OVERVIEW OF SUPERCONDUCTING UNDULATOR DEVELOPMENT AT THE EUROPEAN XFEL

S. Casalbuoni*, S. Abeghyan, L. Biasia, U. Englisch, A. Doosti,
A. Elghandour, E. Fioresi, G. Geloni, S. Karabekyan, A. Nandawadekar, G. Perosa,
A. Rajabi, M. Ronniger, T. Schmidt, H. Sinn, M. Yakopov, P. Ziolkowski,
European XFEL, Schenefeld, Germany
S. Barbanotti, W. Decking. A. Hauberg, C. Helwich, K. Jensch, S. Liu, L. Müller, E. Schneidmiller,
R. Wichmann, T. Wohlenberg, J. Wu,
Deutsches Elektronen-Synchrotron, Hamburg, Germany
A. Hobl, A. Vatagin, W. Walter,
Bilfinger Nuclear & Energy Transition GmbH, Würzburg, Germany

Abstract

This contribution describes the recent progress of the European XFEL superconducting undulators (SCUs) program. This includes: an industrially-produced NbTi-based SCU afterburner foreseen for one of the two hard X-ray lines; a prototype SCU module (S-PRESSO) in production by Bilfinger; two magnetic measurement test stands to perform quality assurance; and further development of SCU technology to reach even larger magnetic fields, by leveraging recent developments in High Temperature Superconducting (HTS) tapes for future upgrades.

INTRODUCTION

We report here about the latest achievements of the Superconducting Undulator (SCU) program at Euroepean XFEL. The program, described in Refs. [1, 2] aims to maintain the European XFEL (EuXFEL) at the forefront of XFELs even as new competing facilities mature. The primary goals of the program are:

- As the first XFEL to implement SCUs, establish a long-term world-leading capability in production of high intensity ultrashort x-rays above 30 keV and enable flexibility for other potential upgrades of EuXFEL (i.e. High Duty Cycle).
- Demonstrate the ability of the EuXFEL team to develop SCU technology. As the first major milestone of the SCU program, install an industrially-produced NbTi-based SCU afterburner in SASE2.
- Gain experience in the installation, commissioning and operation of SCUs in a XFEL environment.
- Further development of SCU technology to reach even larger magnetic fields, by leveraging recent developments in High Temperature Superconducting (HTS) tapes for future upgrades. This could revolutionize all light sources, including the EuXFEL, with increases in undulator magnetic fields by factors of about five.

* sara.casalbuoni@xfel.eu

The program will proceed through two major phases culminating in the installation of up to six SCU modules in the SASE2 tunnel downstream with respect to the presently installed permanent magnet undulators by 2033. These will provide photon with energies > 30 keV and unprecedented pulse energies in the few hundreds μJ range which will be delivered to the three instruments served by the SASE2 undulator line. The six SCU modules consist of a Superconducting undulator PRre-SerieS mOdule (S-PRESSO) and five small series FESTA (Free Electron laser SuperconducTing undulator Afterburner) SCU modules. They plan to be installed downstream with respect to the permanent magnet undulator (PMU) SASE2 line. Phase 1 focuses on developing an industrial partner, further development of SCU technology including HTS tape undulators, test infrastructure, and measuring and installing S-PRESSO delivered by the industrial partner; and Phase 2 on the industrial production and installation of up to five FESTA modules.

In this paper we present FESTA, as well as the dedicated measurement test stands developed for quality assurance of superconducting undulator (SCU) coils, and report on the current status of the S-PRESSO project. We emphasize magnetic measurements on one of S-PRESSO's two 2-m SCU magnets — to our knowledge the longest SCU coil yet manufactured and the longest length at which magnetic characterization of such a coil has been successfully performed. These results demonstrate the capability of the FESTA stands and constitute an important step toward scaling SCU production.

FESTA

The FESTA and S-PRESSO SCU modules will be 5 m long and 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. The main parameters of the SCU modules are listed in Table 1 [3].

Different operation schemes have been investigated. Amplification of the fundamental radiation from the PMUs using the fundamental of the SCUs is feasible for photon en-

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Table 1: Main Parameters of the S-PRESSO and FESTA SCU Modules [3]

Parameter	Value	Unit
Period	18	mm
Peak field	1.82	T
K	3.06	–
Vacuum gap	5	mm
Beam heat load	≤ 10	W

ergies up to approximately 50 keV. To extend the photon energy beyond 50 keV, nonlinear harmonic generation [4] and harmonic lasing have been explored. As a representative case, we studied the impact of undulator magnetic-field errors on FEL performance for harmonic lasing at 60 keV. The photon pulse energy along the six SCU modules installed downstream with respect to the PMUs of SASE2 is reported in Fig. 1. Simulations are performed with Genesis1.3 v4 [5]. Random errors are applied by varying the undulator parameter of every half-period of the undulator: $K_{half} = 0.0934B[\mathrm{T}]\ \lambda_U/2$ [mm], where B is the peak magnetic field on axis and $\lambda_U/2$ is the half period length. Errors on K_{half} follow a normal distribution with root-mean-square values $\Delta K_{half}/ < K_{half} > |_{rms} = 0.3\%, 0.6\%, 1\%$, (shown in green, purple and red, respectively) and were limited to the range $\pm 2\Delta K_{half}/ < K_{half} > |_{rms}$. The green bar represents the variation of the pulse energy over 20 different random-number seeds (different realizations of the shot noise). Intersections of 1.1 m are considered between the last PMU and the first SCU and between SCU modules. Reported in Fig. 1 is also the ideal case (blue line). Errors in K are considered acceptable when $\Delta K_{half}/ < K_{half} > |_{rms} < 0.6\%$ and $|\Delta K_{half}/ < K_{half} > | < 0.012$; under these conditions the pulse energy is reduced by less than 20% relative to the ideal case.

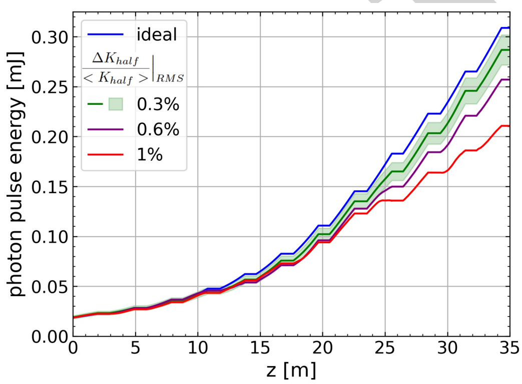

Figure 1: Photon pulse energy at 60 keV along the six SCU modules installed downstream with respect to the SASE2 PMUs in case of harmonic lasing at 60 keV.

During a six-month maintenance and upgrade period at the European XFEL in 2025, most electron beamline components for S-PRESSO and the FESTA SCU modules, together with infrastructure such as power and water supplies, were installed; the tunnel is now prepared for S-PRESSO installation in 2027.

SUNDAE1

With the aim of training the SCU coils up to 2 m length at 4.2 K and 2 K as well as to precisely measure the magnetic field profile along the magnetic axis with Hall probes, the vertical Liquid Helium (LHe) measurement test stand SUNDAE1 (Superconducting UNDulAtor Experiment) has been developed, and commissioned with the 0.3 m long S-PRESSO mock-up coil. Very good agreement has been found with the measurements performed at the CASPER I facility at the Karlsruhe Institute of Technology [6]. More details about the test stand and the commissioning can be found in Ref. [7]. The repeatability error measured over five successive measurements on $\Delta K_{half}/ < K_{half} >$ is about 0.1% [7], and therefore enough to resolve the random errors reported in the previous section and required for the S-PRESSO and FESTA modules.

SUNDAE2

SUNDAE2 is a horizontal test stand to perform quality assurance of the SCU coils installed in the final cryostat. This foresees integral field measurements based on the moving wire technique and local field measurements with Hall probes moving along the magnetic axis and with a pulsed wire system under development. The status of the in-vacuum pulsed wire system and of the overall test stand SUNDAE2 are described in Ref. [8] and [9], respectively. For S-PRESSO and FESTA, the main goal is to measure the straightness of the trajectory along the 5 m SCU modules, to values $< 10^{-4}$T mm^2 with the pulsed wire technique. The pulsed wire setup that will be used in SUNDAE2 has been benchmarked against Hall probes measurement performed on a reference 5 m long and 40 mm period lenght PMU, demonstrating the ability of the system to perform such a measurement [8].

S-PRESSO

The cryostat vessel, the phase shifter with Helmholtz coils and the two SCU coils are manufactured, as well as a prototype of the beam vacuum chamber. The phase shifter has been tested in SUNDAE1, showing that the specified phase integral was reached. One of the 2 m long SCU coils (Magnet A) has also been characterized in SUNDAE1. Approximately 40 quenches were required to train Magnet A [7] to the 810 A operating current needed to achieve the specified on-axis peak field of 1.82 T. This leaves a current margin of about 10% at 4.3 K. Since operation with cryocoolers in the final cryostat has previously been demonstrated for Bilfinger-built SCUs at roughly 3.5 K, this margin provides a comfortable safety buffer [10, 11]. Stability of the coils at nominal current has been demonstrated for more than 10 h.

The FEL process requires that photons emitted along the undulator overlap spatially; this is achieved by maintaining

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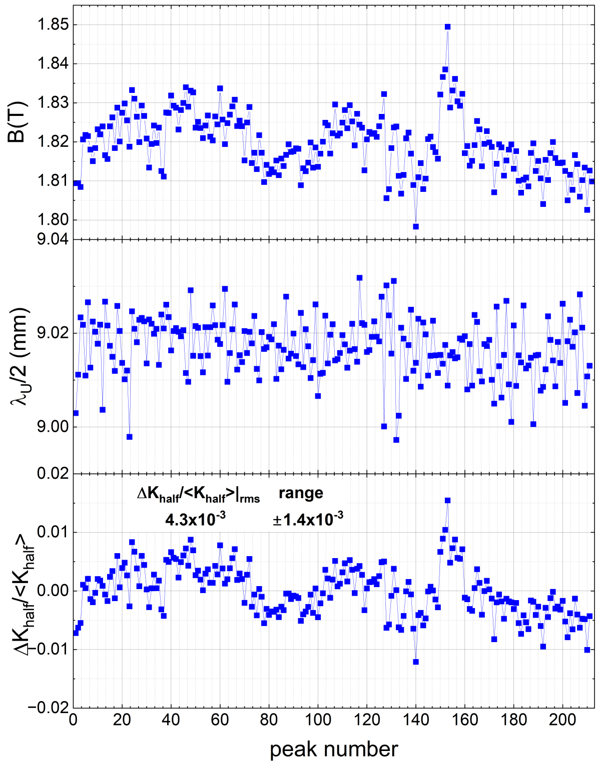

Figure 2: Bottom: $\Delta K_{half}/<K_{half}$, middle: peak field on axis, top: $\lambda_U/2$ are reported for 106 full periods measured with 810 A in the main coils, -0.35 A in both AUX1, 3A and -3A in the entrance and exit AUX2 coils.

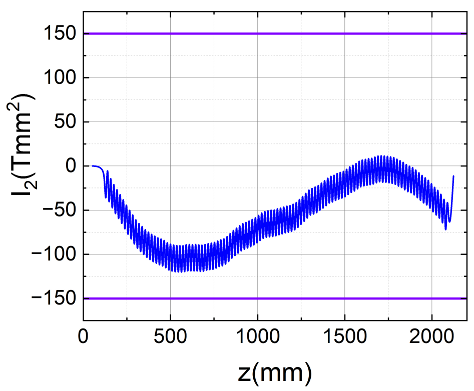

Figure 3: Second field integral along the magnetic axis (blue line), calculated from the magnetic field profile measured with the Hall probe at 810 A in the main coils, -0.35 A in both AUX1, 3A and -3A in the entrance and exit AUX2 coils.

an essentially straight electron-beam trajectory with transverse deviations smaller than the beam dimensions. Since the beam trajectory is proportional to the second magnetic-field integral, the second horizontal and vertical field integrals must be less than 1.5×10^{-4} T m^2. In addition, only very small variations of K_{half} are allowed so that the emitted photons stay in phase and interfere constructively. The manufacturing process is therefore tailored to reach high mechanical accuracies in terms of the planarity of the iron yoke and of the windings, as well as of pole and winding packages widths. Deviations form the ideal geometry of $\lesssim 40\ \mu$m have been measured at room temperature for eight impregnated coils, corresponding to four 2 m long magnets [3]. Magnetic simulations considering the above measured geometries show, for all four magnets, including the two S-PRESSO magnets, $\Delta K_{half}/ < K_{half} > |_{rms} < 1\%$. The measurement shown in Fig. 2 reveals an increase in the value of $\Delta K_{half}/ < K_{half} > |_{rms}$ from room temperature to cold conditions by a factor of four. This, already observed in a Bilfinger-built SCU operating in the KIT synchrotron [12], can be attributed to movements of the winding packages. The measured deviations of K_{half} limit photon pulse-energy loss to under 20% (i.e., pulse energy $\gtrsim$ 80% of ideal) at 60 keV, comfortably meeting acceptance criteria. Figure 2 shows that the robust support structure, which secures the magnet's top and bottom coils, effectively prevents long-range magnetic field errors - under cryogenic conditions and strong magnetic forces. The second field integral, proportional to the trajectory of the electrons, obtained by integrating the magnetic field profile measured with the Hall probe is within $\pm$150 T mm^2 (see Fig. 3), corresponding to 5μm at 16.5 GeV, so much smaller than the diamensions of the electron beam $\sigma = 20\ \mu$m. The second field integral can be varied by using the auxiliary coils wound in the end grooves with 0.256 mm diameter NbTi wire: AUX1 are wound in the first and last groove, while AUX2 in the second and second but last [6]. Powering with different currents the two ends allows also removing the background constant field. Adjustment of the auxiliary coils current therefore depends on the different ambient fields and might be different in the final cryostat in the measurements with SUNDAE2 and after installation in the tunnel. For the case reported in Fig. 3 AUX1 were both powered with -0.35 A and AUX2 with 3 A and -3 A. While the AUX1 coils were powered to provide both a kick in the opposite direction, the AUX2 coils provide a kick in same direction. The measurements reported in Figs. 2 and 3 validate the design and manufacturing process of the S-PRESSO and FESTA SCU magnets.

CONCLUSIONS AND OUTLOOK

In conclusion, we presented the status of the SCU program at EuXFEL, covering FESTA (small-series SCU production), S-PRESSO, and the magnetic test stands for quality assurance. Magnetic characterization of one of S-PRESSO's 2-m SCU magnets — to our knowledge the longest SCU coil produced and magnetically characterized — validates the coils' design and manufacturing, enables integration of these tests into the production workflow, and represents an important step toward scaling SCU production.

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