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ANALYSIS OF PARAMETER SPACE OF SOFT X-RAY FREE ELECTRON LASER AT THE EUROPEAN XFEL DRIVEN BY HIGH AND LOW ENERGY ELECTRON BEAM

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Abstract

Three undulator beamlines: SASE1 and SASE2 (hard X-ray), and SASE3 (soft X-ray) are in operation at the European XFEL serving six user instruments. Next stages of the facility development are installation of two undulator beamlines in empty tunnels SASE4 and SASE5 as middle term upgrade, and extension of the facility with the second fan of undulators as long term upgrade. Construction of soft X-ray beamlines is considered in both upgrade scenario. In the case of SASE4/SASE5 electron beam with energies 8.5 GeV - 17.5 GeV will be used in order to provide simultaneous operation of new undulator beamlines with existing SASE1-SASE3. One of the scenarios for a second fan of undulators involves using of low energy (2.5 GeV) electron beam. In this paper we analyze parameter space of soft X-ray SASE FELs driven by high energy and low energy electron beam, compare output characteristics, and discuss potential advantages and disadvantages.

INTRODUCTION

Start-up configuration of the European XFEL includes two hard X-ray SASE FELs, SASE1 and SASE2, and one soft X-ray SASE FEL, SASE3 serving six user instruments [1]. All undulators are planar, variable gap devices. SASE1 and SASE2 are equipped with identical undulators with 4 cm period length. SASE3 undulator has similar mechanical design, but the period length is 6.8 cm. Radiation wavelength at fixed electron energy is changed by means of changing the undulator gap. Trusted tunability ranges of undulators are limited to $\lambda_{\max}/\lambda_{\min} = 3.6$ for SASE1/SASE2 and 4.5 for SASE3 which is not sufficient for covering all user experiments at one fixed electron energy. By the time, five operating points of the electron beam energy have been fixed (8.5, 11.5, 14, 16.5, and 17.5 GeV) providing most flexible way for simultaneous operation of users at all three beamlines. Full wavelength range covered by start-up configuration spans from 0.05 nm to 5.1 nm.

Start-up of the facility operation proceeded smoothly: all three SASE radiators produce x-ray radiation with parameters close to design values, and all six user stations serve user experiments [2, 3]. Middle term plans of the facility development assume installation of two more SASE FEL beamlines in empty tunnels and construction of four user instruments [1]. Strategic extension of the facility assumes installation of new undulator beamlines and user stations doubling user capacity. Here an option of low energy beamline has been considered when electron beam at the energy of 2.5 GeV is extracted from accelerator and is transported via bypass electron beamline to the undulator for generation of soft X-ray radiation. Upgrade of the the accelerator to CW mode of operation is also included in a long term R&D program [4].

Next generation X-ray FELs should provide wide capabilities for performing user experiments:

- wide tunability range;
- control of the radiation pulse duration;
- coherence control: temporal and spatial;
- polarization control: linear, circular, elliptical;
- wide capabilities for pump-probe experiments involving FEL radiation (fundamental harmonic, higher harmonics, independent colors), laser and accelerator based radiation sources;
- control of the photon flux up to ultimate level.

Not all of these features are implemented in the start-up configuration of the European XFEL. In this paper we discuss possible potential development of soft-Xray/VUV FEL beamline with extended wavelength range and extended user capabilities. We consider two options: high energy option, 8.5 GeV - 17.5 GeV, and low energy, 2.5 GeV option. Our study shows that high energy option has evident advantages in terms of peak radiation power, pulse energy, photon flux, and transverse coherence. Additionally, operation at higher charges and higher electron energies holds potential for generation of the radiation pulse energies on a sub-Joule level [5]. High energy option can be realized on a middle term time scale using present infrastructure of the European XFEL which foreseens installation of two more undulators and four user instruments.

HIGH ELECTRON ENERGY: 8.5 - 17.5 GeV

First step of our study is an overview of parameter space aiming extension of the operating range in the direction of longer wavelengths. The only mean to do this is to increase the undulator period. Figure 1 shows contour plot of the maximum wavelength as function of the undulator period and electron beam energy. We find that undulator with period length 10 to 12 cm provides maximum wavelength of 25 - 45 nm at the electron energy of 8.5 GeV. Operation at the electron energy of 17.5 GeV with an open undulator gap will allow to reach radiation wavelengths below 1 nm.

Plot in Fig. 2 illustrates main parameters of SASE FEL for the case of 11 cm undulator period length. Numerical example is calculated for electron bunch with baseline parameters: bunch charge 250 pC, peak current 5 kA, rms normalized emittance 0.6 mm-mrad, rms energy spread 2.5 MeV [6]. Blue, black and red colors refer to the radiation wavelength, saturation length, and radiation pulse energy in the saturation regime. Solid lines show values of the parameters for closed

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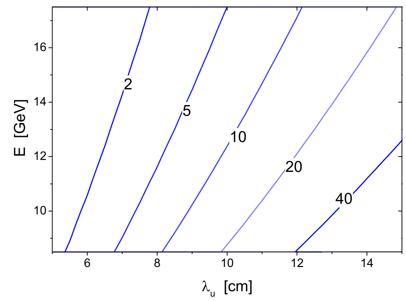

Figure 1: Maximum radiation wavelength as function of the electron energy and undulator period.

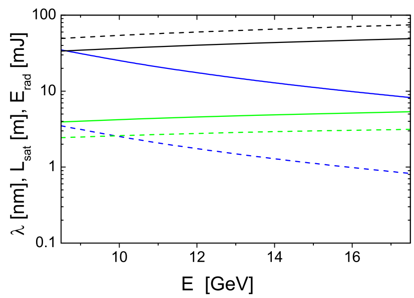

Figure 2: Radiation wavelength (blue), saturation length (black), and radiation pulse energy in the saturation (green) versus electron energy. Solid lines and dashed lines correspond to closed and open undulator gap, respectively. Undulator period is equal to 11 cm. Bunch charge is 250 pC [6]. Simulations are performed with code FAST [7].

undulator gap, and dashed lines represent values for open undulator. Undulator parameter changes from 13.2 (closed gap) to 4.1 (open gap), and wavelength tunability range at fixed energy is $\lambda_{\max}/\lambda_{\min} = 10$. We see that parameters of the SASE FEL change very slowly in the whole wavelength range spanning from 0.8 nm to 35 nm. When SASE FEL operates at closed undulator gap, saturation length changes from 34 m at 8.5 GeV to 49 m at 17.5 GeV, and radiation pulse energy is increased from 4 to 5.3 mJ. Operation at open gap leads to increase of the saturation length by a factor 1.5, and radiation pulse energy falls by a factor 1.6. Such a slow dependence of output characteristics is consequence of small value of the diffraction parameter. In the case under study diffraction parameter is in the range $B = 0.07 - 0.1$ for closed gap, and $B = 0.7 - 1$ for open gap. This feature explains so slow change of output characteristics. Indeed, when energy spread and betatron oscillation effects are negligible, operation of the FEL amplifier is described by the diffraction parameter $B = 2\Gamma\sigma^2\omega/c$ with the gain parameter Γ [8]:

$$\Gamma = \left[\frac{I}{I_{\mathrm{A}}} \frac{16\pi^2 K^2 A_{\mathrm{JJ}}^2}{(1+K^2)\lambda_{\mathrm{w}}^2 \gamma} \right]^{1/2} ,$$

Efficiency of an FEL amplifier in saturation is universal function of the only diffraction parameter B:

$$\eta \simeq \bar{\rho} \qquad \text{for} \quad B < 1 ,$$

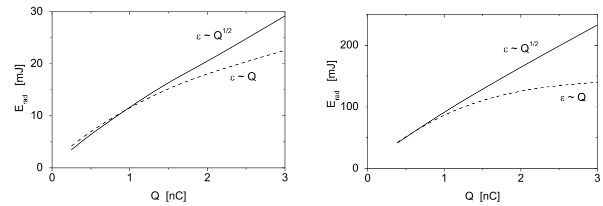

Figure 3: Energy in the radiation pulse versus bunch charge for SASE3 at the European XFEL. Left plot: FEL operates in the saturation regime. Right plot: operation with tapered parameters for the undulator length of 100 meters. Electron energy is 17.5 GeV, radiation wavelength is 1.6 nm. Solid and dashed lines correspond to the emittance scaling as $q^{1/2}$, and q, respectively.

$$\eta \simeq \bar{\rho}/B^{1/3} \quad \text{for} \quad B > 1 ,$$

where 3D FEL parameter $\bar{\rho} = \lambda_{\mathrm{w}}\Gamma/(4\pi)$. FEL gain length scales as $1/B^{1/3}$ for $B > 1$, and changes slowly (in fact logarithmically with B) at small values of diffraction parameter. For large value of the undulator parameter K and small values of diffraction parameter B, the gain parameter scales as $\Gamma \propto 1/\gamma^{1/2}$. As a result, saturation length scales as $L_{sat} \propto \gamma^{1/2}$, and radiation pulse energy in saturation scales as:

$$E_{\mathrm{rad}} \simeq \bar{\rho} \times N_e \times \gamma \times m_e c^2 \propto N_e \times \gamma^{1/2} \times I^{1/2} ,$$

which explains relevant dependencies shown in Fig. 2.

We should note that FEL efficiency can be increased with application of undulator tapering. In the case of diffraction limited beam one can gain a factor up to 10 in efficiency with respect to saturation value. Also, European XFEL holds potential to operate with high charge bunches, up to 5 nC. As a result, very high radiation pulse energies can be achieved as we reported earlier in ref. [5], see Fig. 3.

LOW ELECTRON ENERGY: 2.5 GeV

This option has been analyzed at the design stage of the project [9]. It is assumed to extract electron beam after the last bunch compression stage. Then electron beam is transported via bypass beamline to the undulator and produces radiation. We fix electron energy to 2.5 GeV for this option. The only remaining parameter for optimization is undulator period. In the same way as it has been done in the previous section, we derive dependencies for the wavelength range, saturation length, and radiation pulse energy in the saturation (see Fig. 4).

Let us compare low energy option with high energy option. Saturation length at the radiation wavelength of 1 nm is 40 meters for the low energy option with 3 cm undulator period length, and 70 meters for high energy option with 11 cm undulator period length. However, practical characteristics of the low energy options significantly below those provided by high energy option. Indeed, we see that operation at fixed energy of the electron beam significantly shrinks available

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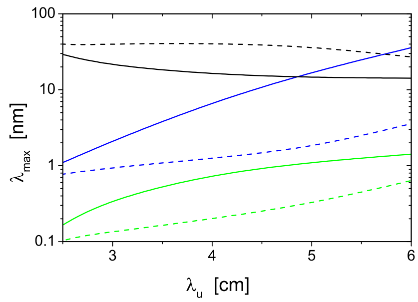

Figure 4: Radiation wavelength (blue), saturation length (black), and radiation pulse energy in the saturation (green) versus undulator period length. Solid lines and dashed lines correspond to closed and open undulator gap, respectively. Bunch charge is 250 pC [6]. Energy of electrons is 2.5 GeV. Simulations are performed with code FAST [7].

wavelength range. For high energy option we combine both means for the wavelength change: undulator gap and electron energy change. Helpful factor was also large K value of the long period undulator. For low energy option undulator K value falls down with undulator period, and tunability range shrinks drastically for shorter undulator periods. Energy in the radiation pulse is by an order of magnitude below that of high energy option. This happens due to two reasons: lower electron energy and operation of FEL process above diffraction limit. The value of the diffraction parameter B is about 30 when operating at the radiation wavelength around 1 nm. Mode degeneration effect can take place in this case reducing transverse coherence and pointing stability of the radiation [10].

DISCUSSION

An option of SASE FEL with long period undulator driven by high energy electron beam can be attractive option for perspective extension of the European XFEL on a middle term period: existing tunnels and infrastructure ideally fit for installation of such undulator. Essential feature of this undulator beamline is extended wavelength range. Use of variable polarization devices (e.g., of APPLE type) solves the problem of polarization control. Installation of a long undulator will be very useful for extension of user capabilities. Longer undulator can be used for generation of two or more independent colors [11, 12]. Installation of chicanes in the beamline will allow to control timing of different colors and organize relevant pump-probe experiments. Several harmonics can be generated as well [13, 14]. Implementation of Harmonic Lasing Self Seeding (HLSS) will allow to control longitudinal coherence [13]. This scheme essentially exploits high undulator K value. Application of the undulator tapering in combination with high charges will allow to generate very powerful radiation with pulse energies on a sub-Joule level [5]. External seeding can be also implemented for longer wavelengths when the effect of the noise growth in frequency multiplication schemes is on a low level [15].

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