LIMITATIONS ON THE OPERATION OF A SOFT X-RAY FEL AT THE EUROPEAN XFEL*

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Abstract

Free electron laser (FEL) process leads to energy loss by electrons and increase of the energy spread. Further use of the electron beam for generation of the FEL radiation is possible, but only for longer wavelength. This technical solution is implemented in the design of the European XFEL. Two undulators, SASE1 and SASE3 are installed in a raw. SASE 1 is designed to operate at fixed photon wavelength of 0.1 nm. The SASE 3 undulator has been placed behind SASE1, and will produce radiation in the wavelength range of 0.4 - 1.6 nm. In this paper we analyze potential option of VUV and soft x-ray FEL operating in the wavelength range of 1.6-6.4 nm, and driven by the spent electron beam after SASE2 undulator. Degradation of the electron beam quality after SASE2 is not completely negligible, and its influence on the performance of the VUV FEL is the subject of the present study.

INTRODUCTION

The baseline specifications of European XFEL give a range of wavelengths between 0.1 nm and 1.6 nm [1]. It would be extremely interesting to extend this range into so-called "water window", i.e. the range between the K-Absorption edges of carbon and oxygen at 4.38 nm and 2.34 nm, respectively. Such an extension has been already discussed at an early design phase of the project [2, 3] in the framework of the concept of future generic FEL beamline [4]. It has been assumed that the wavelength range 0.1-6 nm at fixed electron beam energy of 17.5 GeV can be covered by operating the SASE FEL with four undulators which have different period and tunable gap. In proposed ("after-burner") scheme it will be possible to provide in parallel hard (around 0.1 nm) and VUV radiation for two photon beamlines. The extension of the wavelength range to 6 nm would cover the water window, opening the facility to a new class of experiments. For example, in some modes of operation, VUV FEL radiation could be used with X-ray FEL radiation to do pump-probe experiments with precise intervals between the sources.

Recent workshops on scientific case of the European XFEL raised interest to an extension of its wavelength range for longer wavelengths. Realizing that generic FEL beamline is the subject of a future realization, we consider here the possibility to install VUV - soft x-ray FEL in the beamline after SASE2 undulator. In fact, two tunnels are reserved for installation of spontaneous radiators (see Table 1). With an appropriate optimization of matching sections (about 50 meters) we can have space available for installation of the VUV FEL from 140 to 200 meters. Thus, installation of the undulator with 120 meters magnetic length seems to be realistic.

We show that operation of the VUV FEL with magnetic length of 120 meters is possible in a "parasitic" mode of operation not interfering with the operation of SASE2 FEL. An advantage of the VUV FEL driven by high energy electron beam is high peak power, up to few hundreds GW in the saturation, exceeding project parameters of the FLASH free electron laser [5] by almost two orders of magnitude. Operation of the VUV FEL with not so much disturbed electron beam (e.g. for SASE2 operating at 0.1 nm) would allow to reach even higher output powers close to 0.5 TW.

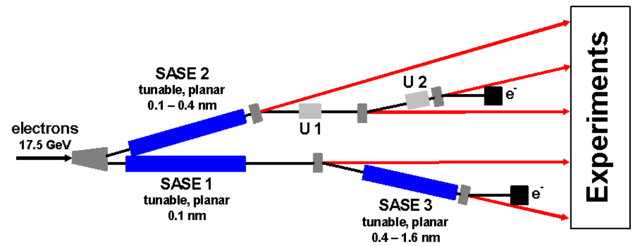

Figure 1: Layout of the European XFEL. Wavelength range 0.1 nm - 1.6 nm is covered with three free electron lasers SASE1, SASE2, and SASE3. Two spontaneous undulators U1 and U2 are considered as future potential options [1]. Lengths of the undulator tunnels are compiled in Table 1.

Table 1: Location of Undulators on XFEL Site

Location	Full length	Available for undulators	Undulator
XS1-XS3	620 m	396 m	SASE1
XS3-XHDU1	301 m	251 m	SASE3
XS1-XS2	550 m	358 m	SASE2
XS2-XS4	190 m		Spont. U1
XS4-XHDU2	250 m		Spont. U2

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EFFECTS OF INCOHERENT RADIATION

We consider the case when VUV FEL is driven by spent electron beam after SASE2 radiator. For illustration we use project parameters of the European XFEL [1]. Electron beam at the exit of linear accelerator has energy of 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. Regardless FEL interaction, electrons always emit incoherent synchrotron radiation. This leads to average loss of the energy of electrons, and growth of the energy spread due to quantum fluctuations of the incoherent undulator radiation. The mean energy loss of each electron into incoherent radiation is given by:

$$d\mathcal{E}/dz = 2r_{\mathrm{e}}^2\gamma^2 H_{\mathrm{w}}^2(z)/3 \quad , \tag{1}$$

where $r_{\mathrm{e}} = e^2/m_{\mathrm{e}}c^2$ is classical radius of the electron, $\gamma = \mathcal{E}/(m_{\mathrm{e}}c^2)$ is relativistic factor, $\mathcal{E}$ is the energy of electron, H is magnetic field, $(-e)$ and m_{e} are the charge and the mass of the electron, respectively, and c is the velocity of light. At the exit of the SASE2 undulator ($L_w = 210$ m), average losses of the electron energy is 75 MeV. We do not consider influence of this effect on the FEL operation since it can be easily compensated by undulator tapering.

Another effect is the growth of the uncorrelated energy spread in the electron beam due to quantum fluctuations of undulator radiation [6–8]. The rate of the energy diffusion is given by [9]:

$$\frac{d\sigma_\gamma^2}{dz} = \frac{14}{15}\lambda\!\!\!^{-}_{\mathrm{c}} r_{\mathrm{e}}\gamma^4\kappa_{\mathrm{w}}^3 K^2 F(K) \, , \tag{2}$$

where $\lambda\!\!\!^{-}_{\mathrm{c}} = \hbar/mc$ is Compton wavelength, $\hbar$ is Planck constant, $\kappa_{\mathrm{w}} = 2\pi/\lambda_{\mathrm{w}}$, $F(K) = 1.42K + (1 + 1.50K + 0.95K^2)^{-1}$ for helical undulator, and $F(K) = 1.70K + (1 + 1.88K + 0.80K^2)^{-1}$ for planar undulator. At the exit of the SASE2 undulator ($L_w = 210$ m), rms energy spread is 4.8 MeV.

EFFECTS OF COHERENT RADIATION

FEL process in the proceeding undulator leads to an essential growth of the energy spread in the electron beam as it is illustrated in Fig. 2. Thus, the range of interest for our study is the energy spread from 1 Mev up to 40 MeV.

In this paper we study scenario of the VUV FEL considered at an earlier stage of the European XFEL project [2,3]. Parameters of the VUV FEL have been elaborated under the following constrains: tunability range from 1.6 nm to 6.4 nm, undulator gap not less than 10 mm, and peak undulator field not higher than 1.7 T. Under these constrains undulator period has been chosen to be 11 cm, and change of the undulator gap between 19 mm and 37 mm provides required wavelength tunability. We assume maximum magnetic length of the undulator to be around 120 m in view of possible available space in the XFEL tunnels (see Table 1). Assuming 20% safety margin for the undulator length, we request saturation to be less than 100 meters.

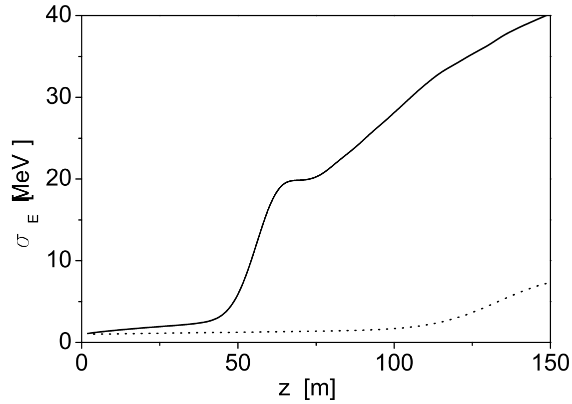

Figure 2: Growth of the energy spread in the electron beam along SASE2 undulator. Solid and dashed line correspond to the operation of SASE FEL at 0.4 and 0.1 nm, respectively.

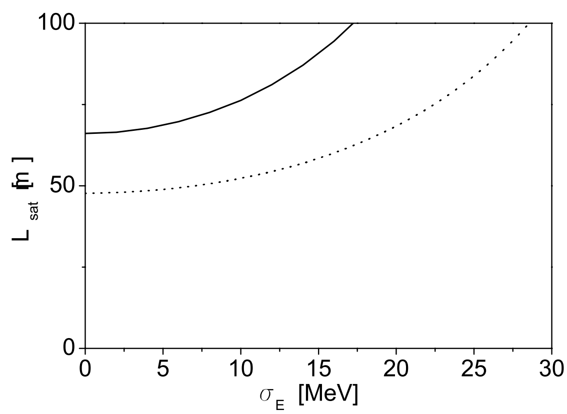

Figure 3: Saturation length of the VUV FEL as a function of the energy spread in the electron beam. Solid and dashed curve correspond to the wavelength of 1.6 nm and 6.4 nm, respectively.

Figure 4 shows dependence on the energy spread of the saturation length of the VUV FEL. We see that at the constrain of the undulator length of 100 meters, VUV FEL operating at the wavelengths of 1.6 nm and 6.4 nm can tolerate energy spread up to 17 MeV, and 27 MeV, respectively. In other words, it can operate nearly with all possible modes of SASE2 FEL, from 0.1 to 0.4 nm when SASE2 just operate in the saturation regime. We can not reach saturation if SASE2 will operate in the deep nonlinear regime with high efficiency.

One should care also about cancellation of the net compaction factor between SASE2 and the VUV undulator. Indeed, in the case when there is net compaction factor,

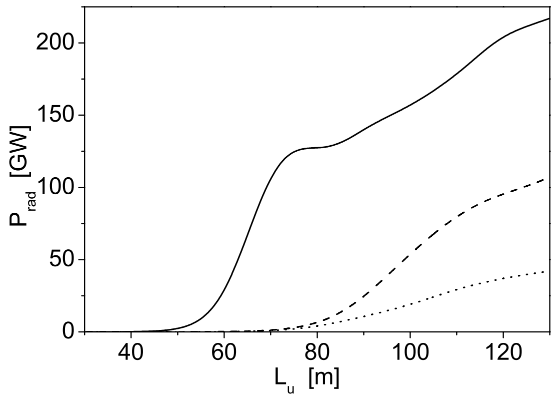

Figure 4: Peak radiation power from the VUV FEL operating at the wavelength of 1.6 nm. Solid curve corresponds to the case of SASE2 "off". Dashed and dotted curve correspond to the case of the SASE2 operating in the saturation at the wavelength of 0.4 nm and zero and 50 μm net compaction factor between SASE2 and VUV undulators, respectively.

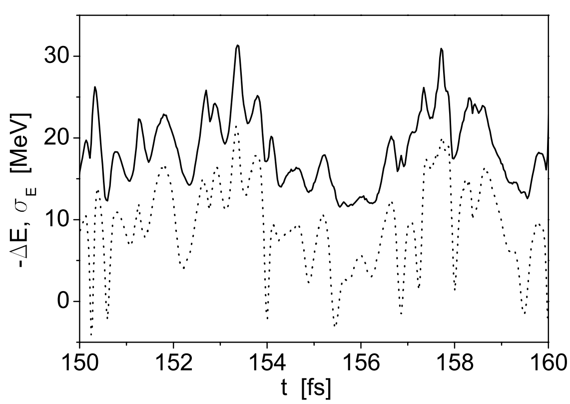

Figure 5: Energy loss (dashed line) and rms energy spread (solid line) along the electron bunch. SASE2 operates at saturation. Wavelength is equal to 0.4 nm.

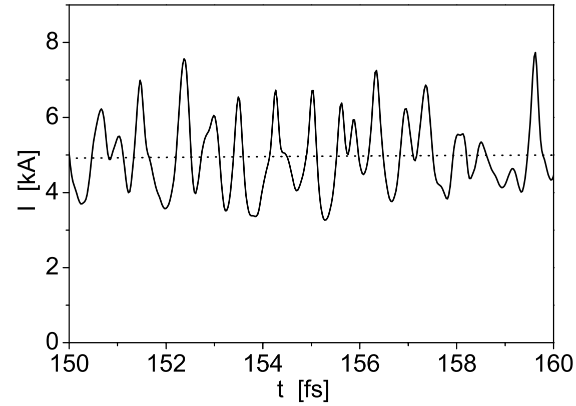

Figure 6: Beam current along the electron bunch. SASE2 operates at saturation. Wavelength is equal to 0.4 nm.Electron beam passed dispersion section with the net compaction factor of 50 μm.

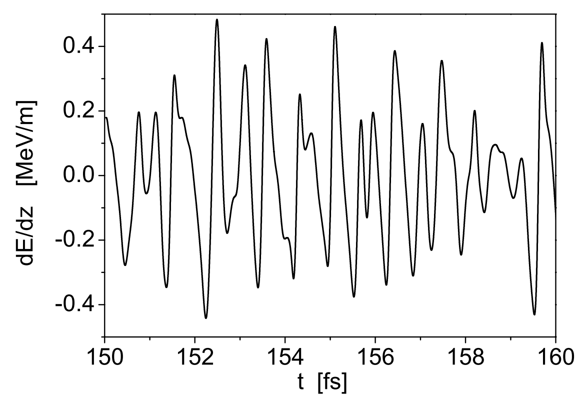

Figure 7: The rate of the energy change in the VUV undulator due to the longitudinal space charge field. VUV undulator is tuned to the resonance wavelength of 1.6 nm. Electron beam passed 50 μm net compaction factor after SASE2 undulator and gained current modulation (see Fig. 6).

average energy loss due FEL process (which occur on a scale of coherence length) will transform to density modulation [10]. Density modulation causes longitudinal space charge field which acts on the particles and change their energy [11]. This effect is not negligible at all and must be taken into account.

Let us consider numerical example. SASE2 FEL operates at the wavelength of 0.4 nm, and just reaches saturation. Figure 5 shows average energy loss and rms energy spread along the electron bunch. Then electron bunch passes dispersion section with net compaction factor of 50 μm, and energy modulation transforms to density modulation as it is shown in Fig. 6. This density modulation produces rather strong longitudinal electric field when electron bunch propagates in the VUV undulator. We can easily estimate the value of dthe effect with simple relation for gaussian beam [12]:

$$\frac{d(\Delta\gamma)}{dz} \simeq 2.4\,\frac{I}{I_{\mathrm{A}}}\,\frac{\ln(\gamma\sigma_z/\sigma_\perp)}{\sigma_z\gamma^2} \qquad (3)$$

where $I_{\mathrm{A}} = 17$kA is the Alfven current, $\sigma_\perp$ is the rms transverse size of the beam, and σ_z should be substututed by typical length of the current spike in Fig. 6. This formula holds when $\sigma_z\gamma \gg \sigma_\perp$. Taking into account typical values (a few kA), and duration (a fraction of fs) of current spike, we estimate that the rate of the energy change is in the range of MeV per meter. Exact calculations of the effect shown in Fig. 7 confirm this simple physical estimate. Note that at the undulator length of a hundred meters peak-to-peak energy modulation induced by the space charge field can reach 100 Mev values.

The figure of merit of influence of the energy chirp on the FEL operation is the energy chirp parameter defined as [13]:

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0\omega_0\rho^2} \qquad (4)$$

where $\omega_0 = 2\pi c/\lambda$ is a resonance wavelength, and ρ is FEL parameter [14]. In our case the value of the FEL parameter is 2×10^{-3}, and radiation wavelength is $\lambda = 1.6$ nm. Using simulation results presented in Figs. 5 and 7 we estimate that while this effect is negligible in the beginning of the undulator, it becomes significant in the end when peak-to-peak jumps of the energy reach a hundred MeV value on a sub-femtosecond time scale. Exact simulations with time-dependent simulation code FAST [15] show that the effect of energy modulation is pretty strong, and saturated power drops significantly. We conclude that when designing SASE afterburner one should care about cancellation of the net compaction factor after the main undulator.

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