EXPECTED PROPERTIES OF THE RADIATION FROM A SOFT X-RAY SASE FEL AT THE EUROPEAN XFEL*

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Abstract

This report deals with an update of parameters of a soft x-ray SASE FEL (SASE3) at the European XFEL. Two scenario of SASE3 operation are considered: nominal mode of operation (fixed energy of the driving electron beam 17.5 GeV, and operating wavelength range 04 - 1.6 nm), and long wavelength mode of operation (fixed energy of 8.75 GeV, and operating wavelength range 1.6 - 6.4 nm). Perspectives for production of high power circularly polarized radiation are discussed. It is shown that installation of 30 m helical undulator will allow to achieve ultimate degree of transverse coherence at an ultimate level of output radiation power.

INTRODUCTION

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. 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 based on a fixed-gap undulator 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. Beamline SASE2 utilizes planar, variable gap undulators with an identical mechanical design. SASE3 undulator will be installed after SASE1 undulator and will operate in a "parasitic" mode using spent electron beam passed through SASE1 undulator.

Technical design of the European XFEL passed several iterations [1–4], and this iterative process is not finished yet. One of the latest changes refer to the soft x-ray radiator SASE3. Originally SASE3 assumed to be a helical device with an installation on a later stage of the project. One of the reasons for postponing its installation was that the construction of a helical FEL undulator is a challenge which requires further R&D. However, growing XFEL user community started to push forward an idea of an earlier start of SASE3 operation, already during the commissioning phase of the project (2013-2014). To find compromise it has been decided to put SASE3 in operation in two stages. The first stage will be a planar device delivering linearly polarized FEL radiation, and the second stage will be available to deliver circularly polarized radiation.

This paper briefly highlights baseline properties of a planar version of SASE3, and its potential upgrade with a helical undulator. Calculations have been performed with time-dependent FEL simulation code FAST [5]. It is shown that additional installation of 30 m long helical structure will allow to produce radiation with a high degree of circular polarization (> 99%), and ultimate level of the radiation power.

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BASELINE OPTION OF SASE3 WITH PLANAR UNDULATOR

Free electron laser SASE3 is driven by the electron beam passed through SASE1 undulator. Project parameters of the electron beam at the entrance of the undulator beamlines are: energy $E_0 = 17.5$ GeV, peak current 5 kA, rms bunch length 25 μm, rms normalized emittance of 1.4 mm-mrad, and rms slice energy spread of 1 MeV [4]. Undulator SASE3 is a planar device with 65 mm period. Change of the wavelength from 0.4 nm to 1.6 nm is provided by the change of the undulator gap from 20 mm to 10 mm.

Electrons always emit synchrotron radiation, and this results in energy loss of 32 MeV and increase of energy spread due to quantum diffusion from 1 MeV to 2.9 MeV

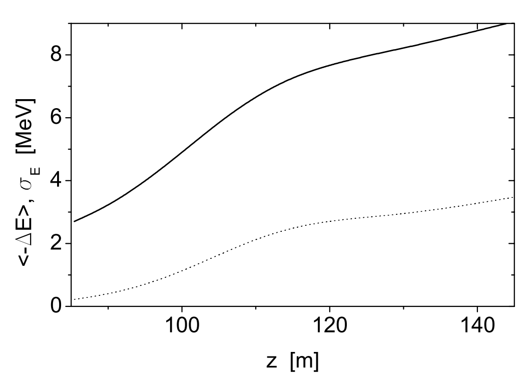

Figure 1: Evolution of the average energy loss (dotted curve) and rms energy spread (solid curve) along the undulator SASE1 (linear energy loss of 0.2 MeV/m due to incoherent radiation is subtracted).

Table 1: Properties of the radiation from SASE3 with planar undulator

Electron energy, GeV	17.5	17.5	8.75	8.75
Status of SASE1 (on/off)	on	on	off	off
Wavelength, nm	0.4	1.6	3.2	6.4
Pulse energy, mJ	6	14 (27)	9.5 (24)	12 (35)
Peak power, GW	60	140 (270)	95 (240)	140 (250)
Average power, W	180	420 (810)	285 (720)	360 (750)
pulse duration (FWHM), fs	100	100	100	100
Angular divergence (FWHM), μrad	3.4	11.4 (6.6)	16. (9.4)	30. (16.)
Photon Beam size (FWHM), μm	58	68 (80)	90 (136)	96 (168)
Spectrum bandwidth (FWHM), %	0.2	0.32	0.29	0.37
ρ	1×10^{-3}	1.6×10^{-3}	1.46×10^{-3}	1.84×10^{-3}
Saturation length, m	110	64	47	37
# photons/pulse	0.120×10^{14}	0.112×10^{15}	0.153×10^{15}	0.386×10^{15}
Peak flux [phot/s]:	0.120×10^{27}	0.112×10^{28}	0.153×10^{28}	0.386×10^{28}
Average flux [phot/s]:	0.362×10^{18}	0.338×10^{19}	0.459×10^{19}	0.115×10^{20}
Peak brilliance	0.145×10^{34}	0.536×10^{33}	0.204×10^{33}	0.102×10^{33}
Average brilliance	0.437×10^{25}	0.160×10^{25}	0.612×10^{24}	0.307×10^{24}

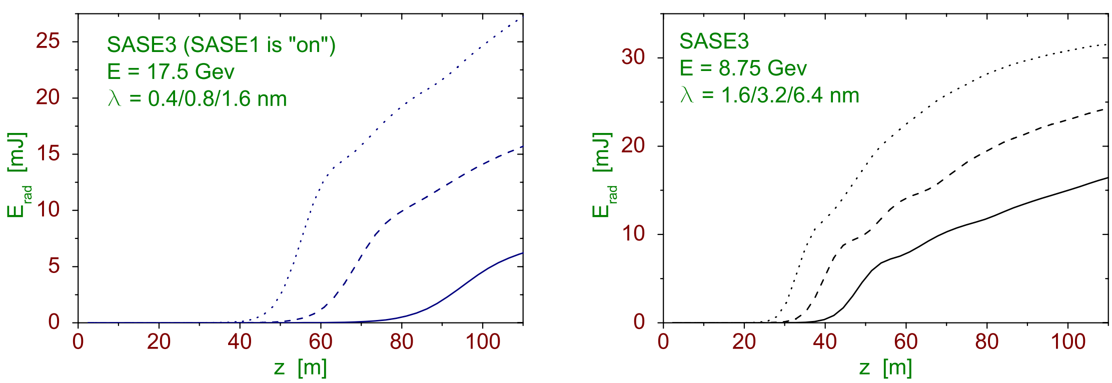

Figure 2: SASE3: evolution of the energy in the radiation pulse versus undulator length. Left plot: energy 17.5 GeV (wavelengths 0.4, 0.8, and 1.6 nm). Right plot: energy 8.75 GeV (wavelengths 1.6, 3.2, and 6.4 nm).

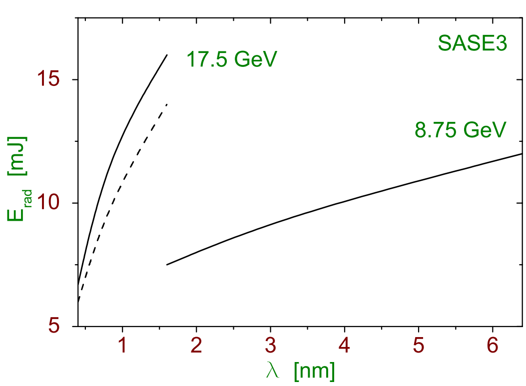

Figure 3: SASE3: Energy in the radiation pulse in the saturation versus radiation wavelength. Solid and dashed lines refer to the case SASE1 off and on, respectively.

when electron beam passes 165 m long undulator SASE1. In the presence of FEL process electron beam gains significant energy spread as it is illustrated with Fig. 1. In the saturation regime energy spread is equal to 8 MeV (about ρE_0), and distribution of the particle in energy is well fits to the gaussian. Figure 2 shows evolution of the energy in the radiation pulse along undulator length. We see that there is sufficient safety margin for long wavelengths, and undulator length of about 130 m is required to provide safety margin of 20% for the shortest wavelength of 0.4 nm. Table 1 presents detailed set of the main parameters of the radiation for operation in the saturation regime. Numbers in brackets correspond to the full undulator length of 110 m.

Operation of the facility at the electron energy of 8.75 GeV allows to cover with SASE3 wavelength range from 1.6 nm to 6.4 nm with pulse energy (and peak radiation power) which is by two orders of magnitude higher than that of FLASH facility [6] (see Table 1 and Fig. 2).

It should be noticed that due to high value of the undulator field and high energy of electrons we have rather big value of SR losses in SASE3. For instance, for operation of SASE3 at 17.5 GeV and tuning to the wavelength of 1.6 nm peak power of SR will be about 650 GW, and average SR power will reach 2 kW level. Energy loss by an electron are about 65 MeV which would require undulator tapering to keep FEL resonance condition along the undulator.

POTENTIAL UPGRADE OF SASE3 WITH A HELICAL UNDULATOR

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. Currently two options are under study: i) a concept of a cross-planar afterburner, and ii) a concept of a helical afterburner. A concept of a cross-planar afterburner has been described elsewhere [7, 8]. Main SASE undulator is a planar and operates in the saturation regime. Undulators of the afterburner are short pieces of planar magnetic structure. ”Short” means that i) they operate as radiators only not disturbing density modulation gained in the main SASE undulator; ii) slippage of the radiation is much less than coherence length. Thus, radiated wavepackets are identical, but have crossed polarization. Application of phase shifter allows to prepare helical polarization. This scheme holds potential of providing relatively high degree of circular polarization with small shot-to-shot fluctuations, but at relatively small output power, an order of magnitude below the saturation. While technical realization of the afterburner itself is rather simple, significant problem arises by the demand for a high degree of circular polarization of the output radiation. One should separate powerful (saturated) radiation from the main undulator which has linear polarization, and relatively weak (by an order of magnitude) circularly polarized beam from the cross-planar undulator. Solution of this problem is provided by displacement of the axes of the main undulator and the afterburner. Note that demand of conservation of the beam bunching significantly complicates design of the matching section [9].

Assuming, however, that at some day ”D” technology of helical undulators will be available, we consider here the case of a helical radiator which naturally produces circularly polarized radiation. Parameters of the helical undulator are described in the XFEL TDR [4]. It is APPLE type device with period length of 80 mm. Wavelength tunability is provided by the change of the gap from 10 mm to 23 mm. Maximum saturation length of a helical SASE3 FEL is achieved at a minimum wavelength of 0.4 nm, and is about 90 meters (see Fig:4). Tunnel length of the SASE3 undulator is 301 m, and about 250 m of it can be used for the undulator installation. Straightforward solution would be to place full length helical undulator in line after a planar one. It looks like that it can be possible with an appropriate optimization of the tunnel infrastructure. This would be an ideal solution of the problem: photon beams with planar and helical polarization at full power would be available. Switching of the SASE process between undulators (providing switching of the polarization from linear to circular) can be done rather quickly with SASE switchers [10].

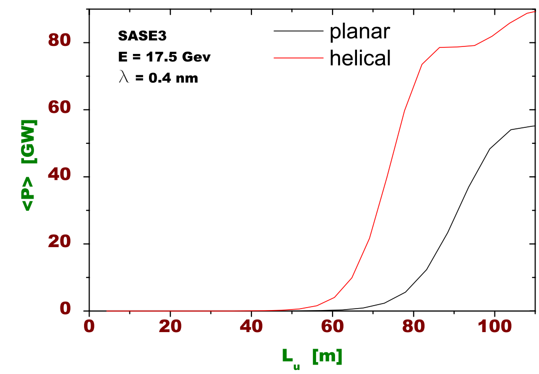

Figure 4: Radiation power versus undulator length for planar and helical options of SASE3. Wavelength of the radiation is equal to 0.4 nm.

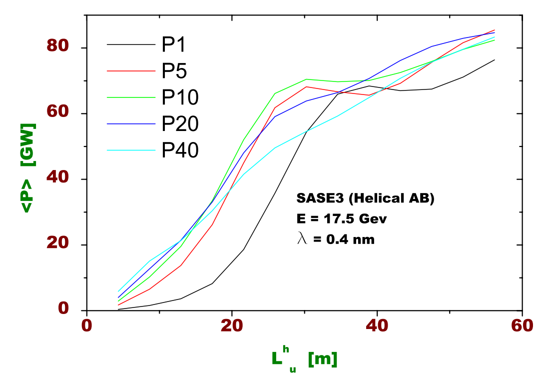

Figure 5: Radiation power versus undulator length in the helical afterburner. Different curves correspond to different levels of the radiation power at the exit of the planar undulator, from 1% to 40% in terms of the saturated power.

Less straightforward, but more elegant solution of the problem of a helical radiator is installation of a helical afterburner after a planar undulator. Electron beam gains density modulation in the planar undulator. This density modulation (scalar quantity) serves as a seed for the FEL process in the helical undulator producing radiation with helical polarization. Let us consider operation of this setup in more details. We tune the FEL process in the planar undulator such that controllable level of the output power is achieved at the end of the undulator. Then electron beam enters helical afterburner, and both, beam density modulation and resonant fraction of the radiation initiate amplification process. Evolution of the radiation power along the helical afterburner is traced in Fig. 5 for different levels of the radiation power at the exit of the planar undulator. Another insight into the problem is behavior of the output power at fixed length of the helical section. Relevant dependencies are presented in Fig. 6. We note that for each

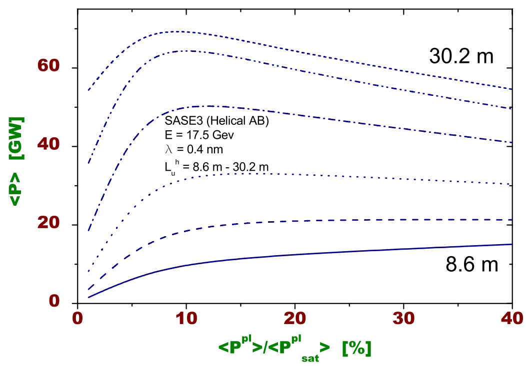

Figure 6: Radiation power from a helical afterburner versus power of a planar stage for different lengths of a helical afterburner, from 8.6 m to 30.2 m.

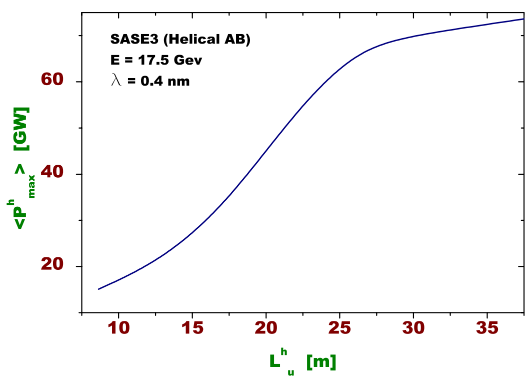

Figure 7: Optimized output power from helical afterburner as function of the undulator length

length of the helical section there is certain level of input seed from a planar part such that output radiation power reaches maximum level. Thus, we can define maximum value of the radiation power as a function of the length of the helical afterburner (see Fig. 7). General feature is that higher output power is produced in a longer undulator, but at smaller SASE level in the planar section. This means that increase of the length of the helical undulator increases not only the radiation power, but also the degree of circular polarization. Thirty meters of the helical afterburner would be sufficient to produce ultimate level of the radiation power with high degree of circular polarization, of about 99%. Note that purity of the output radiation from a helical afterburner can be also improved by means of using collimation system in the photon beamline. Indeed optimum operation of the proposed setup is achieved when the first, planar part of the FEL amplifier operates in the linear regime, and FEL process enters in the saturation regime in the helical afterburner. It is well known that angular divergence of the radiation from an FEL amplifier is shrinked when FEL process enters saturation [11], and angular collimation will suppress the radiation power from the planar undulator.

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