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A pre-series prototype for the superconducting undulator afterburner for the European XFEL

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Abstract. We propose to develop, characterize and operate a superconducting undulator (SCU) afterburner consisting of 5 undulator modules (1 module = 2 SCU coils of 2 m length and 1 phase shifter) plus a pre-series prototype at the SASE2 hard X-ray beamline of European XFEL. This afterburner will produce an output in the order of 10^{10} ph/pulse at photon energies above 30 keV. The project is divided into the production of a pre-series prototype module and a small-series production of 5 modules. Central goals of this R&D activity are: the demonstration of the functionality of SCUs at an X-ray FEL, the set up of the needed infrastructure to characterize and operate SCUs, the industrialization of such undulators, and the reduction of the price per module. In this contribution, the main parameters and specifications of the pre-series prototype module are described.

1. Superconducting undulator afterburner

The European XFEL (EuXFEL) plans to develop the technology of superconducting undulators (SCUs) as part of its facility development program. Superconducting undulator technology enables, for the same period length and vacuum gap, about a three-times stronger magnetic field, in comparison to the permanent-magnet undulators (PMUs) currently used at the EuXFEL facility. The use of SCUs will improve the performance and flexibility of the EuXFEL FEL sources, both in terms of reach towards higher photon energies and in terms of tuning range of an individual FEL undulator.

The benefits of SCUs R&D for the EuXFEL strategic plans are manifold: 1) Enabling lasing at very high photon energies towards 100 keV, fully exploiting the capability of the FEL linac with the highest electron beam energy worldwide [1]. FEL lasing at such photon energies will enable new types of experiments and thereby open the access to new scientific applications of FEL radiation [2]. 2) Enhancing the tunability range up to a factor of ten for future soft X-ray SASE (self-amplified spontaneous emission) lines, allowing to cover the complete photon energy range offered by the present soft X-ray experiments at EuXFEL with the same electron beam energy. 3) The continuous-wave (CW) operation mode upgrade under consideration at the EuXFEL limits the electron beam energy to 7-8 GeV. In this case, a SASE SCU line allows to cover the same photon energy range as provided now by the installed PMUs with higher electron beam energies (up to 17.5 GeV).

A SCU afterburner is proposed for SASE2, which is one of the hard X-ray undulator lines. Before the small-series production of five modules, a pre-series prototype module (S-PRESSO) will be produced and installed in the EuXFEL, for a total of six SCU modules as sketched in Fig. 1. Each module will contain two 2 m long undulator coils, horizontal and vertical correctors at the exit of the first set of SCU coils and at the entrance of the second set of SCU coils, as well as a phase shifter (see Fig. 1). Each module is 5 m long, as the presently installed PMUs. This allows to use the same room temperature intersections with focusing quadrupoles, phase shifters and electron beam diagnostics, as in the present undulator lines. Two horizontal and vertical correction coils, placed at the beginning and at the end of the intersection, will also be employed. All modules will be cooled with cryocoolers. An RF gate valve will be used to separate the PMU line from the SCUs, so that when warm up of one SCU will be needed, i.e. for maintaining the cryocoolers, the vacuum chamber in the PMU line does not need to be vented. Absorbers are needed all along the undulator line to prevent synchrotron radiation from the upstream undulators to heat the vacuum chambers downstream. The absorbers in the intersections along the PMU line have an aperture of 8 mm diameter, while the ones along the SCU afterburner, including the one after the last PMU, will have one of 4 mm. The diameter of the absorbers in the SCU sections is reduced since, while the vacuum chamber of the PMU has a vertical vacuum gap of 8.6 mm, the SCUs will have 5 mm.

In order to characterize the magnetic field of the modules of the SCU afterburner two setups are being developed: SUNDAE1 and SUNDAE2 (Superconducting UNDulator Experiment) [3, 4]. SUNDAE1 is a vertical cryostat, which will serve for training of the up to 2 m long SCU coils and for measurement of the magnetic field distribution with a Hall probe in liquid (4 K) or superfluid helium (2 K). SUNDAE2 is a measurement system to characterize the magnetic field of the complete SCU module. The moving wire is foreseen to measure the field integrals. To characterize the magnetic field profile along the magnetic axis a Hall probe moving on a sledge and the pulsed wire method are being developed and will be applied [4, 5].

The potential photon performance of the six SCU afterburner modules is addressed in detail

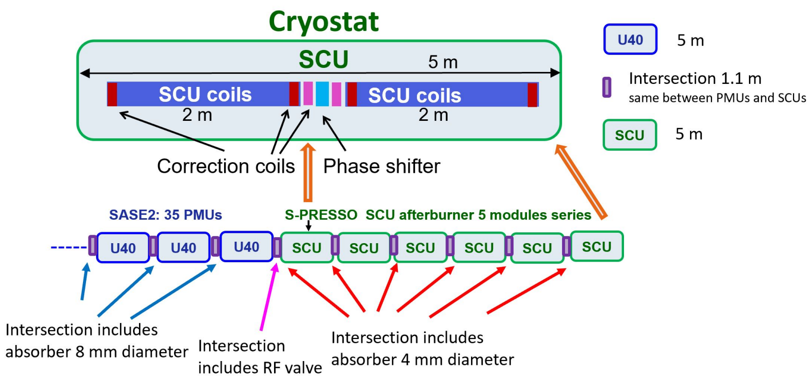

Figure 1. Sketch of the SCU afterburner after SASE2 (bottom) and of one SCU module (top).

in Ref. [6] and it is presented in Figure 2. The expected range of photons per pulse reachable is shown in the dashed violet area and violet line. The upper limit (violet squares) considers the SCUs tuned to amplify the output of the fundamental frequency of SASE2 from a number N_1 PMUs of the SASE2 undulator line. Simulation studies on the output of the fundamental of the SASE2 PMUs show promising results between 30 and 50 keV [7]. Lasing with the PMUs above 30 keV has not yet been experimentally demonstrated at EuXFEL, which means that reaching the upper limit might be challenging, and above 50 keV is out of range for the PMUs. The lower

Table 1. Electron beam parameters at EuXFEL used to calculate the photons per pulse generated by the SCU afterburner

Energy	16.5 GeV
Normalized emittance	0.4 mm mrad
Initial energy spread	3 MeV
Current	5 kA
Bunch length	30 fs

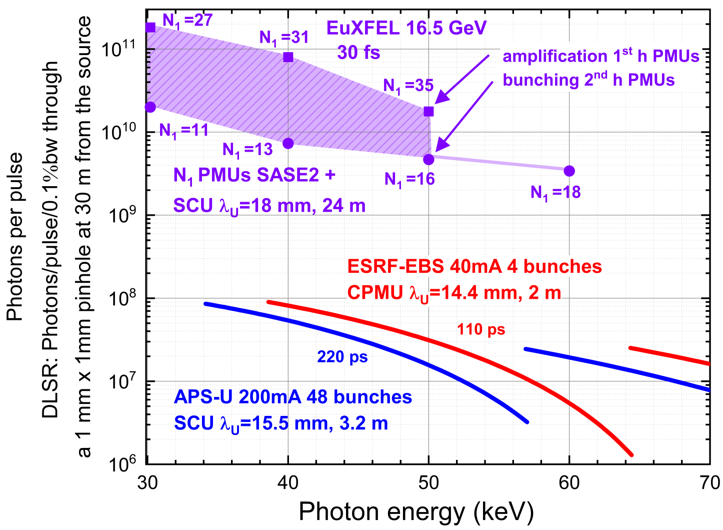

Figure 2. Photons per pulse generated by the afterburner, made of six SCU modules with 18 mm period length and a magnetic length of 24 m, are shown as a function of the photon beam energy. The calculation has been done using the code GENESIS 1.3 v.2 [8], with the electron beam parameters shown in Table 1. The number of photons per pulse are compared to the one calculated using SPECTRA [9] from typical short period undulators at the ESRF-EBS [10] and APS-U [11] through a pinhole of 1 mm × 1 mm at 30 m from the source.

limit (violet circles) is obtained by using the bunching of the second harmonic generated in N_1 PMUs. The SCUs are tuned to the second harmonic of the PMUs. In this scheme, primarly the bunching of the second harmonic of the PMUs is used to obtain an efficient amplification of the fundamental of the SCUs. This scheme can be extended to photon energies larger than 50 keV. The photons per pulse generated by the SCU afterburner are calculated using the code GENESIS 1.3 v.2 [8], with the electron beam parameters shown in Table 1, and are reported in Figure 2 as a function of the photon beam energy. The simulations do neither consider wakefields nor tapering. A flat top 1 μm long bunch ($\sim$ 3 fs) is considered and the photons for a pulse of 30 fs, reported in Figure 2, are obtained by the number resulting from the simulations multiplied by a factor of 10. More detailed studies considering wakefields, tapering, a more realistic bunch distribution and optimized electron bunch properties are ongoing. The photons per pulse are compared to the ones calculated using SPECTRA [9] from typical short period undulators at high energy diffraction limited storage rings (DLSRs) as the ESRF-EBS [10] and APS-U [11] through a pinhole of 1 mm × 1 mm at 30 m from the source. The number of photons per pulse produced by the afterburner are more than two orders of magnitude higher than the ones available at the DLSRs as ESRF-EBS and APS-U, in pulses more than 5000 times shorter. Additional schemes for amplifying and/or using the bunching of the higher harmonics produced by the SASE PMUs and to reach higher photon energies are under study. The degree of transverse coherence of the flux produced by the SCU afterburner at European XFEL is also expected to be larger than the one obtainable at DLSRs.

2. S-PRESSO

With S-PRESSO we aim to test the alignment of the two 2 m long SCU coils in the 5 m long cryostat, the mechanical tolerances necessary for the FEL process and the implementation of the module in the accelerator. S-PRESSO will be used to amplify the fundamental frequency produced by the PMUs of SASE2 in the hardest part of the X-ray spectrum which they can generate. In this configuration it will be possible to measure the contribution of the SCUs to the FEL amplification process at specific photon energies. Moreover, harmonic configuration tests at larger photon energies, as described in Section 1, are planned.

The main parameters of S-PRESSO are summarized in Table 2. A study of the magnetic performance of the SCU coils has been made using a rectangular NbTi wire with cross section of 0.45 x 0.75 mm^2 (insulated 0.5×0.8 mm^2), non annealed ARMCO as yoke material, and a magnetic gap of 6 mm. In order to cover photon energies above about 25 keV with 16.5 GeV electron beam energy, a period of 18 mm has been chosen. With the geometry shown in Figure 3, 6 windings per layer and 15 layers per groove, a peak field on axis of 1.82 T is obtained, considering operating at a temperature of 4.2 K with 1 K temperature margin. S-PRESSO will be cooled with cryocoolers and the SCU coils are expected to reach temperatures below 4.2 K, therefore increasing the temperature margin considered above. The magnetic simulations have been performed with FEMM [12]. Space is left on top of the groove for possible racetrack shimming coils wound around one pole with a thin NbTi superconducting wire of about 0.25 mm diameter (see Figure 3). Shimming with a current of 10 A in the wire enables a correction on the peak field of more than 1%. Ten power supplies for the shimming coils are foreseen. One power supply can feed more than one shimming coil. A study on the expected photon performance with a $\Delta K/K < 0.0015$ and the corresponding mechanical accuracies is presented in Ref . [13]. We expect to be able to reach the needed accuracies < 50 μm without adding local shimming coils [14]. However, in case needed, shimming coils will be added, as shown in Figure 3. A possible design for the superconducting phase shifter is presented in Ref. [15]. The field integrals are limited by the transverse dimensions and divergence of the electron beam. The strict limit on the value of the roll-off $= |B(x = \pm 2mm - B(x = 0mm)|/|B(x = 0mm)|)$ is determined by allowing measurable shifts of the coils of the order of 50 μm along all three axes, being the shifts caused by possible misalignments of the two sets of SCU coils inside the cryostat. The allowed misalignment between the two 2 m long coils in order to keep the error budget contribution to K negligible, such that $\Delta K/K < 0.0015$ for each set of SCU coils, is shown in Figure 3.

Table 2. Main Parameters of S-PRESSO

Period	18 mm
Peak field	1.82 T
K	3.06
Vacuum gap	5 mm
First field int. (x,y)	$< 4 \times 10^{-6}$ T m
Second field int. (x,y)	$< 10^{-4}$ T m^2
$\Delta K/K$ rms	< 0.0015
Roll off at ± 2 mm	$< 5 \times 10^{-5}$
Beam heat load	10 W

The total budget for the beam heat load is 10 W. In order to screen the vacuum chamber walls from the synchrotron radiation from the upstream undulators, an appropriate absorber has to be installed. The synchrotron radiation of the upstream undulators simulated with SPECTRA [9] is used as input in the ray tracing program BDSIM [16]. The results show that

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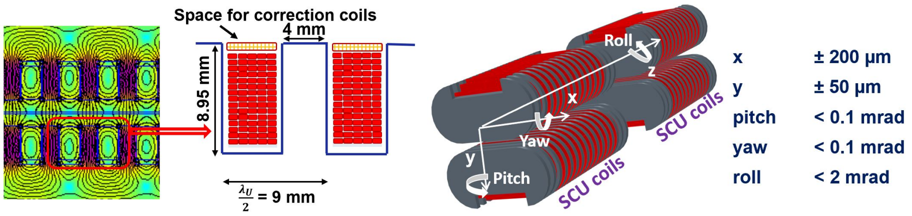

Figure 3. Left: FEMM simulations of the 18 mm period SCU coils. The magnetic flux lines are indicated. The color scales with the absolute value of the magnetic flux density (magenta highest to cyan). Middle: Geometry of the SCU coils: the wire of the main coils (red) and the shimming coils are shown. Right: Sketch of the two SCU coils with the reference axes and angles, and the maximum allowed misalignment between them.

an absorber of 4 mm diameter installed after the SASE2 PMUs line completely screens the S-PRESSO vacuum chamber walls from the synchrotron radiation of the SASE2 PMUs. The exact geometry and position of this absorber are under study. This is required to limit the heat load contributions coming from the scattered particles at the absorber, which might go through the vacuum chamber walls and hit the SCU coils, well below 1 mW. The beam heat load due to resistive wall heating is calculated for a copper pipe with 5 mm diameter considering the extreme anomalous skin effect [17], which holds for the very short bunches of EuXFEL. For 2700 bunches at 10 Hz, and a bunch charge of 250 pC , the bunch profile plotted in Figure 4, and a surface with an oxide layer of 20 nm and 1000 nm roughness a maximum heat load of 2.2 W/m is obtained. Being the cold vacuum chamber at 10-20 K about 4.5 m long, the total budget of 10 W is not exceeded. Figure 4 also shows the energy change per meter for a copper pipe with 5 mm diameter and a surface, without oxide layer and flat (black line, 1 W/m), with an oxide layer of 5 nm and 300 nm roughness (red line, 1.4 W/m), with an oxide layer of 5 nm and 1000 nm roughness (green line, 1.8 W/m), and with an oxide layer of 20 nm and 1000 nm roughness, the last one being the worst case for a non passivated surface [18, 19]. For 1 nC bunch charge, the bunch is longer, and to limit the beam heat load below 10 W, runs with about half of the bunches, that is 1350 at 10 Hz, will be permitted. The budget of 10 W is an upper limit, since normally the 2700 bunches at 10 Hz are shared between three SASE lines. The beam heat load due to geometric impedance is neglected since the vacuum chamber cross section will be constant. RF bellows are foreseen at 300 K: steps less than 0.1 mm are required to limit the beam heat load to below 0.2 W for 250 pC and 1 nC with respectively 2700 and 1350 bunches at 10 Hz.

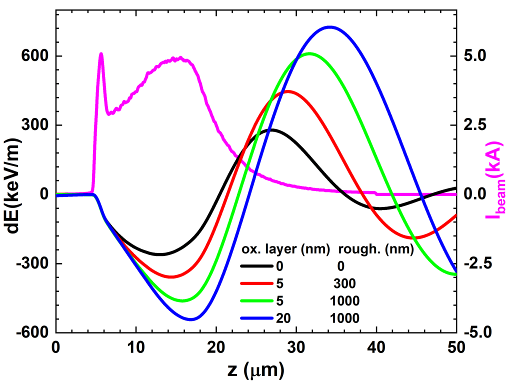

Figure 4. Current profile of the electron bunch for a charge of 250 pC (magenta line). Energy change per meter for a copper pipe with 5 mm diameter and a surface, without oxide layer and roughness (black line, 1 W/m), with an oxide layer of 5 nm and 300 nm roughness (red line, 1.4 W/m), with an oxide layer of of 5 nm and 1000 nm roughness (green line, 1.8 W/m), and with an oxide layer of 20 nm and 1000 nm roughness (blue line, 2.2 W/m).

3. Conclusions
As a first step for an afterburner to be installed at SASE2, which will be a unique photon source worldwide (Fig. 2), a pre-series SCU module, S-PRESSO, has been specified. The contract is assigned to Bilfinger Noell GmbH. S-PRESSO will be installed and tested at the end of SASE2. The overlap at high photon energies with the PMUs of the SASE2 line will allow to study the efficiency of the FEL process in the S-PRESSO above 25 keV. To reach even higher photon energies, additional configurations using higher harmonics of the PMUs are under study.

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