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# TOWARDS A 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 five undulator modules (1 module = 2 times SCU coil of 2 m length and 1 phase shifter) at the SASE2 hard X-ray beamline of European XFEL. This afterburner has the potential to produce an output of more than $10^{10}$ 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 five modules. Central goals of this R&D activity are: the demonstration of the functionality of SCUs at a 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 (S-PRESSO) are described.

## INTRODUCTION AND MOTIVATION

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 allow to 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, especially in the area of material sciences with a focus on new energy technologies. 2) Enhancing the tunability range up to 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 would limit the electron beam energy to 7-8 GeV. In this case a SASE SCU line would allow to cover the same photon energy range as provided now by the installed PMUs with higher electron beam energies (up to 17.5 GeV).

An SCU afterburner consisting of five undulator modules, as sketched in Fig. 1, is proposed for SASE2. 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 inset of 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.

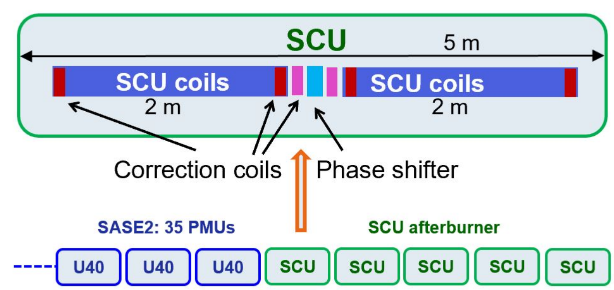


Figure 1: Sketch of the SCU afterburner after SASE2 (bottom) and of one SCU module (top).

Before the small-series production of five modules, a pre-series prototype module (S-PRESSO) will be produced and installed in the EuXFEL. Aims of S-PRESSO are 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.

While for the afterburner modules a 2 K cryoplant is under consideration, in order to test this first device with electron beam a cooling scheme based on cryocoolers is planned.

S-PRESSO will be used to amplify the fundamental produced by the PMUs of SASE2 in the hardest X-ray part of the 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 are planned.

The projected photon performance of the five modules of the SCU afterburner is presented in Fig. 2. The SCUs

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further amplify on their fundamental, the output of the fundamental of SASE2. Here, the photons per pulse generated by the SCU afterburner at two different period lengths of 15 mm and 18 mm calculated using the code GENESIS 1.3 v.2 [2], with the electron beam parameters shown in Table 1, are reported as a function of the photon beam energy. The photons per pulse are compared to the ones calculated using SPECTRA [3] from typical short period undulators at high energy diffraction limited storage rings (DLSRs) as the ESRF-EBS [4] and APS-U [5] through a pinhole of 1 mm × 1 mm at 30 m from the source. The 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. The simulations do not consider wakefields, synchrotron radiation losses and tapering. At higher photon energies the SCU afterburner will still be tuned on its fundamental. Schemes for amplifying and/or using the bunching of the higher harmonics produced by the SASE PMUs are under study. The degree of transverse coherence of the flux produced by the SCU afterburner at European XFEL is also about an order of magnitude larger than the one obtainable at DLSRs.

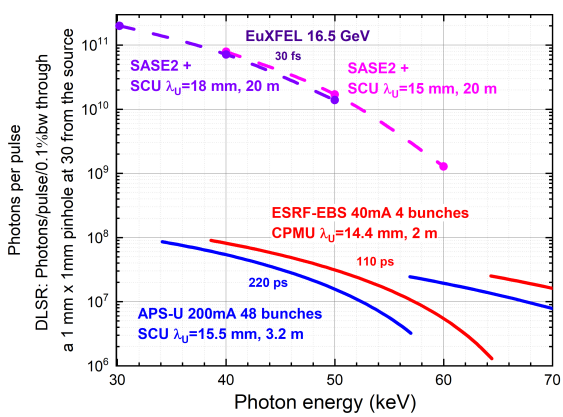


Figure 2: Photons per pulse generated by the afterburner, made of five SCU modules with both 15 and 18 mm period length and a magnetic length of 20 m, are shown as a function of the photon beam energy. The calculation has been done using the code GENESIS 1.3 v.2 [2], with the electron beam parameters shown in Table 1. The photons per pulse are compared to the ones calculated using SPECTRA [3] from typical short period undulators at the ESRF-EBS [4] and APS-U [5] through a pinhole of 1 mm × 1 mm at 30 m from the source.

## SCU COILS LAYOUT

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, 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 Fig. 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. The magnetic simulations have been performed with FEMM [6]. Space is left on top of the groove for possible shimming coils wound with a thin NbTi superconducting wire of about 0.25 mm diameter. Shimming with a current of 10 A in the wire, a correction on the peak field of more than 1% can be obtained.

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 |

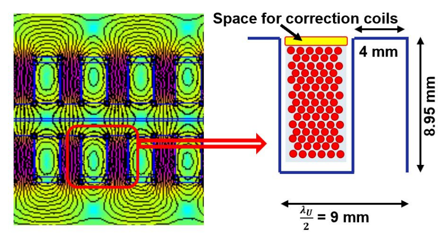


Figure 3: Left: FEMM simulations of the 18 mm period SCU coils. The magnetic flux lines are indicated. The color scales with the absolute value of the magnetic flux density (magenta highest to cyan). Right: Geometry of the SCU coils: the red circles represent the wire in the groove.

To improve the performance at higher photon energies (see Fig. 2), shorter periods down to 15 mm should be considered. With a similar geometry as the one shown in Fig. 3, 5 windings per layer and 15 layers per groove, a peak field on axis of 1.77 T is obtained considering operating at a temperature of 2 K with 1 K temperature margin. With 16.5 GeV electron beam energy, a minimum photon energy of 42.3 keV is reached.

## S-PRESSO

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 main parameters of S-PRESSO are summarized in Table 2. A study on the expected photon performance with a $\Delta K/K < 0.0015$ and the corresponding mechanical accuracies are presented in Ref. [7]. We expect to be able to reach the needed accuracies < 50 µm without adding local shimming coils. However, in case needed, shimming coils will be added, as shown in Fig. 3. A possible method to be applied to characterize the magnetic field of the coils is the pulsed wire currently developed at EuXFEL for long undulators with short periods [8].

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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) | $< 1.5 \times 10^{-4}$ T m |
| Second field int. (x,y) | $< 10^{-4}$ T m$^2$ |
| $\Delta K/K$ rms | <0.0015 |
| Roll off at $\pm 2$ mm | $< 5 \times 10^{-5}$ |
| Beam heat load | 10 W |

The field integrals are limited by the transverse dimensions and divergence of the electron beam. The strict limit on the roll-off value (roll-off = $|B(x = \pm 2$ mm - B(x= 0 mm)|/|B(x= 0 mm)|) 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 Fig. 4.

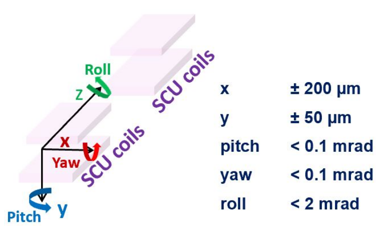


Figure 4: Sketch of the two SCU coils with the reference axes and angles, and the maximum allowed misalignment between them.

A possible design for the phase shifter is presented in Ref. [9]. Both physical and magnetic lengths need to be minimized. In the proposed design, the physical length is 90 mm and the magnetic length 80 mm (the magnetic length includes all magnetic fields except for $< 1.5 \times 10^{-4}$ T m of first field integral at each end of the phase shifter).

In order to screen the vacuum chamber from the synchrotron radiation from the upstream undulators, an appropriate absorber has to be installed. Ray tracing results show that an absorber of 4 mm diameter installed after the SASE2 PMUs line completely screens the S-PRESSO vacuum chamber from the synchrotron radiation of the SASE PMUs. The exact geometry and position of this absorber are under study. This is needed to eliminate heat load contributions coming from the scattered particles at the absorber, which might go through the vacuum chamber and hit the SCU coils.

The pressure of the beam vacuum at room temperature should be $< 10^{-7}$ mbar.

The beam heat load due to resistive wall heating is calculated considering the extreme anomalous skin effect [10],

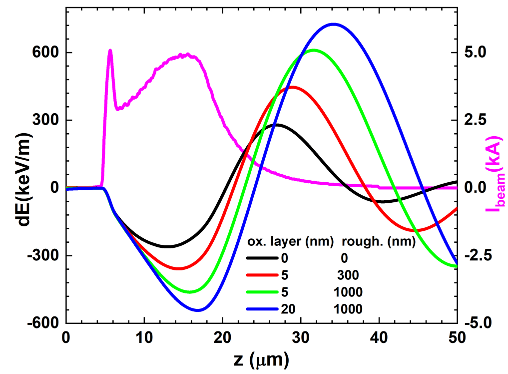


Figure 5: Current profile of the electron bunch for a charge of 250 pC (magenta line). Energy change per meter for a copper pipe with 5 mm diameter and a surface, without oxide layer and roughness (black line), with an oxide layer of 5 nm and 300 nm roughness (red line), with an oxide layer of of 5 nm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

which holds for the very short bunches of EuXFEL. For 2700 bunches at 10 Hz, and a bunch charge of 250 pC and the bunch profile plotted in Fig. 5, a heat load of 2 W/m is obtained. Figure 5 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), with an oxide layer of 5 nm and 300 nm roughness (red line), with an oxide layer of 5 nm and 1000 nm roughness (green line), and with an oxide layer of 20 nm and 1000 nm roughness (blue line), the last one being the worst case for a non passivated surface [11, 12]. As an upper limit, a total heat load of 10 W is considered for the 5 m long vacuum chamber. 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 10 W are 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 between 50 K and 300 K: steps less than 0.1 mm are required to limit the beam heat load to below 0.2 W for both cases of 250 pC and 1 nC with respectively 2700 and 1350 bunches at 10 Hz.

## CONCLUSIONS

As a first step for an afterburner to be installed at SASE2, which will be a unique photon source worldwide (see Fig. 2), a pre-series SCU module, S-PRESSO, is under study at EuXFEL. S-PRESSO will also be installed 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 SASE FEL process in the S-PRESSO, and compare it to the one of the PMUs between 25 keV and 60 keV. To reach even higher photon energies than 60 keV, additional configurations using higher harmonics of the PMUs are under study.

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## REFERENCES


[1] W. Decking *et al.*, "A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator", *Nature Photonics*, vol. 14, no. 6, pp. 391–397, May 2020. doi:10.1038/s41566-020-0607-z

[2] S. Reiche, "GENESIS 1.3: A fully 3-D time dependent FEL simulation code", *Nucl. Instrum. Meth. A*, vol. 429, no. 1–3, pp. 243–248, Jun. 1999. doi:10.1016/s0168-9002(99)00114-x

[3] T. Tanaka and H. Kitamura, "SPECTRA: a synchrotron radiation calculation code", *J. Synchrotron Radiation* vol. 8, no. 6, pp. 1221–1228, Oct. 2001. doi:10.1107/s090904950101425x

[4] EBS Storage Ring Technical Report, https://www.esrf.fr/files/live/sites/www/files/about/upgrade/documentation/Design%20Report-reduced-jan19.pdf

[5] Advanced Photon Source Upgrade Project, "Final Design Report", Argonne National Lab., Lemont, IL, USA, Rep. APSU-2.01-RPT-003, May, 2019.

[6] FEMM, https://www.femm.info/wiki/HomePage

[7] B. Marchetti, S. Casalbuoni, V. Grattoni, and S. Serkez, "Study of the Tolerances for Superconducting Undulators at the European XFEL", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB035.

[8] J. E. Baader and S. Casalbuoni, "Pulsed Wire Magnetic Field Measurement System for Short-Period Long Undulators", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB126.

[9] V. Grattoni, J. E. Baader, and S. Casalbuoni, "Superconducting Phase Shifter Design for the Afterburner at the European XFEL", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB036.

[10] B. Pobodebov, "Resistive wall wakefields in the extreme anomalous skin effect regime", *Phys. Rev. Spec. Top. Accel Beams*, vol. 12, no. 4, p. 044401, Apr. 2009. doi:10.1103/physrevstab.12.044401

[11] M. Dohlus, "Impedance of beam pipes with smooth shallow corrugations", Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany, Rep. TESLA 2001-26, 2001.

[12] A. Tsakanian *et al.*, "The effect of the metal oxidation on the vacuum chamber impedance", Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany, Rep. TESLA-FEL 2009-05, May 2009.