EXPECTED PROPERTIES OF THE RADIATION FROM THE EUROPEAN XFEL OPERATING AT THE ENERGY OF 14 GEV

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Abstract

This report deals with the analysis of the parameter space of the European XFEL. An impact of two potential changes is analyzed: consequences of the operation with low-emittance beams, and decrease of the driving energy of the accelerator from 17.5 to 14 GeV.

INTRODUCTION

Baseline parameters of the European XFEL assumed to start operation at fixed charge of 1 nC, peak current 5 kA, normalized rms emittance 1.4 mm-mrad, and energy spread at the undulator entrance of 1 MeV [1]. Recent LCLS experience demonstrated feasibility for production of multi-GeV electron beams with small charge, low emittance and high peak current [2]. SLAC electron accelerator operated in a wide range of electron beam parameters with bunch charge from 20 pC to 250 pC and peak current from 1 to 5 kA. Wide range of FEL modes of operation have been provided for user experiments with different properties of the photon pulse (duration, pulse energy, divergence, spectrum width). Another motivation for revision of the parameter space of the European XFEL are recent results from the test stand of the electron gun obtained at PITZ (DESY, Zeuthen). It has been experimentally demonstrated that prototype of the EXFEL photoinjector is capable to produce electron bunches with significantly smaller emittance and wider range of bunch charges [3, 4]. Starting point for our analysis is a new set of baseline parameters of the electron beam at the European XFEL presented in Table 1 [5]. The question of practical interest is an impact of a change of the electron beam parameters on the operation of the European XFEL. Two scenarios for the electron beam energy are considered: 17.5 Gev and 14 GeV. Undulator parameters are the same as in XFEL TDR [1]: period length of 3.65 cm, 4.8 cm, and 6.8 cm for SASE1, SASE2, and SASE3, respectively. Minimum undulator gap is 10 mm.

Table 1: Properties of the Electron Beam at the Undulator Entrance (New Baseline Parameters, April 2010 [5])

Bunch charge	nC	0.1	0.25	0.5	1
Peak current	kA	2.5	3	4	5
Emittance norm.	mm-mrad	0.42	0.6	0.77	1.05
Energy spread rms	MeV	3	2.6	2.3	2
Pulse duration rms	fs	12	25	40	60

In the following we present the results of impact of the electron beam parameters change on the main characteristics of the radiation: wavelength range (tunability), pulse duration, peak and average radiation power, photon flux, peak and average brilliance, spectrum width, coherence time, degree of transverse coherence. FEL process is simulated with time-dependent FEL simulation code FAST [6].

DEFINITION OF SATURATION POINT

It is well known that the radiation power from SASE FEL grows continuously along the undulator so that there is no position where it achieves the maximum (what is usually understood as saturation point). Therefore, in many cases one uses a qualitative (and subjective) definition of the saturation point. As a consequence, saturation power may be uncertain within a factor of two. In fact, this uncertainty clearly seen when comparing design parameters for the radiation presented by different groups and individuals. Also, it has been assumed frequently that the radiation from a SASE FEL has nearly complete transverse

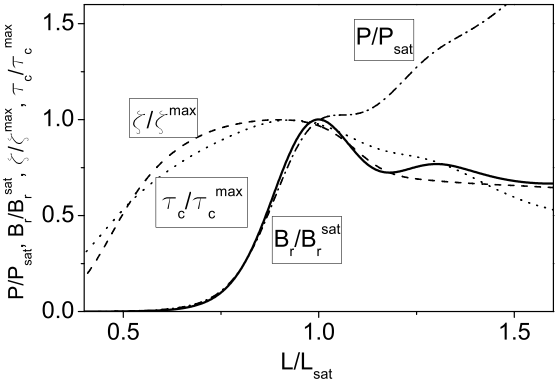

Figure 1: Evolution of main characteristics of SASE FEL along the undulator: brilliance (solid line), radiation power (dash-dotted line), degree of transverse coherence (dashed line), and coherence time (dotted line). Brilliance and radiation power are normalized to saturation values. Coherence time and degree of transverse coherence are normalized to the maximum values. Undulator length is normalized to saturation length. The plot has been derived from the parameter set corresponding to $\hat{\epsilon} = 1$. Calculations have been performed with the simulation code FAST [6].

Table 2: Comparative Table of the Properties of the Radiation from SASE1 Operating in the Saturation Regime

	Units	2006 / 17.5 GeV	2010 / 17.5 GeV	2010 / 14 GeV
Electron energy	GeV	17.5	17.5	14
Bunch charge	nC	1	1	1
Peak beam current	A	5000	5000	5000
Normalized rms emittance	mm-mrad	1.4	1.05	1.05
rms energy spread	MeV	1	2	2
Wavelength	nm	0.1	0.1	0.1
Energy per pulse	mJ	1.3	1.7	1.2
Peak power	GW	11.7	15.6	11
Average power	W	39	52	37
Coherence time	fs	0.28	0.22	0.24
Degree of transverse coherence		0.62	0.78	0.66
Number of photons per pulse	10^{12}	0.6	0.8	0.6
Average flux of photons	10^{16}	2.	2.6	1.9
Peak brilliance	B/10^{33}	1.7	2.1	1.5
Average brilliance	B/10^{24}	6	7.6	5
Saturation length	m	124	97	108

coherence. We should note that this is not the case for short wavelengths and relatively large value of the emittance. Recently, a strict definition of the saturation point was introduced as the point where peak brilliance reaches its maximum [7–9]. This always happens because transverse and longitudinal coherence get worse in the nonlinear regime and lead to a decrease of the brilliance despite the fact that the power grows steadily (see Fig. 1). The use of the strict definition for the saturation point and accounting for a finite transverse coherence leads to the reduction of saturation parameters presented in earlier studies (and in the TDR 2006 [1] as well) by a factor of 2-3.

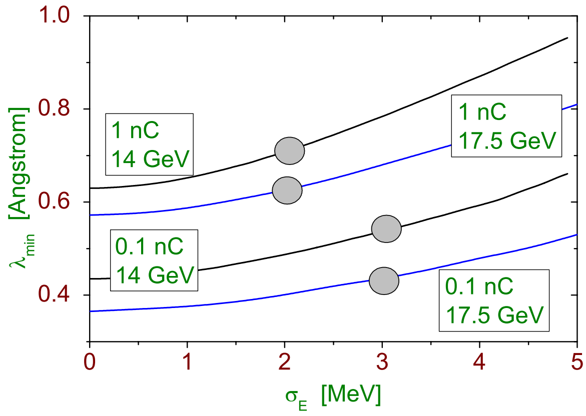

Figure 2: Minimum wavelength of SASE1 versus energy spread for bunch charge of 0.1 and 1 nC, and electron energy of 14 GeV and 17.5 GeV. Circles refer to working points from Table 1. Undulator length is equal to 165 meters. Parameters of SASE1 are optimized for minimum gain length.

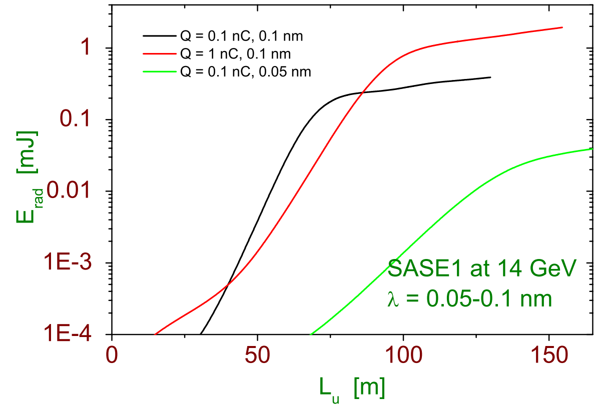

Figure 3: Energy in the radiation pulse for SASE1 versus undulator length. Electron beam energy is 14 GeV. Parameters of the electron beam are compiled in Table 1. Black and red curve refer to the wavelength of 0.1 nm and bunch charge of 0.1 nC and 1 nC, respectively. Green curve refers to the case with the wavelength of 0.05 nm and bunch charge 0.1 nC. Parameters of SASE1 are optimized for minimum gain length.

SATURATION CHARACTERISTICS

We start with comparative analysis of SASE1 operation which involves three different scenarios: i) parameters of electron beam from TDR 2006 [1] and energy 17.5 GeV; ii) new parameters of the electron beam [5] and energy 17.5 GeV; iii) new parameters of the electron beam [5] and energy 14 GeV. Relevant results are compiled in Table 2 for SASE1 operating at the wavelength of 0.1 nm in the saturation regime. Averaged characteristics are calculated for 30000 pulses per second. The same rms length of electron bunch of 80 fs is used in all cases to simplify comparison of the radiation properties. Brilliance is calculated according

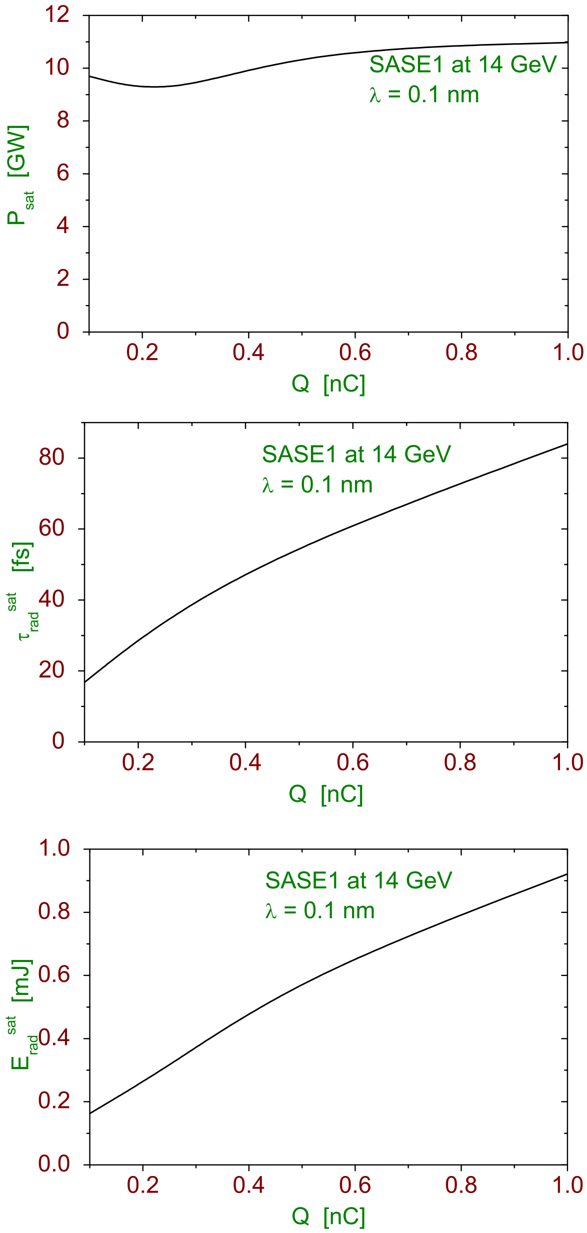

Figure 4: Peak saturation power, radiation pulse duration (FWHM), and radiation pulse energy for SASE1 versus bunch charge. Electron beam energy is 14 GeV. Wavelength is 0.1 nm. Plot is the result of application of fitting formulae [9] and parameters of the electron beam from Table 1.

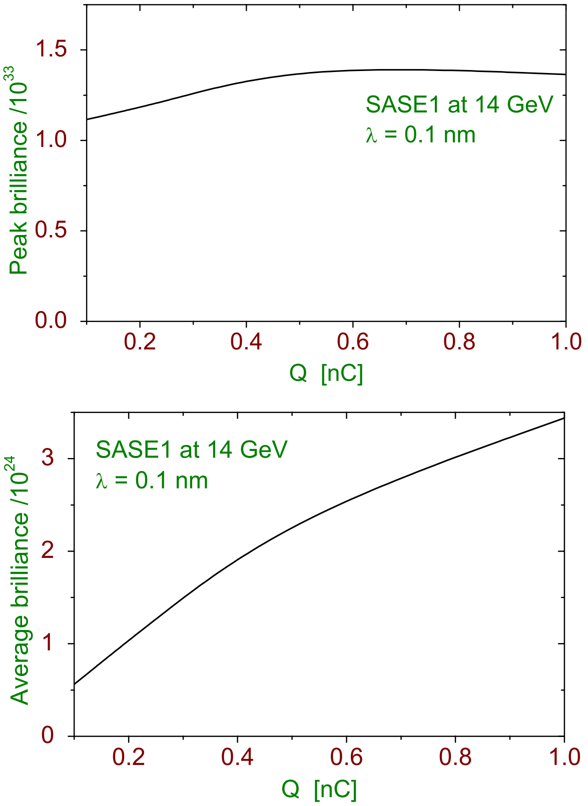

Figure 5: Peak and average brilliance for SASE1 versus bunch charge. Electron beam energy is 14 GeV. Wavelength is 0.1 nm. Plot is the result of application of fitting formulae [9] and parameters of the electron beam from Table 1.

to refs. [7–9] in all cases. To simplify comparison of averaged characteristics we use the same pulse duration and pulse pattern (repetition rate). We note that transition from TDR 2006 baseline parameters to new baseline parameters listed in Table 1 results in visible improvement of all characteristics of the radiation. One can see that two main steps: improve of emittance (positive factor), and decrease of energy to 14 GeV (negative factor) nearly compensate each other in the range of charges around 1 nC, and bring us back in the parameter space of TDR 2006.

With fixed energy of the electron beam change of the radiation wavelength is provided by the change of the undulator gap. Maximum wavelength is defined by minimum undulator gap. Maximum wavelength of SASE1 is equal to 0.1 nm and 0.156 nm for the energy of electron beam of 17.5 GeV and 14 GeV, respectively. Minimum wavelength is defined by the quality of the electron beam (peak current, emittance, energy spread) and undulator length. Relevant plots for SASE1 are presented Fig. 2 for two bunch charges 0.1 nC and 1 nC, and two operating energies 17.5 GeV and 14 GeV. We see that tunability range is extended when the bunch charge is decreased. With project value of the energy spread (see Table 1) it is possible to operate SASE1 in the saturation at the wavelength of 0.05 nm at the bunch charge of 0.1 nC (see Fig. 3). Such a reduction of the minimum wavelength happens due to smaller emittance of a low charge beam. In fact, impact on the tunability range of the electron energy reduction is mainly parallel shift of the operating wavelength range to longer wavelengths. Impact of the emittance reduction leads to the extension of tunability range in the direction of shorter wavelengths.

Application of similarity techniques to the results of numerical simulations allows to define general parametric de-

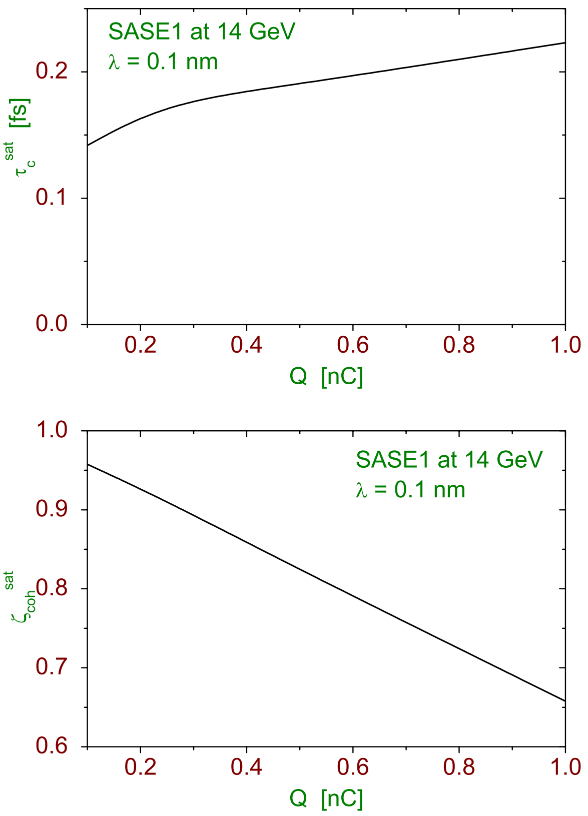

Figure 6: Coherence time and degree of transverse coherence for SASE1 versus bunch charge. Electron beam energy is equal 14 GeV. Wavelength is 0.1 nm. Plot is the result of application of fitting formulae [9] and parameters of the electron beam from Table 1.

pendencies of the saturation characteristics of SASE FEL. Relevant studies have been performed in paper [9] in approximation of small energy spread. Application of these formulae give approximate description of the saturation characteristics in the whole range of operating charges. Figures 4, 5, and 6 show evolution of main characteristics versus bunch charge for SASE1 operating at the saturation. Radiation wavelength is equal to 0.1 nm and electron energy is equal to 14 GeV. Electron bunch shape has been approximated by gaussian with rms pulse length given in Table 1. Averaged characteristics were calculated for the following pulse pattern: macropulse repetition rate 10 Hz, macropulse duration 600 μs, and micropulse repetition rate 4.5 MHz (27000 pulses per second).

An important conclusion is that peak power and peak brilliance of SASE1/SASE2 operating around 0.1 nm depend rather weakly on the bunch charge. This is the result of compensation of emittance decrease by decrease of peak current (see Table 1). Pulse duration is increased with bunch charge. Since peak power weakly depends on charge, the radiation pulse energy (and number of photons per pulse) grows with the bunch charge. Average brilliance grows with charge as well. This means that high charge mode of operation will be more preferable for user experiments relying on high photon flux. We note that degree of transverse coherence strongly depend on bunch charge. Being rather high, about 95%, at the bunch charge of 0.1 nC, it falls down to 66% at the bunch charge of 1 nC. Increase of the energy up to 17.5 GeV will allow to improve the latter value to about 78%. With small charge of 0.1 nC operation of SASE1 is possible down to the wavelength of 0.05 nm as we see from Fig. 3. However, the degree of transverse coherence degrades pretty much down to the value of about 40%.

DISCUSSION

With an updated set of the electron beam parameters for the European XFEL [5] we expect significant improvement of the characteristics of the radiation and extension of the operating wavelength range. Operation at smaller energies becomes possible, but for the price of reduction of photon flux, coherence properties of the radiation, and reduction of the operating wavelength range from the side of short wavelengths.

ACKNOWLEDGMENTS

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