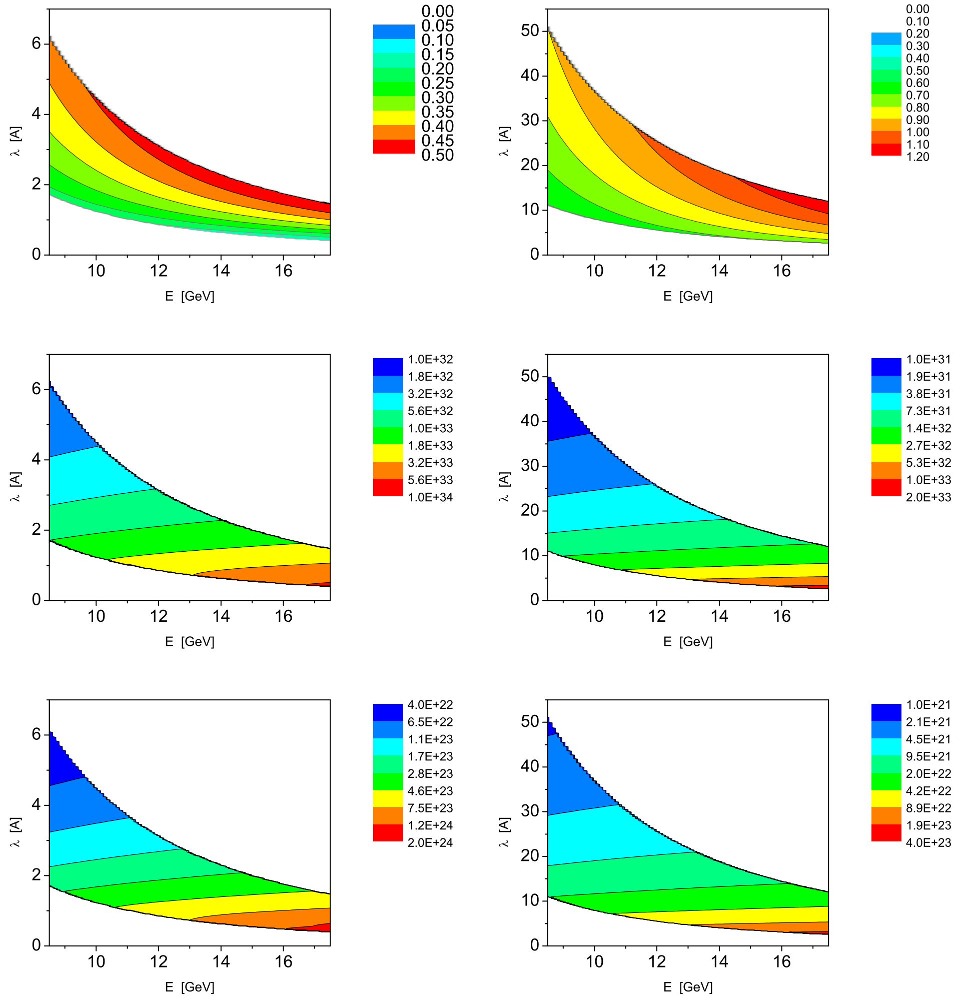

Figure 1: An overview of main photon beam properties of the European XFEL for SASE1/2 (left column) and SASE3 (right column). Contour plots present pulse energy (top row), peak brilliance (middle row), and average brilliance (lower row). Units for the pulse energy and brilliance are mJ and photons/sec/mm^2/rad^2/0.1% bandwidth, respectively. Bunch charge is equal to 0.1 nC. Calculations have been performed with FEL simulation code FAST [8].

tuning of SASE1 to higher pulse energies leads to higher induced energy spread in the electron beam, and to degradation of the SASE3 performance. For instance, operation of SASE3 at the energy of 17.5 GeV is impossible at any wavelength if wavelength of SASE1 is longer than 0.1 nm, and radiation power of SASE1 is tuned by a factor of 1.5 above saturation power.

POTENTIAL EXTENSIONS BEYOND BASELINE OPTION

There are several potential extensions beyond baseline option which can be realized at a very early stage of the European XFEL operation without additional hardware, or by means of extensions of the functions of the present hardware. Some ideas are pretty old, and some other appeared just recently. Some proposal rely on parameters of the electron beam beyond baseline option. Several groups perform theoretical and simulation studies of different options. There is also experimental activity at FLASH and LCLS on verification of advanced concepts. Here we briefly highlight several extensions related to the European XFEL with references to the most fresh publications.

Efficiency Increase by Undulator Tapering

Undulator tapering will allow to increase significantly FEL power. Many studies on this subject have been performed for the parameters of the European XFEL (see [1, 6, 16, 17] and references therein). Benefit in the photon flux can be pretty high. For instance, it can be up to one order of magnitude for SASE3 operating in the wavelength range above 1 nm. However, coherence properties of the radiation degrade with respect to SASE FEL operating in the saturation with untapered undulator. Increase of the brilliance is visibly less than increase of the radiation power [17]. Users relying just on photon flux will have

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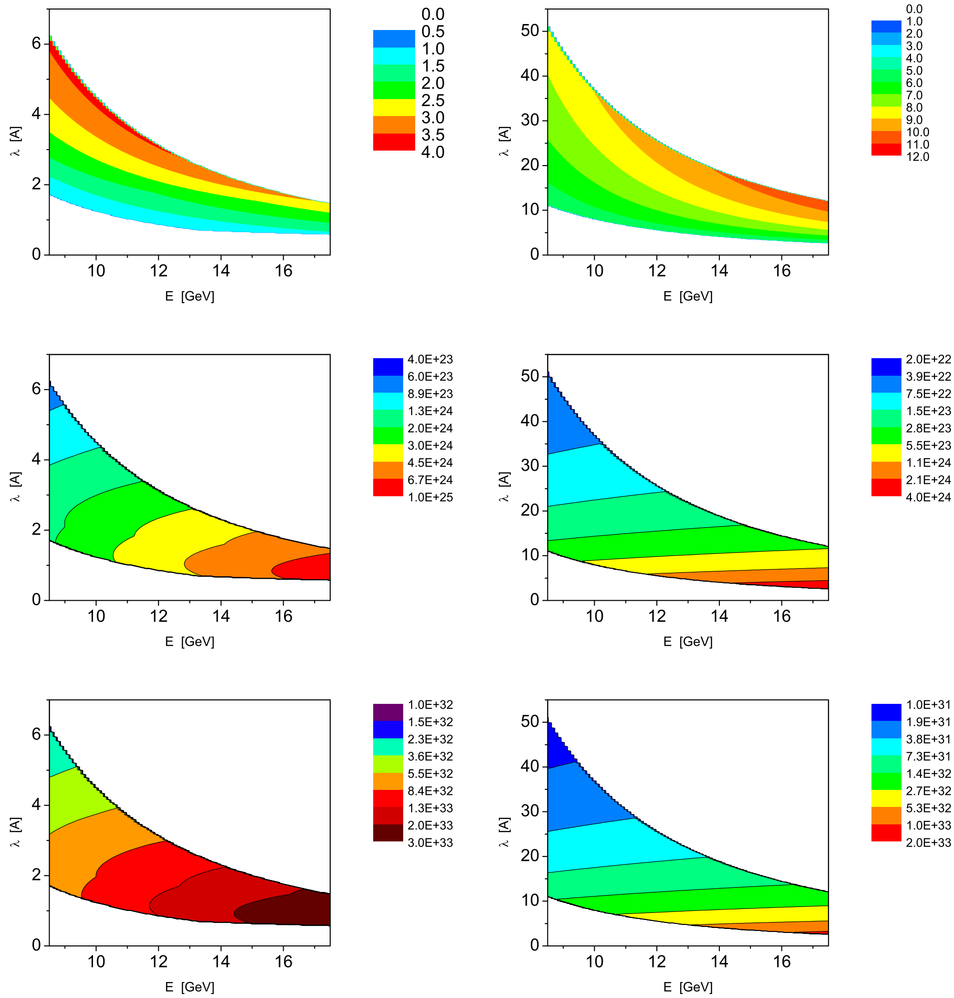

Figure 2: An overview of photon beam properties of the European XFEL for SASE1/2 (left column) and SASE3 (right column). Contour plots present pulse energy (top row), peak brilliance (middle row), and average brilliance (lower row). Units for the pulse energy and brilliance are mJ and photons/sec/mm^2/rad^2/0.1% bandwidth, respectively. Bunch charge is equal to 1 nC. Calculations have been performed with FEL simulation code FAST [8].

profit from the undulator tapering. Note that undulator tapering is routine procedure at LCLS [18].

Extended Range of Electron Beam Parameters

Several options are under consideration exploiting higher peak currents, and higher bunch charges to increase pulse energy and peak power (see [6, 19] and references therein). Dedicated activity on simulation, production and characterization of high charge bunches in XFEL-type electron gun is ongoing at PITZ [20, 21]. Another direction of studies is production of ultrashort pulses. This activity also involves both, simulation studies for XFEL and experimental studies at FLASH (see [22–24] and references therein). For instance, use of higher charges in combination with tapering will allow to generate sub-Joule energies in the radiation pulse [6]. Note that there can be some technical complications for operation with charges which are not in the gate of baseline parameters [5]. It is our experience of FLASH operation with small charges that limitations of the electron beam diagnostic are not a stopovers, but they significantly complicate tuning, since some feedback system stop to work because of noisy measurements.

Multicolor Mode of Operation

Betatron switcher [15] mentioned in the previous section can be used in long undulators for providing multi-color operation. Different parts of the undulator are tuned to different resonance wavelength. Fast kicker and steerer force lasing of selected bunch in specific part of the undulator similar to that described in the caption to Fig. 3.

Harmonic Generation

Contrary to nonlinear harmonic generation, harmonic lasing in a high-gain FEL can provide much more intense, stable,and narrow-band FEL beam which is easier to handle if the fundamental is suppressed [25]. At the European XFEL

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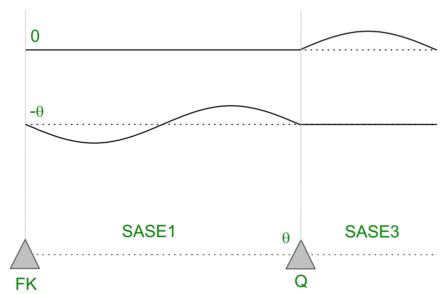

Figure 3: A schematic illustration of the betatron switcher for decoupling of operation of SASE1 and SASE3 [6, 15]. Here "FK" stands for a fast kicker (giving different kicks to selected bunches) and "Q" for a quadrupole or a static steer (giving the same static kick to all bunches). Lasing to saturation takes place only on straight sections of beam orbit. Bunches not disturbed by fast kicker lase only in SASE1 (top curve), while those deflected by fast kicker lase in SASE3 only (bottom curve).

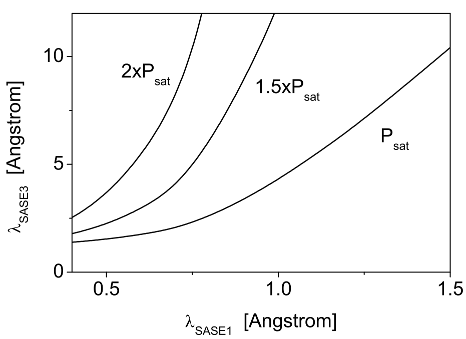

Figure 4: Minimum wavelength of SASE3 versus operating wavelength of SASE1. Electron energy is 17.5 GeV, bunch charge is 1 nC. Minimum wavelength is defined by the condition of saturation at the length of SASE3 undulator of 100 meters. $P_{\rm sat}$, $1.5 \times P_{\rm sat}$, and $2 \times P_{\rm sat}$ denote power of SASE1 in terms of saturation power. Operation of SASE3 in saturation is possible for the wavelengths above the curves. Calculations have been performed with FEL simulation code FAST [8].

the harmonic lasing would allow to extend operating range ultimately up to 100 keV. Currently this option is studied for implementation in the MID instrument [26]. Dedicated experimental program on harmonic generation is ongoing at LCLS [27].

"Pink" Photon Beam

Some user application require "pink" photon beam with spectrum width of several per cent. Two options of spectrum increase has been considered so far: formation of the energy chirp in the bunch train [5], and formation of the energy chirp within electron bunch [28].

Harmonic Lasing Self-Seeded FEL

A concept of a harmonic lasing self-seeded FEL (HLSS) has been proposed recently [25]. A gap-tunable undulator is divided into two parts by setting two different undulator parameters such that the first part is tuned to a sub-harmonic of the second part. Harmonic lasing occurs in the exponential gain regime in the first part of the undulator, also the fundamental stays well below saturation. In the second part of the undulator the fundamental mode is resonant to the wavelength, previously amplified as the harmonic. The amplification process proceeds in the fundamental mode up to saturation. In this case the bandwidth is defined by the harmonic lasing (i.e. it is reduced by a significant factor depending on harmonic number) but the saturation power is still as high as in the reference case of lasing at the fundamental in the whole undulator, i.e. the spectral brightness increases. Application of the undulator tapering in the deep nonlinear regime would allow to generate higher peak powers approaching TW level [29]. Modification of the HLSS scheme, named purified SASE - pSASE [30], is under consideration as well [31].

Afterburners and Polarization Control

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 linearly polarized background from the main undulator. An elegant technique for such a suppression has been proposed recently: an application of the reverse taper in the main undulator [32]. In this case the density modulation (bunching) 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. Technique for the suppression of the output power with negative tapering has been successfully demonstrated recently at LCLS [33].

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. Considering SASE3 undulator of the European XFEL as a practical example, it has been demonstrated 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 [32]. This option has been granted high priority as the first upgrade of the European XFEL [5].

Self-Seeding Option

Self-seeding option [34] has also high priority as the first upgrade of the European XFEL (see [5, 35–37] and references therein). Both, hard and soft x-ray options are un-

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der consideration with optimization on dedicated beamline for bio-imaging [38]. As soon as fine measurements of the electron beam and FEL parameters will be performed, an upgrade for self-seeding option will be launched [5].

Longitudinal Space Charge Amplifier

Longitudinal space charge instability can be used in the schemes for generation of vacuum ultraviolet (VUV) and X-ray radiation [39]. A typical longitudinal space charge amplifier (LSCA) consists of few amplification cascades (drift space plus chicane) with a short undulator behind the last cascade. If the amplifier starts up from the shot noise, the amplified density modulation has a wide band, on the order of unity. The bandwidth of the radiation within the central cone is given by inverse number of undulator periods. A wavelength compression could be an attractive option for LSCA since the process is broadband, and a high compression stability is not required. LSCA can be used as a cheap addition to the existing or planned short-wavelength FELs. In particular, it can produce the second color for a pump-probe experiment. It is also possible to generate attosecond pulses in the VUV and X-ray regimes [40]. Some user experiments can profit from a relatively large bandwidth of the radiation, and this is easy to obtain in LSCA scheme. Recently LSCA scheme has been successfully demonstrated at SLAC [41].

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