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Simulation studies of superconducting afterburner operation for the European XFEL

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Abstract. European XFEL is a multi-beamline x-ray free-electron laser (FEL) user facility driven by a superconducting accelerator with a nominal photon energy range from 250 eV to 25 keV. An afterburner undulator based on superconducting undulator technology is currently being investigated to enable extension of the photon energy range towards harder x-rays. This afterburner undulator would be installed downstream of the already operating SASE2 FEL beamline, emitting at the fundamental or at a harmonic of the upstream undulator system. In this contribution we describe the layout under study and present numerical simulations.

1. Introduction

As part of its facility development program, European XFEL plans to develop superconducting undulator (SCU) technology. A very attractive application enabled by the combination of short-period SCUs with the high electron energies available at European XFEL [1] is the extension of the photon energy range towards harder x-rays. For a detailed description of the European XFEL SCU project, the reader is referred to Ref. [2]. In Ref. [3] tolerance requirements are studied on the basis of numerical FEL simulations.

The proposed SCU afterburner would be installed directly at the exit of the already existing SASE2 hard x-ray permanent-magnet undulator (PMU) beamline. A total of 6 SCU modules – each with two 2-m-long superconducting undulator coils – would be installed, resulting in a total magnetic length of 24 m.

The high-brightness electron bunches generated in the superconducting linear accelerator of European XFEL enter the SASE2 undulator beamline. Operating as self-amplified spontaneous emission (SASE) FEL, the spontaneous undulator radiation emitted by the electron bunch at the beginning of the undulator initiates the exponential FEL amplification process [4, 5, 6, 7]. During the FEL amplification process, the growing light field acts back on the bunch, generating longitudinal density and energy modulations with the period given by the fundamental light wavelength $\lambda_1 = \frac{\lambda_u}{2\gamma_0^2}\left(1+K^2/2\right)$ (λ_u is the period length of the planar undulator, K the dimensionless undulator parameter, and γ_0 the electron energy in units of $m_e c^2$). As the exponential amplification process comes close to saturation, strong microbunches that can have rich harmonic content are generated. This process is known as non-linear harmonic generation (NHG) [6, 4, 5, 8, 9] and the amount of generated harmonic bunching (at odd and even harmonics) depends on the parameters of the system, including emittance and the slice energy spread [4].

Table 1. Simulation parameters ($h = \lambda_{1,\mathrm{PMU}}/\lambda_{1,\mathrm{SCU}}$).

Parameter	**Value**
electron beam energy	16.5 GeV
initial energy spread	3 MeV
bunch peak current	5 kA
bunch length	1 µm
normalized emittance	0.4 mm mrad
$\langle\beta\rangle$	30 m
SCU operation at harmonic h	$h = 1$ or $h = 2$
undulator period of SCU	18 mm
maximum undulator parameter of SCU	3.06
total magnetic length of SCU system	24 m

The bunched electrons then enter the SCU system which is tuned either to the identical wavelength as the PMU ($\lambda_{1,\mathrm{SCU}} = \lambda_{1,\mathrm{PMU}}$, $h = 1$) or to a harmonic ($\lambda_{1,\mathrm{SCU}} = \lambda_{1,\mathrm{PMU}}/h$, in the present work harmonic $h = 2$). In the former case, the FEL process continues the power growth in the SCU undulator. In the latter case, the second-harmonic bunching generated in the PMU drives coherent emission from the SCU afterburner at its fundamental (which is the second harmonic of the PMU).

2. Simulations

2.1. Description of the Simulation Process

The numerical simulations are done with the FEL simulation code “GENESIS 1.3”, version 2 [10]. The simulation runs are configured, controlled, and post-processed by software based on the OCELOT software package [11, 12]. As the system under study comprises two undulator beamlines with different parameters, two sequential runs are needed: The first run generates the ideal flat-top electron bunch distribution with the initial parameters of the slices compiled in Table 1 and simulates the SASE FEL process in the SASE2 PMU beamline. The resulting phase-space distribution is stored and loaded into the second run (for $h = 2$, an harmonic up-conversion is performed) which simulates the generation of electromagnetic radiation in the SCU afterburner beamline. The light field generated in the first run is only propagated for SCU operation at the fundamental of the PMU. In case the SCU is tuned to the second harmonic of the PMU, the second run starts with an all-zero light field. It can be estimated that the second harmonic power emitted by the FEL in the PMUs is weak; in the SCUs the coherent emission driven by the bunching generated in the PMUs soon exceeds these power levels. The resulting particle distributions and light fields can be retained for further processing.

The simulations described in the present work do not take into account several effects: (i) Energy losses due to synchrotron radiation (SR) in the undulators (SR-induced energy spread is included in the simulations) and wakefields are not taken into account; (ii) the undulators (PMU and SCU) are currently not tapered; (iii) the electron bunch is currently an ideal flat-top distribution with identical slice parameters.

2.2. Simulation Results

Simulations were carried out to study the potential photon performance of the SCUs operating at the fundamental or the second harmonic of the PMUs for the emitted photon energies of

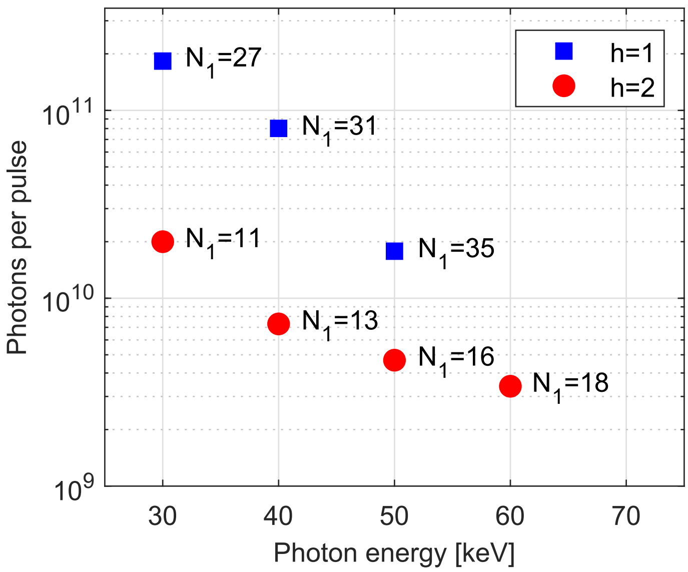

Figure 1. Photons per pulse for the studied operation modes ($h = 1$, squares) and ($h = 2$, circles). Next to the points, the number N_1 of active SASE2 PMUs is indicated. Simulation for SCU with $\lambda_u = 18$ mm and 24 m total magnetic length using the parameters in Table 1 and scaled to 30 fs.

30 keV, 40 keV, 50 keV, and 60 keV (60 keV only $h = 2$). The photon numbers obtained from the simulation were scaled to 30 fs and are indicated in Figure 1. The $h = 1$ operation is indicated with blue squares in Fig. 1. Numerical simulations studying the photon output from the SASE2 PMUs show promising results between 30 keV and 50 keV [13], however FEL lasing at photon energies higher than 30 keV still has to be demonstrated at European XFEL. Operating the SCU afterburner at the second harmonic of the PMUs ($h = 2$, red circles in Fig. 1) relaxes this constraint. In Ref. [2], the number of photons per pulse from typical short-period undulators at the high-energy diffraction-limited storage rings (DLSRs) ESRF-EBS and APS-U is calculated with the code SPECTRA [14] for a 1×1-mm^2 pinhole at 30 m from the source. The SCU afterburner would produce more than two orders of magnitude more photons per pulse, with the pulses being more than 5000 times shorter [2].

For otherwise fixed parameters, the FEL power gain length increases for shorter wavelengths. Therefore also the active PMU length needed to generate the desired electron bunch parameters for $h = 2$ operation depends on the wavelength. Here the number N_1 of active SASE2 PMUs increases from $N_1 = 11$ (30 keV, $h = 2$) to $N_1 = 18$ (60 keV, $h = 2$) out of a total of 35 PMUs available at SASE2 beamline. The active SASE2 PMU length was determined by scanning the number N_1 of active PMUs to optimize the photon output from the SCU afterburner. There are two competing effects: (i) Adding more PMUs increases the average second harmonic bunching until a maximum is reached. (ii) A longer PMU FEL beamline generates more energy spread which in the SCU afterburner eventually reduces the generated bunching because of its R_{56}. For shorter SCU beamlines the optimum N_1 is typically larger. We note that for these simulations the same shotnoise seed was used.

As the PMUs are operating as SASE FEL, a time-resolved study is required because the SASE start-up process results in time-dependent parameters (for instance power of the light field, fundamental and second harmonic bunching, slice energy spread) at the interface to the SCUs. We show simulation results for the SCU afterburner tuned to a photon energy of 40 keV at the second harmonic of the SASE2 PMUs. In Figure 2a, the fundamental bunching (wavelength corresponding to photon energy 40 keV) at the entrance and at the exit of the SCU afterburner is shown. The bunching at the entrance of the SCU afterburner was generated as second harmonic bunching in the SASE2 PMUs operating as FEL at the fundamental photon energy of 20 keV. In this case, at the end of the SCU afterburner the bunching factor in most slices exceeds the

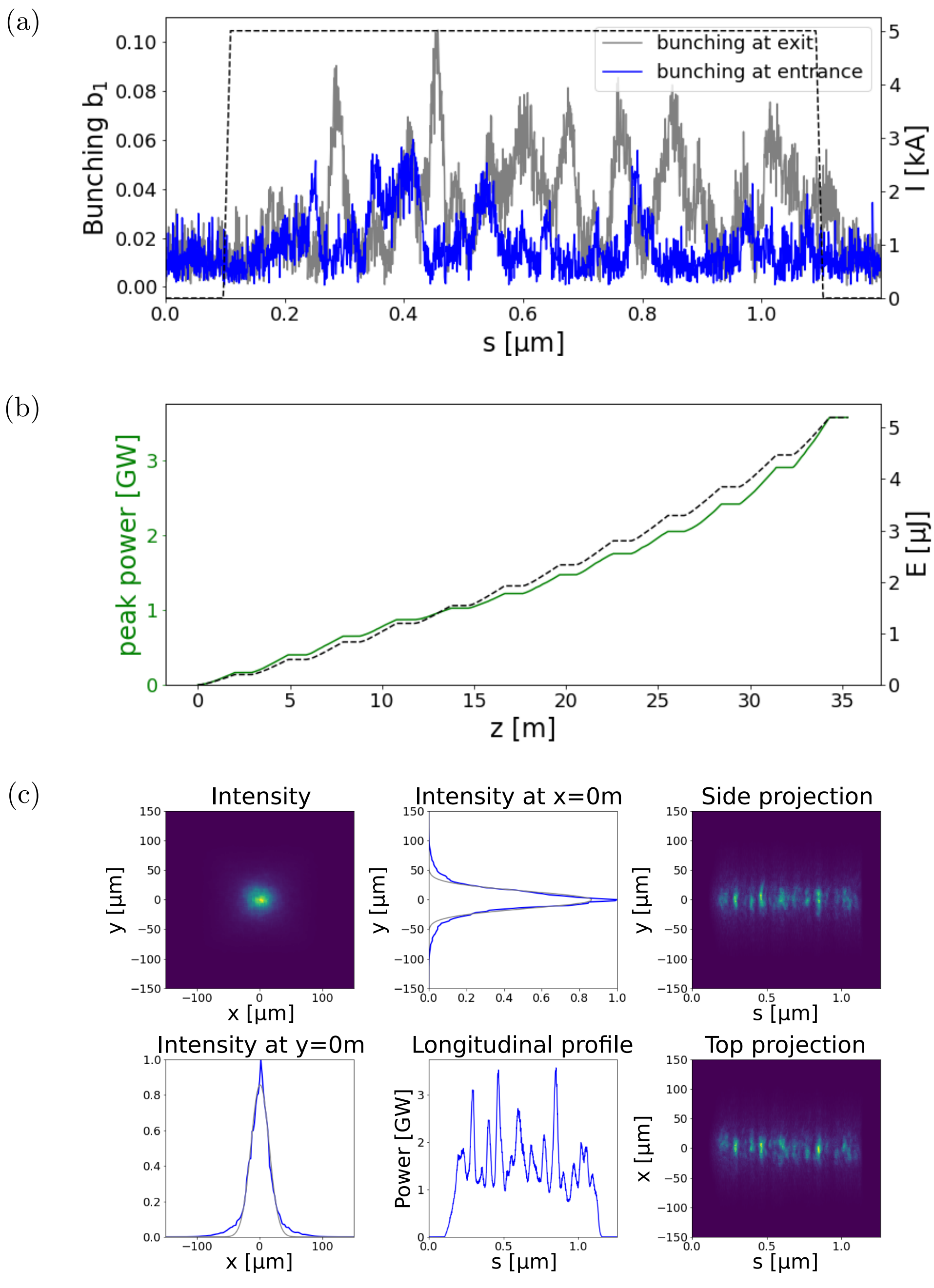

Figure 2. Simulation for SCU afterburner at 40 keV (tuned to second harmonic of SASE2 PMUs). (a) Longitudinal profile of fundamental bunching b_1 at the entrance and the exit of the SCU afterburner. The bunching at the entrance of the SCU afterburner is the result of second harmonic bunching generated in the FEL process in the SASE2 PMUs. The current profile is indicated as dashed line. (b) Evolution of peak power (solid green) and photon pulse energy (dashed, values for 1-µm-long flat-top electron bunch). (c) Transverse intensity profile and lineouts at $x = 0$ m and $y = 0$ m (in blue, Gauss fit in gray) and longitudinal profiles of the generated photon pulse.

initial bunching factor.

The evolution of photon pulse peak power and photon pulse energy (for 1-µm-long electron bunch) is shown in Figure 2b. Finally, the transverse and temporal profiles of the generated photon pulse can be seen in Figure 2c.

2.3. Simulations: Planned Steps

The simulations described in this contribution were performed with version 2 of the FEL code "GENESIS 1.3" [10]. It is planned to add the currently not-included effects to the simulation model.

The new version 4 of "GENESIS 1.3" [15], which is under active development, provides important new functionality such as the so-called "one4one" simulation mode, which tracks the actual electrons instead of macroparticles. This allows to re-slice the electron bunch distribution during manipulation operations, such as harmonic up-conversion, and enables simulation studies of advanced FEL schemes.

Simulations based on version 4 of "GENESIS 1.3" are currently being prepared. As part of this process, we contributed to the development of the code, for instance with functionality facilitating working with the datasets describing electrons and fields, as they can reach considerable slice counts for the very short wavelengths of interest for this project.

3. Conclusions

Numerical simulations were conducted to study the potential photon performance of an SCU afterburner for photon energies in the range from 30 keV to 60 keV, both for operation of the SCU at the same wavelength as the PMUs or at the second harmonic of the PMUs. The number of photons per pulse is more than two orders of magnitude higher (in pulses more than 5000 times shorter) than that computed for the parameters of typical short-period undulators at high-energy diffraction-limited storage rings [2]. We plan exploring the parameter space to increase the photon energy to even higher values.

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