SPATIAL PROPERTIES OF THE RADIATION FROM SASE FELS AT THE EUROPEAN XFEL

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Abstract

Recently DESY and the European XFEL GmbH performed revision of the baseline parameters for the electron beam and undulators. Operating range of bunch charges has been extended from 20 pC to 1 nC. Different modes of FEL operation become possible with essentially different properties of the radiation. This paper is devoted to the analysis of spatial properties of the radiation (fundamental and harmonics), an important subject for design of photon beam lines and planning user's experiments.

INTRODUCTION

Early version of the European XFEL project implemented operation of the facility with fixed bunch charge of 1 nC and rather conservative value for the emittance 1.4 mm-mrad [1]. Recent success of FLASH and Linac Coherent Light Source (LCLS) demonstrated feasibility for reliable production, compression, and acceleration of electron beams with small emittance [2,3]. Results of the Photo Injector Test Facility in Zeuthen (PITZ) demonstrated the possibility to generate electron beams with smaller charge and emittance [4, 5]. Intensive work on revision of electron beam parameter space of the European XFEL has been performed [6–9] which resulted in a new set of baseline parameters. Parameter space has been significantly extended in terms of the bunch charge and electron energy [10]. In parallel there was also revision of the undulator parameters based on user's requirements. It has been decided that SASE1 and SASE2 undulators will have period of 4 cm, and SASE3 undulator will have period 6.8 cm [11]. As a result, different modes of FEL operation become possible with essentially different properties of the radiation. Variation of the bunch charge will allow to control radiation pulse duration in wide limits. An important factor related to emittance reduction is significant change of angular divergence of the radiation with new baseline parameters. This forced corresponding revision of the photon distribution system [12].

In paper [13] we presented a comprehensive overview of radiation properties of SASE FEL radiators driven by electron beam with new baseline parameters. An important missed topic was spatial properties of the higher harmonic radiation. This paper fills the gap. Present study makes use of fitting formulae based on application of similarity techniques to the results of extended numerical simulations [14–17, 19]. As a result, it becomes possible to describe complicated phenomena with simple parametric dependencies.

BASIC RELATIONS

Design of the focusing system of XFEL assumes nearly uniform focusing of the electron beam in the undulator, so we consider axisymmetric model of the electron beam. It is assumed that transverse distribution function of the electron beam is Gaussian, so rms transverse size of matched beam is $\sigma = \sqrt{\epsilon\beta}$,where $\epsilon = \epsilon_{\rm n}/\gamma$ is rms beam emittance, γ is relativistic factor, and β is focusing beta-function. In the following we apply similarity techniques to the analysis of the FEL amplifier operation. Key notions of the three-dimensional theory of the FEL amplifier which we use here are is the gain parameter Γ and diffraction parameter B [20, 21]:

$$\Gamma = \left[\frac{I}{I_{\rm A}}\frac{8\pi^2K^2A_{\rm JJ1}^2}{\lambda\lambda_{\rm w}\gamma^3}\right]^{1/2} , \qquad B = 2\Gamma\sigma^2\omega/c\,. \qquad (1)$$

Here I is the beam current, $I_{\rm A} = 17$ kA is Alfven's current, λ is radiation wavelength, $\omega = 2\pi c/\lambda$, $\lambda_{\rm w}$ is undulator period, and K is rms undulator parameter. Coupling factor is $A_{\rm JJ1} = 1$ for helical undulator, and $A_{\rm JJh} = J_{(h-1)/2}(K^2/2(1+K^2)) - J_{(h+1)/2}(K^2/2(1+K))$ for planar undulator. J_n is the Bessel function of the first kind.

With given parameters of electron beam and undulator period the only parameter remaining for optimization of the FEL gain is focusing beta function. In the parameter range $1 \lesssim \hat{\epsilon} = 2\pi\epsilon/\lambda \lesssim 5$ optimum beta function is given explicitly by expression [14]:

$$\beta_{\rm opt} \simeq 11.2\left(\frac{I_A}{I}\right)^{1/2}\frac{\epsilon_n^{3/2}\lambda_{\rm w}^{1/2}}{\lambda K A_{JJ1}}(1+8\delta)^{-1/3} ,$$

$$\delta = 131\,\frac{I_A}{I}\,\frac{\epsilon_n^{5/4}}{\lambda^{1/8}\lambda_{\rm w}^{9/8}}\,\frac{\sigma_\gamma^2}{(KA_{JJ1})^2(1+K^2)^{1/8}} , \qquad (2)$$

where $\sigma_\gamma = \sigma_{\rm E}/m_{\rm e}c^2$. When energy spread is not important for amplification process, diffraction parameter for optimized x-ray FEL (with optimum beta function given by (2) yields in a simple relation:

$$B \simeq 12.5 \times \hat{\epsilon}^{5/2} . \qquad (3)$$

FUNDAMENTAL HARMONIC

We start illustration of spatial properties with specific numerical example for SASE1 and SASE3 operating with bunch charge 100 pC. Other parameters of SASE1 (SASE3) are energy 14 GeV (17.5 GeV), radiation wavelength 0.25 nm (1.6 nm) [13]. Evolution along the undulator of the spot size of the radiation and angular divergence of the radiation is shown in Fig. 1. Simulations have

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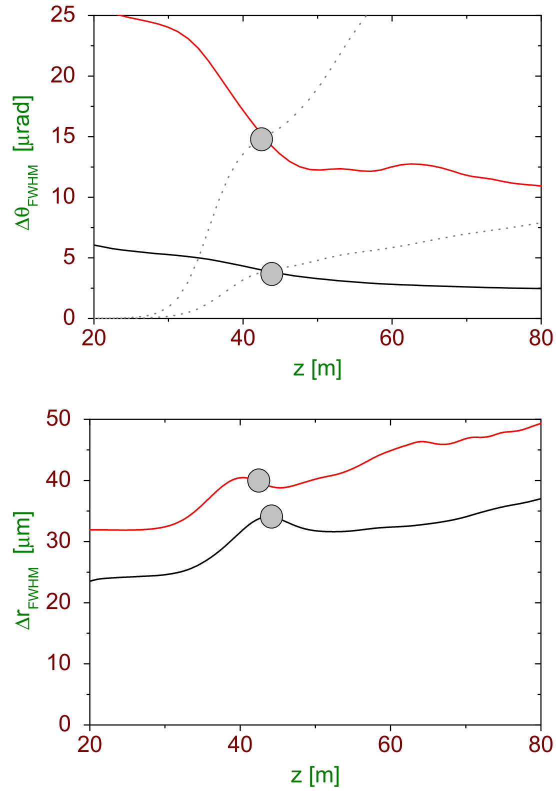

Figure 1: Radiation spot size (bottom) and angular divergence (top) of the radiation versus undulator length for SASE1 (SASE3). Black and red curves refer to the case of SASE1 and SASE3, respectively. Parameters of SASE1 (SASE3) are: electron energy is 14 GeV (17.5 GeV), bunch charge is 100 pC, wavelength is 0.25 nm (1.6 nm). Dotted lines show radiation pulse energy. Circles denote saturation point.

been performed with tim-dependent FEL simulation code FAST [22]. Both values, spot size and divergence evolve in the amplification process. Scale of the values depends on the choice of the electrom beam parameters and wavelength. From practical point of view it is important to know characteristics of the radiation at the saturation point when brilliance of the radiation of fundamental harmonic reaches maximum value. Circles on the upper plot mark relevant saturation points. Our studies show that spatial properties of the radiation mode at the saturation point are mainly defined by the diffraction parameter B. For normalized values of the FWHM spot size and angular divergence we have:

$$\begin{aligned} \Delta\hat{r}_{\mathrm{FWHM}} &\simeq \ln(8.2/B^{1/5})\,, \\ \Delta\hat{\theta}_{\mathrm{FWHM}} &\simeq \simeq \ln(3.3B^{1/3})\,. \end{aligned} \qquad (4)$$

Here dimensional values are normalized as $\Delta\hat{r}_{\mathrm{FWHM}} = \Delta r_{\mathrm{FWHM}}/(\sigma\sqrt{2})$, and $\Delta\theta_{\mathrm{FWHM}} = \Delta\theta_{\mathrm{FWHM}}\lambda/(2\sqrt{2}\pi\sigma)$. Dependencies given by Eq. (4) are rather simple as it is shown in Fig. 2. Calculations

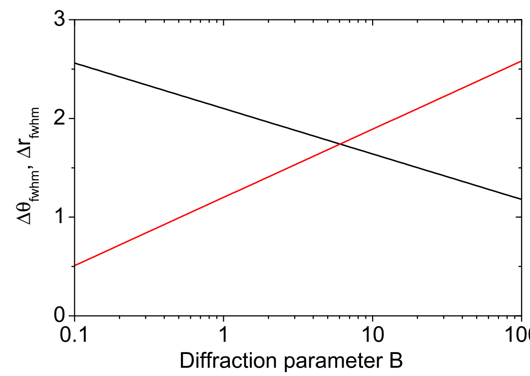

Figure 2: Normalized FWHM size (black curve) and angular divergence (red curve) of SASE FEL radiation versus diffraction parameter. SASE FEL operates at the saturation point.

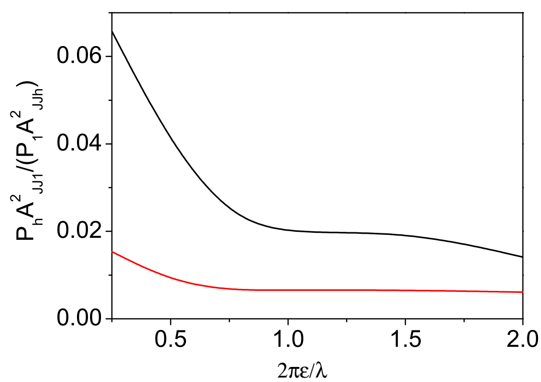

Figure 3: Optimized XFEL. Ratio of powers in the 3rd (black line) and the 5th harmonic (red line) to the power of the fundamental harmonic versus parameter $\hat{\epsilon} = 2\pi\epsilon/\lambda$. SASE FEL operates at the saturation point.

of the value of the diffraction parameter is essentially simple for the case of optimized x-ray FEL (3). There is a range of parameters (e.g. long wavelength FELs) when conditions of optimum focusing can not be realized due to the limitations of the focusing system (in the case of the European XFEL we set lower limit on beta function to 15 meters). In this case Eq. (1) should be used for calculation of diffraction parameter. For numerical example presented in Fig. 1 the values of diffraction parameters are 7.6 and 0.51, and rms size of the electron beam 14.5 μm and 13.1 μm for SASE1 and SASE3, respectively. Using Eq. (4) and other parameters of the problem we find angular divergence and spot size at the saturation point to be 3.6 μrad and 35 μm for SASE1, and 13.4 μrad and 41 μm for SASE3. Comparison with Fig. 1 shows that Eq. (4) provides reasonable practical accuracy.

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Table 1: European XFEL: Baseline parameters of the electron beam at the undulator entrance (December 2010 revision [10])

Bunch charge	nC	0.02	0.1	0.25	0.5	1
Peak beam current	kA	4.5	5	5	5	5
Normalized rms emittance	mm-mrad	0.32	0.39	0.6	0.7	0.97
rms energy spread	MeV	4.1	2.9	2.5	2.2	2
rms pulse duration	fs	1.2	6.4	16.6	30.6	76.6

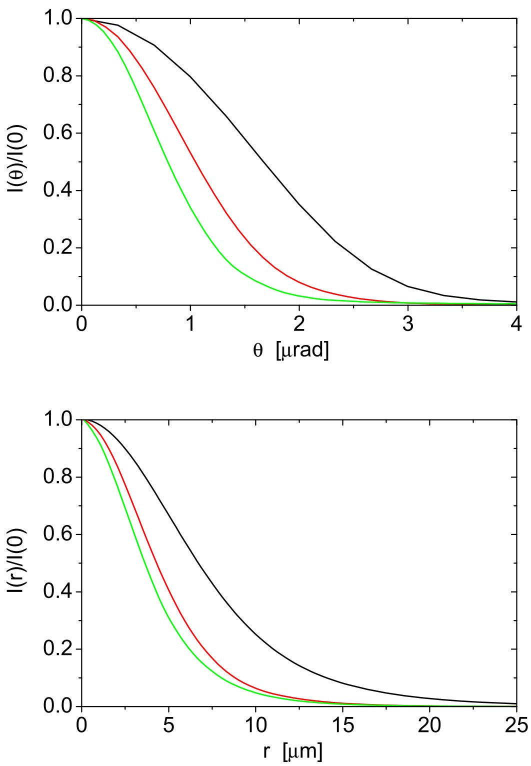

Figure 4: Distribution of the radiation intensity in the far (top) and near (bottom) zone. SASE FEL is optimized to maximum gain and operates in the saturation. Emittance parameter is $\hat{\epsilon} = 0.5$. Dimensional units related to the problem are: radiation wavelength is 0.1 nm, rms size of the electron beam is $\sigma = 5\ \mu$m. Black, red, and green lines correspond to the 1st, 3rd, and 5th harmonic.

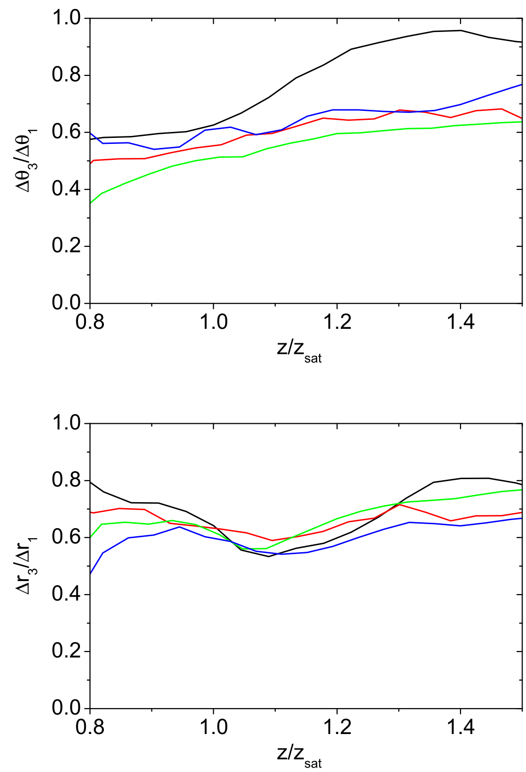

Figure 5: Ratio of for the 3rd and the 1st harmonic of the angular divergence (top) and the spot size (bottom). Undulator length is normalized to the saturation length. Black, red, green, and blue curve correspond to the values of the emittance parameter $\hat{\epsilon} = 0.5$, 1, 1.5, and 2, respectively.

HIGHER HARMONICS

We consider the case when the bunching at higher harmonics is mainly defined by the nonlinear beam bunching in the fundamental harmonic. In the case of optimized x-ray FEL the ratios of the power of higher harmonics to the power of the fundamental harmonic are universal functions of emittance parameter when we factorize them with the ratio of coupling factor $A^2_{\mathrm{JJh}}/A^2_{\mathrm{JJ1}}$ [18, 19]. Relevant plots are presented in Fig. 3. For large values of the undulator parameter K asymptotic values of $A^2_{\mathrm{JJh}}/A^2_{\mathrm{JJ1}}$ are equal to 0.22 and 0.11 for the 3rd and the 5th harmonic, respectively. In the range of emittance parameter from 0.25 to 2 contributions to the total power of the 3rd (5th) harmonic is between 0.3 - 1.4% (0.07 - 0.16%). Contribution of higher harmonics to the total power grows in the deep nonlinear regime, and may constitute substantial amount depending on quality of the electron beam [19].

Figure 4 shows distributions of the radiation intensity in the far and near zone for the 1st, 3rd, and 5th harmonic. Data correspond to the value of the emittance parameter $\hat{\epsilon} = 0.5$, radiation wavelength 0.1 nm, and rms size of the electron beam $\sigma = 5\ \mu$m. SASE FEL is optimized to maximum gain and operates in the saturation regime. Intensity distributions shrink for higher harmonics. For the 3rd harmonic both ratios of the widths of intensity distributions (angular and spot size) are about 0.6. Analysis of the emit-

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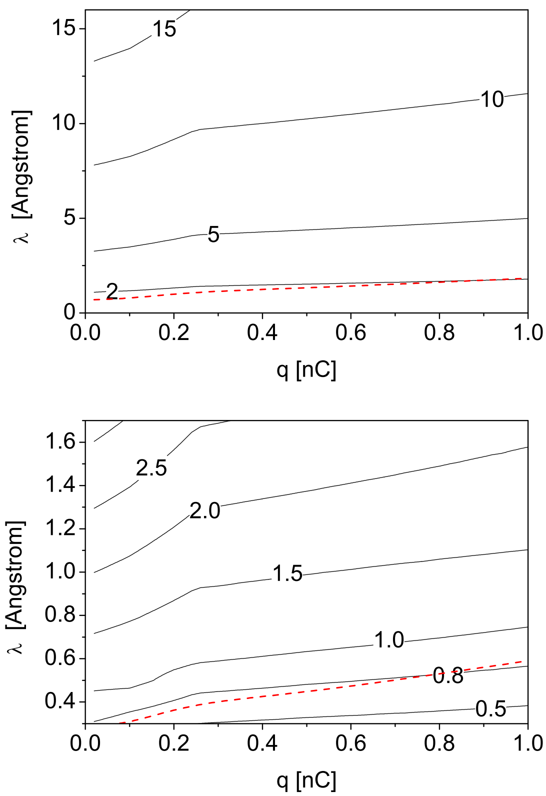

Figure 6: FWHM angular divergence of the radiation for SASE1 (top) and SASE3 (bottom) FELs operating in the saturation versus bunch charge and operating wavelength. Electron energy is 17.5 GeV. Numbers on contour lines denote units of μrad. Red dashed curve shows minimum of the radiation wavelength at the undulator length of 165 m. Parameters of the electron beam are presented in Table 1. Focusing beta function is optimized for minimum gain length.

tance parameter space $\hat{\epsilon} = 0.5 - 2$ (see Fig. 5) shows that ratio of the widths of the distributions for the 3rd and the 1st harmonic is in the limits 0.55 ± 0.05. For the time of preparation of this manuscript simulations for the 5th harmonic are in the progress. Preliminary results indicate that at the values of $\hat{\epsilon} \sim 0.5$ spot size and angular divergence shrink further, and constitute about 50% of the values for the fundamental harmonic.

SUMMARY

Application of similarity techniques provides not only an elegant way for deeper insight into FEL physics. We demonstrated here that with proper normalization of parameters spatial properties of the radiation from x-ray FELs are simple functions of the only diffraction parameter B (see Eq. (4)). Diffraction parameter itself can be easily calculated for the whole parameter space of the European XFEL compiled in Table 1. As an example of application of presented formulae we conclude our paper with the plots for angular divergence of the radiation from SASE FELs at the European XFEL operating at the nominal energy of 17.5 GeV (see Fig. 6). Angular divergence of the 3rd harmonic shrinks to about 60% of the divergence of the fundamental harmonic.

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