PROPERTIES OF THE RADIATION FROM THE EUROPEAN X-RAY FREE ELECTRON LASER

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Abstract

Success of the Linac Coherent Light Source (LCLS) demonstrated feasibility for reliable production, compression, and acceleration of electron beams with emittances significantly smaller than original baseline parameters [1]. Experimental results from the Photo Injector Test Facility in Zeuthen (PITZ) and FLASH demonstrated the possibility to generate electron beams with small charge and emittance [2, 3]. Computer modelling of the beam formation system also indicate on the possibility to preserve electron beam quality during acceleration and compression [4]. Recently these trends have been analyzed, and baseline parameters of the European XFEL have been revised. As a result, different modes of FEL operation become possible with essentially different properties of the radiation.

HARD X-RAY FELS

Technical Design Report of the European XFEL (2006) assumed operation with the bunch charge of 1 nC and the value of the normalized emittance 1.4 mm-mrad [5]. It has been planned to operate XFEL at fixed energy of 17.5 GeV and cover wavelength range from 0.1 nm to 1.6 nm in three undulators. Recent revision of the European XFEL parameters includes extension of the range for bunch charges, change of the period of all SASE undulators (4 cm for SASE1 (SASE2) and 6.8 cm for SASE3), and extension of operating wavelength range from 0.05 nm to 5 nm by means of operation at three electron energies 17.5 GeV, 14 GeV, and 10.5 GeV [6–8]. Safety margin for emittance has been reduced, and baseline values are between 0.32 mm-mrad and 0.97 mm-mrad when bunch charge changes from 20 pC to 1 nC.

Comprehensive analysis of new parameter space of FELs has been performed in [9]. It has been shown that revised parameters of the electron beam provide more possibilities for effective operation of SASE FELs. Table 1 presents comparison of parameters of hard x-ray FELs before and after revision. Averaged characteristics are calculated for the same pulse pattern in both cases. We see that transition from TDR 2006 baseline parameters to new baseline parameters of 2010 results in visible improvement of all characteristics of the radiation. The matter of importance here is degree of transverse coherence which reaches ultimate values with new baseline parameters. Variation of the bunch charge will allow to control radiation pulse duration in wide limits.

SOFT X-RAY FEL

Concept of the European XFEL assumes to use SASE3 as an afterburner of SASE1 [5]. FEL amplification process is accompanied by the energy loss of electrons and growth of the energy spread in the electron beam. This may prevent effective operation of SASE3 FEL when relative value of FEL induced energy spread in SASE1 exceeds FEL amplification bandwidth of SASE3. We consider different cases when SASE1 can operate not only in the saturation regime, but also in the deep nonlinear regime when radiation power exceeds saturation level significantly. Simulations are performed with FEL simulation code FAST [14] in two steps. First, we calculate amplification process in SASE1 FEL and calculate characteristics of the electron beam at the exit of SASE1 undulator. At the second step these characteristics are used as initial conditions for simulation of amplification process in SASE3 undulator. From these simulations we derive minimum wavelength at which SASE3 is saturated as function of operating wavelength and the level of output power in SASE1 FEL. Results of simulations for specific case of electron energy 17.5 GeV and bunch charge 1 nC are presented in Fig. 1. An area above curves is parameter space available for simultaneous operation of SASE1 and SASE3. Operation of SASE1 at the saturation level leaves relatively large area available for simultaneous operation of SASE1 and SASE3. Increase of the pulse energy in SASE1 essentially limits possibilities for simul-

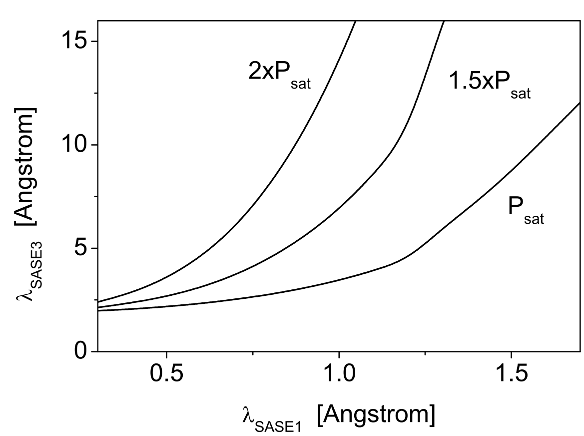

Figure 1: Minimum wavelength of SASE3 versus operating wavelength of SASE1. Electron energy is 17.5 GeV, bunch charge is 1 nC. Minimum wavelength is defined by the condition of saturation at the length of SASE3 undulator of 100 meters. $P_{\rm sat}$, $1.5 \times P_{\rm sat}$, and $2 \times P_{\rm sat}$ denote power of SASE1 in terms of saturation power.

Table 1: Comparative table of the properties of the radiation from SASE1 as of TDR 2006 and December 2010 revision (electron energy 17.5 GeV, wavelength 0.1 nm)

	Units	SASE1 2006	SASE1 (2010)		
Bunch charge	nC	1	1	0.25	0.02
Pulse energy	mJ	1.3	1.80	.697	.635E-01
Peak power	GW	11.7	16.8	30.0	37.8
Average power	W	35.2	48.7	18.8	1.71
FWHM spot size	μm	53.8	42.7	34.2	27.3
FWHM angular divergence	μrad	1.22	1.35	1.60	2.00
Coherence time	fs	0.29	.201	.164	.135
FWHM spectrum width, $\Delta\omega/\omega$	%	.081	.117	.144	.175
Degree of transverse coherence	#	.62	.820	.950	.960
FWHM pulse duration	fs	110	107.	23.2	1.68
Degeneracy parameter	#	.106E+10	.139E+10	.235E+10	.246E+10
Number oh photons per pulse	#	.656E+12	.907E+12	.351E+12	.319E+11
Average flux of photons	ph/sec	.177E+17	.245E+17	.947E+16	.862E+15
Peak brilliance	#	.179E+34	.237E+34	.399E+34	.417E+34
Average brilliance	#	.540E+25	.685E+25	.250E+25	.189E+24
Saturation length	m	131.	100.	70.6	57.6

*Units of photons/sec/mm^2/rad^2/0.1% bandwidth.

taneous operation. Extended simulations for the whole parameter range (electron energies and bunch charges) shows that there is always a possibility to use SASE3 as an afterburner in some range of wavelengths [9]. Degradation of the beam quality in the SASE1 undulator leads also to the reduction of the radiation power in the SASE3 undulator. However, it remains sufficiently high. Application of a fast kicker for killing amplification process in SASE1 provides radical solution for decoupling of operation of SASE1 and SASE3 [10].

OPTION OF HIGH CHARGE OPERATION

In order to explore the high charge option let us perform a brief analysis for the case of the European XFEL keeping the baseline value of the peak beam current of 5 kA fixed and scaling the emittance linearly and as a square root of charge. Operation of SASE FELs in a short (around 0.1 nm) wavelength range is well described as an optimized XFEL [11, 12]. In this parameter range the peak power in the saturation regime scales inversely proportional to the emittance. As a result, the radiation pulse energy grows proportionally to $q^{1/2}$. For instance, for SASE1 operating at 0.1 nm wavelength, we expect an increase of the radiation pulse energy by approximately factor of 2 for the 1 nC case with respect to the 0.25 nC case.

The situation changes qualitatively for the case of SASE3 operating at longer wavelengths. Let us consider the case of SASE3 operating at the energy of 17.5 GeV and radiation wavelength 1.6 nm. The undulator period is equal to 6.8 cm, and the undulator length is equal to 100 m. We fix the peak current to 5 kA, change the bunch charge in the range 0.25 nC - 3 nC and assume emittance scaling as $q^{1/2}$ and q as suggested by the measurements. The reference point is a charge of 1 nC and a normalized emittance of 1 mm mrad. The value of the external beta function is equal to 15 m. This range of FEL parameters corresponds to the diffraction limited (thin) electron beam when saturation length and FEL efficiency at saturation slowly evolve with the value of the emittance, in fact - logarithmically [13]. As a result, we can expect linear growth of the radiation pulse energy with charge. The results of simulations with the code FAST [14] confirm this simple physical consideration (see Fig. 2). Increase of the bunch charge from 0.25 nC to 3 nC results in an increase of the radiation pulse energy nearly by an order of magnitude. An essential feature of the SASE3 undulator is its extended length for operation as an afterburner of the electron beam used in the SASE1 undulator. This extra undulator length can be effectively used for the undulator tapering and increases the FEL efficiency when operating with "fresh" electron bunches not disturbed in SASE1. We see from the lower plot in Fig. 2 that pulse energies above 0.2 J can be achieved for $\epsilon_n \propto q^{1/2}$. In any case, even for the unfavorable case of $\epsilon_n \propto q$, we still can expect significant benefit for SASE3 operation with pulse energies about a factor of 2 above the baseline values for a bunch charge of 1 nC.

Recently PITZ performed experiment on production of high charge electron bunches [15] which demonstrated good properties of the electron beam in terms of emittance. Within the accuracy of measurements performed at the bunch charge of 2 nC we observe that the scaling of the emittance produced by an optimized XFEL gun lies somewhere in-between of linear and square root dependence on charge. A value of 1.4 mm mrad for the normalized emittance at the charge of 2 nC has been used in the simulations. This implies a certain safety margin to the measured values.

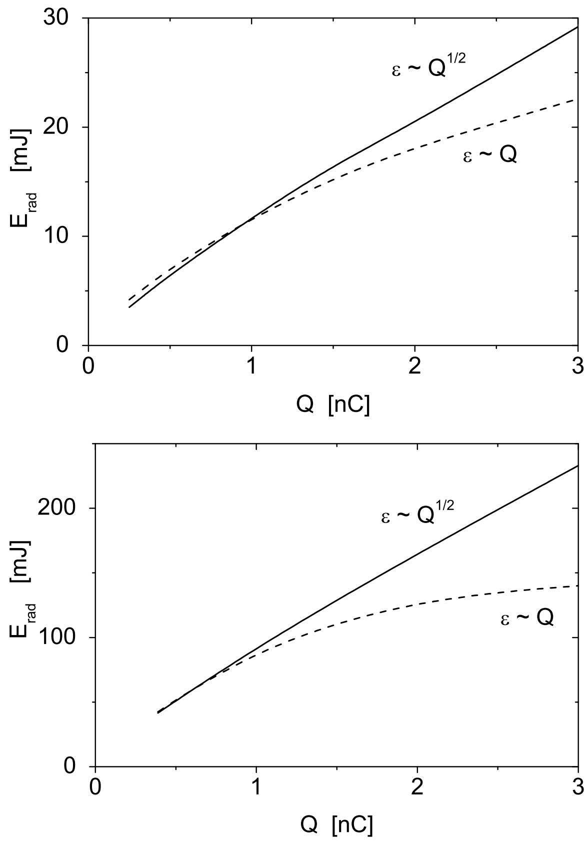

Figure 2: Energy in the radiation pulse versus bunch charge for SASE3 at the European XFEL. Left plot: FEL operates in the saturation regime. Right plot: operation with tapered parameters for the undulator length of 100 meters. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm. Solid and dashed lines correspond to the emittance scaling as $q^{1/2}$, and q, respectively.

SASE FEL simulations based on these assumptions for the electron beam demonstrate the possibility to generate very high pulse energies of 0.1 ... 0.2 J and peak powers above 1 TW in the SASE3 undulator (see Fig. 3).

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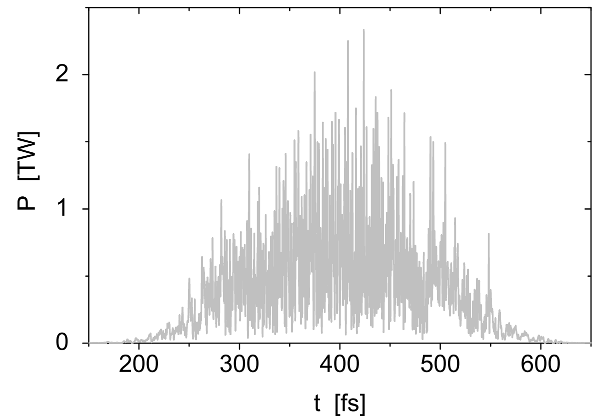

Figure 3: Temporal structure of the radiation pulse from SASE3 with tapered undulator at the undulator length 100 m. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm, bunch charge is 2 nC, normalized rms emittance is 1.4 mm-mrad, peak beam current is 5 kA.

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