ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP061

SUPER-X: SIMULATIONS FOR EXTREMELY HARD X-RAY GENERATION WITH SHORT PERIOD SUPERCONDUCTING UNDULATORS FOR THE EUROPEAN XFEL

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Abstract

The European XFEL is a high-repetition multi-user facility with nominal photon energy range covering almost 3 orders of magnitude: 250 eV - 25 keV. In this work we explore the possibility to extend the photon energy range of the facility up to 100 keV via combination of superconducting undulator technology, period doubling and harmonic lasing, thus allowing for excellent tunability. To this purpose, we propose a dedicated FEL line, discuss its overall concept and provide analytical and numerical estimations of its expected performance.

INTRODUCTION

The European XFEL first lased in 2017 [1] and can currently sustain simultaneous operation of three separate FEL lines, SASE1, SASE2 and SASE3 [2]. One distinctive trait of the facility is its high-energy, supercounducting linear accelerator reaching up to 17.5 GeV and up to 27000 pulses per second distributed in 10 macrotrains with an intra-train repetition rate up to 4.5 MHz. In the mid-term, two novel FEL lines will be installed in two already available empty tunnels [3] and possibly, in the longer term, a second fan of FEL tunnels will be excavated [4]. The high electron energy strongly hints at the possibility of generating extremely hard X-ray pulses well beyond the nominal 25 keV with an ad-hoc superconducting FEL undulator line that we call Super-X. In this paper we explore Super-X up to the 100 keV range. We assume -from the very beginning- the use of a nominal electron beam as is, from start-to-end simulations, at the entrance of the SASE1 undulator, i.e. not spoiled by collective interactions or wakes during the transport to different undulator lines. Superconducting undulators (SCU) can produce, with respect to permanet magnet ones, for the same period length and vacuum gap a higher peak field on axis. This allows to increase the photon energy range as well as the flux. Superconducting technology allows period doubling using a single magnetic structure. Period doubling further increases the photon energy tunability [5–8]. Although other technical realizations of super-hard X-ray FEL lines have been positively assessed [9], Super-X is an appealing option for reaching lasing at ultra-high photon energies with a large tunability range considering SASE and additional advanced FEL schemes discussed in this contribution.

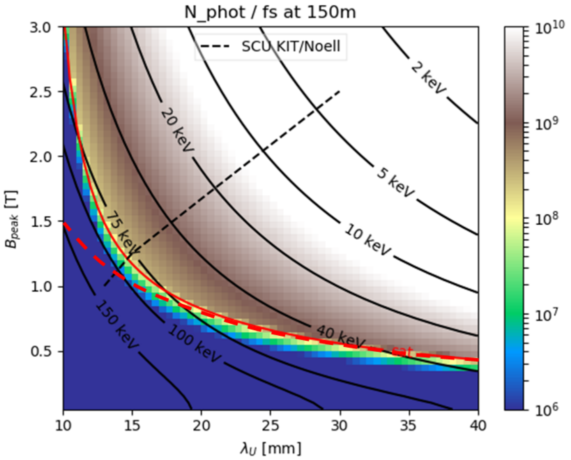

Figure 1: Estimated performance of a SCU XFEL line. The black dotted line shows the state-of-the-art magnetic field achievable for a 5 mm vacuum gap. The red solid and dashed lines refer to FEL saturation, the dashed line excluding quantum fluctuations effects.

ANALYTICAL ESTIMATIONS

We envision a SCU system with a geometrical length of 150 m, which fits conservatively the empty tunnels currently available at the European XFEL [3], and a filling factor of about 80%. In order to study the relevant parameter space we parametrized the 3D gain length according to [10, 11], which provide two alternative methods to estimate the FEL performance. We fixed, as just described, a total setup length of 150 m, assumed a flat-top electron beam with a current of 5 kA, an energy of 17.5 GeV, a normalized slice emittance of 0.4 mm mrad, an rms energy spread of 1 MeV and average betatron functions around 30 m. Using [10,11] we estimated the number of photons per femtosecond duration of the electron bunch as a function of on-axis peak magnetic field and undulator period, for different photon energies. We validated our estimations with time-dependent FEL simulations performed with Genesis [12] and Simplex [13]. Results are shown in Fig. 1. The black dotted line refers to the maximum magnetic field in reach of state-of-the-art SCU assuming a

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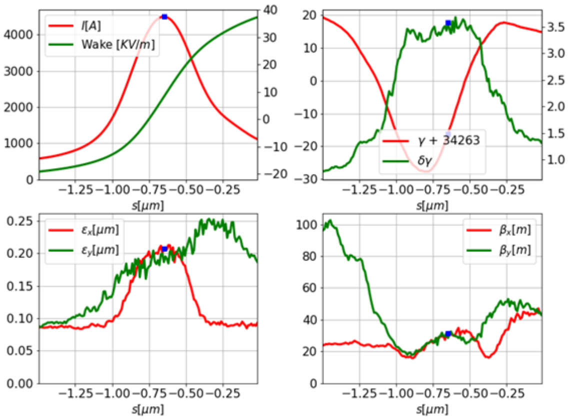

Figure 2: Simulated 20 pC nominal electron bunch at the entrance of SASE1.

vacuum gap of 5 mm [5], and defines the minimum achievable photon energy. The crossing of the continuous red line with the continuous black lines (which specify a certain photon energy) shows the period length at which saturation can be achieved for the setup considered here. When quantum diffusion of energy spread is ignored, see [14], the red dashed line must be used instead. This preliminary analysis shows that an acceptable number of photons of about 10^9 per femtosecond length of the radiation pulse can be reached for periods between 15 mm and 20 mm, at photon energies in the 100 keV range near saturation.

SIMULATIONS

We followed up analytical estimations with more detailed FEL simulations.

For the electron beam we used both simplified models and start-to-end simulations. The radiation output depends considerably on the electron beam quality. In Fig. 2 we show an example of a start-to-end simulation for the electron beam performed for a 20 pC bunch, where the emittance is smallest, at the entrance of SASE1. Compared to the model beam considered in the previous section, here the normalized emittance is decreased from 0.4 mm mrad to 0.2 mm mrad.

We assumed an undulator period of 18 mm. The impact of random undulator field errors was included by adding, every half period, random deviations from the design field with a relative rms of 0.15%, corresponding to the half of those measured in the KIT-Noell undulator operating in the KIT synchrotron [15] and corrected the field integrals. Such tolerance reduction allows one to obtain radiation power levels comparable to those of an ideal undulator (Fig. 3). Otherwise, field errors can be efficiently dealt with by compensating the added path with phase shifters. Figure 4 shows the Wigner distribution function and its marginals (power and spectral profiles). The total photon yield is of about $9 \cdot 10^8$ photons.

Here we assumed a 5 mm vacuum gap, and the presence of resistive wakes alters the Wigner distribution significantly. In first approximation, because of wakes, different parts

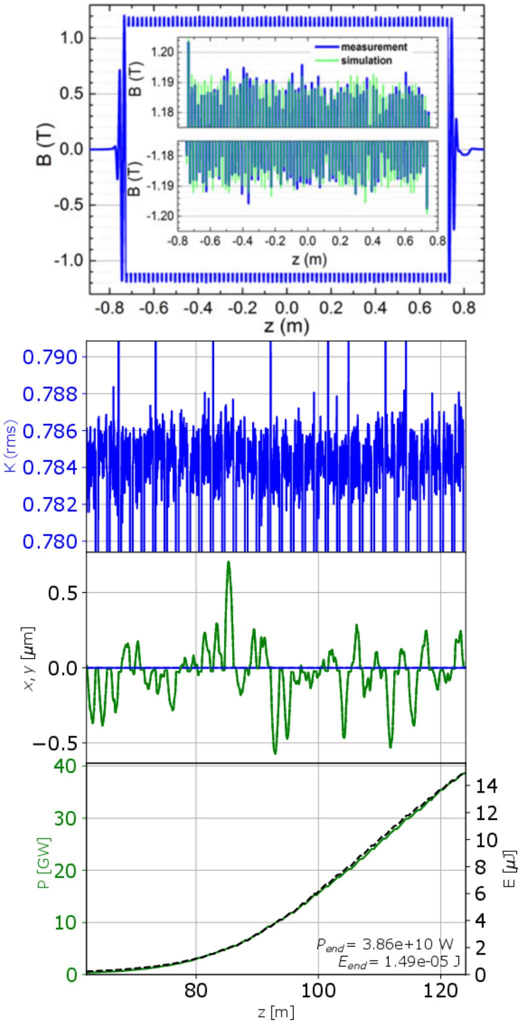

Figure 3: Top subplot: measured magnetic field errors of the existing U20 undulator (reproduced from reference [15] under the Creative Commons Attribution License (CCBY) 4.0 license). Bottom subplot: undulator K value calculated period-wise assuming half the RMS value of the measured errors, electron beam trajectory in such undulator and radiation power growth.

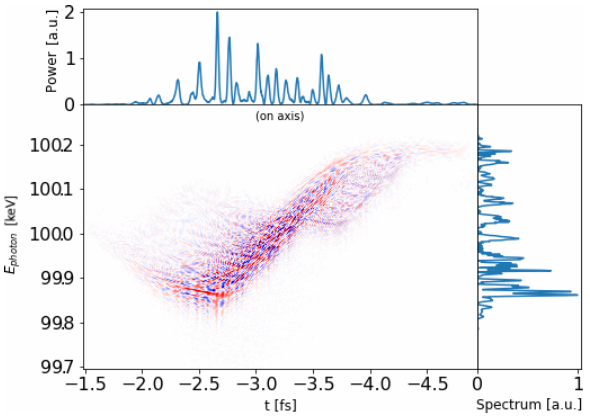

Figure 4: Wigner distribution and its marginals for the start-to-end electron bunch in Fig. 2. Resistive undulator wakes and field errors are included in the simulations (see text).

of the electron beam loose energy at different rates, e.g. wakes are responsible for a change in the electron beam chirp along the undulator. However, only one energy loss rate can be compensated via linear undulator tapering. In this way, longitudinal wakefields limit the maximum duration of the lasing window and their effect cannot be ignored. The combined effects of initial electron energy chirp and resistive wakes ”tilt” the Wigner distribution, thus increasing the spectral bandwidth.

Finally, transverse coherence was found to deteriorate considerably, down to a degree of about 60%. This value strongly depends on the electron beam characteristics. For example, an increase in emittance from 0.2 mm mrad to 0.4 mm mrad would yield a further decrease of the degree of coherence to about 20%.

SPECIAL MODES OF OPERATION

One peculiar option of SCUs is the possibility of doubling the period, by changing the current direction in a subset of the windings [16]. This allows for switching between e.g. 18 mm and 36 mm using the same magnetic structure. By this, the spectral reach of the SCU is substantially increased, see Fig. 1 and allows for tuning the setup between a few keV and around 100 keV. Such large tunability range will enable advanced lasing schemes and can be also beneficial to facilities designed to operate a single undulator line for diverse experiments. Period doubling would also enable self-seeding operation at high energies. One may, in fact, seed at around 15 keV using the doubled period and subsequently tune part of the radiator at a higher harmonic.

If the European XFEL will enable CW operation [17, 18], the maximum electron beam energy will be decreased, possibly down to 7.8 GeV. Then, the SCU line could allow reaching photon energies between 10 keV to 20 keV with a period of 18 mm, and between 2 keV and 10 keV with the doubled 36 mm period.

Finally, the implementation of an SCU line would allow, for a particular choice of undulator period around 20 mm, to take better advantage of Harmonic Lasing (HL) [19]. Figure 5 shows the ratio of the gain lengths of HL at the 3rd harmonic (assuming the HL undulator period λ_u as a free parameter) and of a 20 mm period SCU operating at fundamental. 3D effects and quantum fluctuations are taken into account. One can see that a 40 mm period undulator, lasing with optimised 3rd harmonic cannot compete with the 20 mm SCU operating at the fundamental, moreover the HL method applied to the SCU, i.e. at 20 mm period, can clearly bring an advantage.

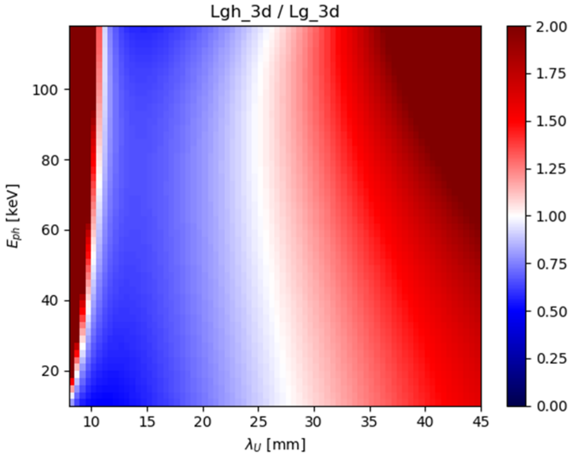

Figure 5: Ratio of the gain length for the HL setup to that of a 20 mm-period SCU operating at fundamental.

CONCLUSIONS

We discussed the concept of Super-X, a dedicated ultra hard X-ray SCU FEL line for the European XFEL. The use of SCUs allows for wide photon energy tunability: in particular, exploiting the period doubling option, one could continuously reach the range spanning from a few keV up to around 100 keV. Moreover, in case a CW mode of operation would be enabled at the European XFEL, SCUs could be the only way to reach into the 20 keV range. Here we estimated the expected performance of a 150 m-long FEL line for the European XFEL, with the help of known parametrizations [10, 11] benchmarked with Genesis and Simplex. Around 100 keV, a European XFEL-class, fresh electron bunch would yield around 10^9 photons per femtosecond with low transverse coherence. At those photon energies the photon beam characteristics were found to strongly depend on the electron beam characteristics and on the photon energy itself. Electron beam energy chirps and resistive undulator wakefields are expected to substantially modify the FEL beam Wigner distribution effectively yielding an increase in the radiation bandwidth. Random period-wise field errors can be efficiently dealt with by correcting the field integrals and compensating the added path with phase shifters. Moreover, the use of harmonic lasing becomes beneficial around a choice of 20 mm period, while period doubling would allow self-seeding at a subharmonic of the target photon energy (for example, self-seeding at 15 keV with a target energy of 30 keV).

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