FIRST RESULTS FROM THE SUNDAE1 TEST STAND AT EUROPEAN XFEL

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Abstract

European XFEL is planning the installation of superconducting undulators as afterburners downstream with respect to SASE2, one of the hard X-ray undulator lines, to provide even harder X-ray photon energies and a larger tuning range. The Superconducting undulator PRE-SerieS mOdule (S-PRESSO) consisting of two pair of coils, a phase shifter, and correction coils is in production by Bilfinger Nuclear & Energy Transition GmbH. In order to perform quality assurance of the superconducting coils a vertical test stand SUNDAE1 (Superconducting UNDulAtor Experiment) has been developed. SUNDAE1 allows to train the superconducting coils, as well as to measure the magnetic peak field profile by means of Hall probes. We report here on first results.

INTRODUCTION

Superconducting undulator (SCU) technology is strategically important for the future development of the European XFEL, as it would extend the accessible photon energy range and better exploit the accelerator capability [1].

Because of the strategic relevance of superconducting undulators to the European XFEL facility, a project to develop an SCU afterburner for the SASE2 line has been initiated. The main parameters of its pre-series prototype module, Superconducting undulator PRE-SerieS mOdule (S-PRESSO), have been reported in Ref. [2].

With the main goal of training and measuring the magnetic field profile of superconducting undulator coils with Hall probes, SUNDAE1 is a Liquid helium bath vertical test stand developed at European XFEL [3]. In this contribution, we report on the commissioning of SUNDAE1, as well as the first results obtained for one of the two 2 m-long SCU magnets of S-PRESSO, which is, to the best of our knowledge, the first 2 m-long superconducting magnet ever to be characterized.

EXPERIMENTAL SETUP

SUNDAE1 has been described in more detail in Refs. [1] and [3]. The system includes an insert to lead the current from the power supplies down to the magnet which is vertically attached. The insert with the attached magnet is hosted in a liquid helium bath vertical cryostat with operation capability at 4 K (~1 bar) and at 2 K (~30 mbar).

Two bipolar power supplies rated ± 1500 A and six 20 A power supplies, each fitted with its own quench detector, are available for use. It is possible to power coils with a maximum current of 3000 A. To locate possible quenches, five Cronosflex HISO-8 units are used. The SUNDAE1 insert consists of a main top flange carrying all sensor connectors, current flanges, and cryogen inlets/outlets. Current leads and LN_2 and LHe heat exchangers (HEs) are mounted below the flange. The cryogenic sections are vertically separated by super-insulated baffles.

Copper parts of the high-current (500 A and 1000 A) and low-current (20 A) leads are cooled by LN_2 heat exchangers. The HTS sections of the 20 A leads are also connected to LN_2 heat exchangers, while their HTS and LTS (NbTi wire-in-channel) ends are thermally anchored to the LHe bath using copper braids. For the 500 A and 1000 A leads, the HTS sections are cooled by dedicated LHe heat exchangers, and their HTS and LTS ends are similarly thermally anchored to the LHe bath.

Temperatures at the end of the LN_2-cooled copper section and before the HTS section are monitored with PT100 sensors, while the top of the NbTi wire-in-channel section is monitored using Cernox sensors.

The tested magnet consists of a main coil powered with 1000 A, and two auxiliary coils, as described in Ref. [3], which can be tuned to minimize the second field integral.

SUNDAE1 is equipped with a quench detection system and data acquisition system for the quench events diagnostics. Further, the system is capable of measuring local magnetic field using Hall probes, which are mounted on a 4 mm-thick sledge driven by a linear motion system (LMS). The LMS can scan over 2.4 m between coils with gaps as small as 6.5 mm with a resolution of 1 µm. This allows characterization of coils up to 2 m long. The Hall probe used for the characterizations reported below has been calibrated at the Karlsruhe Institute of Technology and has a calibration error of ± 0.1 mT. In the future, Hall probes are planned to be calibrated at European XFEL [4].

BENCHMARKING SUNDAE1 WITH CASPER1

The magnetic field profile, as well as the magnetic field quality in terms of $(\frac{\Delta K_{\text{half}}}{K_{\text{half}}})$ rms, as defined below, are measured and compared in the test stands SUNDAE1 and CASPER1 for the same magnet: the S-PRESSO mock-up [5].

The quantities $B_{\mathrm{peak}}[n]$ and $\hat{z}[n]$ denote, respectively, the magnitude of the n-th absolute peak in the magnetic-field profile B and the corresponding position of that peak along the longitudinal coordinate z. If N is the total number of absolute peaks, the complete set of $N-1$ half-period lengths are obtained from

$$\lambda_{\mathrm{half}}[n] = \hat{z}[n+1] - \hat{z}[n], n = 1,2,3,\dots,N-1.$$

The associated half-period K-parameter sequence is then defined as

$$K_{\mathrm{half}}[n] = 93.36\, B_{\mathrm{peak}}[n] \times \lambda_{\mathrm{half}}[n], n = 1,2,3,\dots,N-1.$$

Where B is expressed in T and λ_{half} in m. Finally, the normalized quantity $\Delta K_{\mathrm{half}}/\overline{K_{\mathrm{half}}}$ is introduced to measure the relative deviation of $K_{\mathrm{half}}[n]$ from its mean value $\overline{K_{\mathrm{half}}}$, namely

$$\frac{\Delta K_{\mathrm{half}}}{\overline{K_{\mathrm{half}}}} = \frac{K_{\mathrm{half}}[n] - \overline{K_{\mathrm{half}}}}{\overline{K_{\mathrm{half}}}}.$$

CASPER1 is a liquid He test facility developed and operated by the Institute of Beam Physics and Technology (IBPT), Karlsruhe Institute of Technology (KIT) [6]. It has been used to characterise several SCU coils up to 350 mm long, including the S-PRESSO mock-up [5].

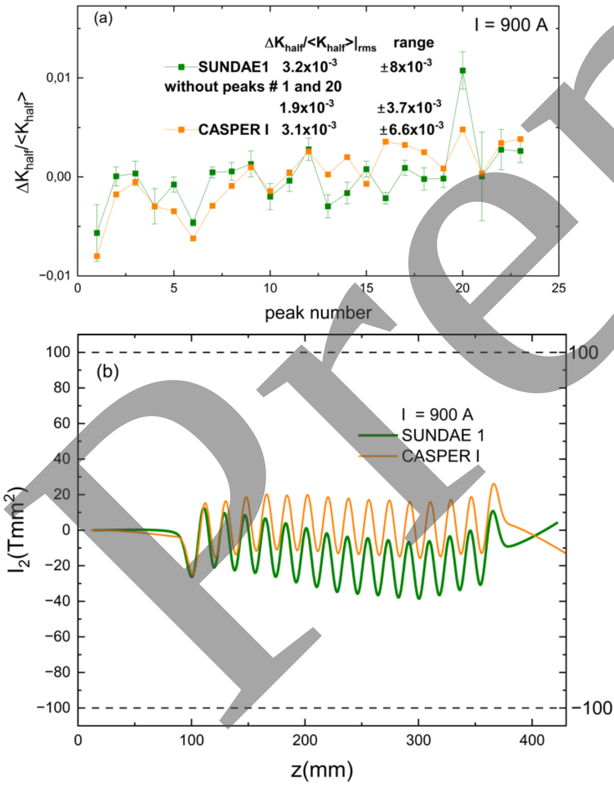

Figure 1: Comparison of (a) $(\frac{\Delta K_{\mathrm{half}}}{\overline{K_{\mathrm{half}}}})$ and (b) the second field integral of the S-PRESSO mock-up at a main coil current of 900 A as measured using CASPER1 (orange) and SUNDAE1 (green).

Figure 1 benchmarks the performance of SUNDAE1 against CASPER1 using measurements of the S-PRESSO mock-up at 900 A. In Fig. 1(a), the relative half-K variation measured on SUNDAE1 follows the CASPER1 distribution closely over the full set of peaks. The $(\frac{\Delta K_{\mathrm{half}}}{\overline{K_{\mathrm{half}}}})$ rms values namely 3.2×10^{-3} for SUNDAE1 and 3.1×10^{-3} for CASPER1 are in good agreement. While in the CASPER1 measurement a slight tapering was observed, this is gone in the SUNDAE1 measurements. A reason could be a smoother and straighter movement of the sledge within the rails. Further, removing the peaks 1 and 20 a quality improvement with respect to CASPER1 is observed. The $\frac{\Delta K_{\mathrm{half}}}{\overline{K_{\mathrm{half}}}}$ variation reflects the magnetic peak field variation along the coils. The measurements, repeated 5 times, show that the relative uncertainty in $\frac{\Delta K_{\mathrm{half}}}{\overline{K_{\mathrm{half}}}}$ expressed as rms, is below 0.03%, indicating high precision and repeatability of the system.

In Fig. 1(b), the second field integral measured on both test stands is reported, showing also very good agreement. In both cases, the measurements remain well within the specified limits indicated by the dashed lines.

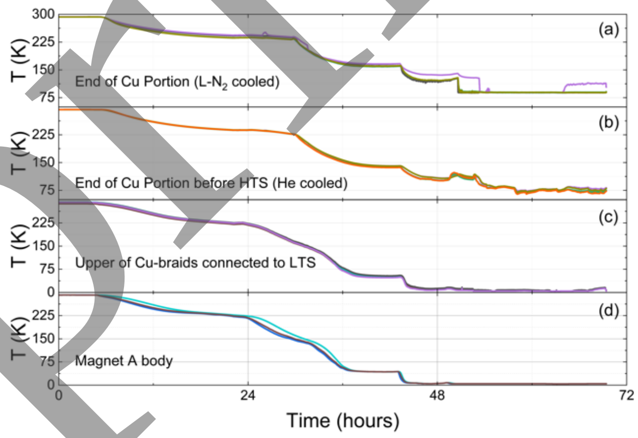

Figure 2: Temperature profiles of the current leads during cooldown (a–d) phase of magnet A.

The S-PRESSO mock-up coil is trained in SUNDAE1, the training results confirm preservation of training memory after thermal cycling where it went from about 58 quenches to only 5 quenches after three years storage at room temperature. [6]. Further, the stable coil operation at 900 A is tested for 16 h.

S-PRESSO 2 M LONG MAGNET

Figure 2 and Fig. 3 show the temperature evolution at different locations of the current leads and magnet during cooldown and warm up of one of the 2 m long S-PRESSO SCU coils (in the following referred to as magnet A), respectively. To avoid mechanical stresses and consequent long-range deformations along the magnet, which was manufactured to keep tight mechanical tolerances < 50 µm, a temperature gradient of less than 40 K has to be kept between the magnet's higher and lower parts, during cooldown and warm up. A maximum of 30 K was reached. Cooling lasted about 60 h: all three current leads stages reached the design temperatures. Warm-up lasted 112 h.

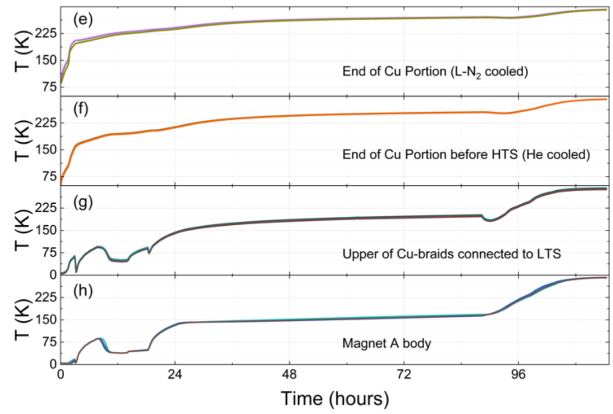

Figure 3: Temperature profiles of the current leads during warm up (e–h) phase of magnet A.

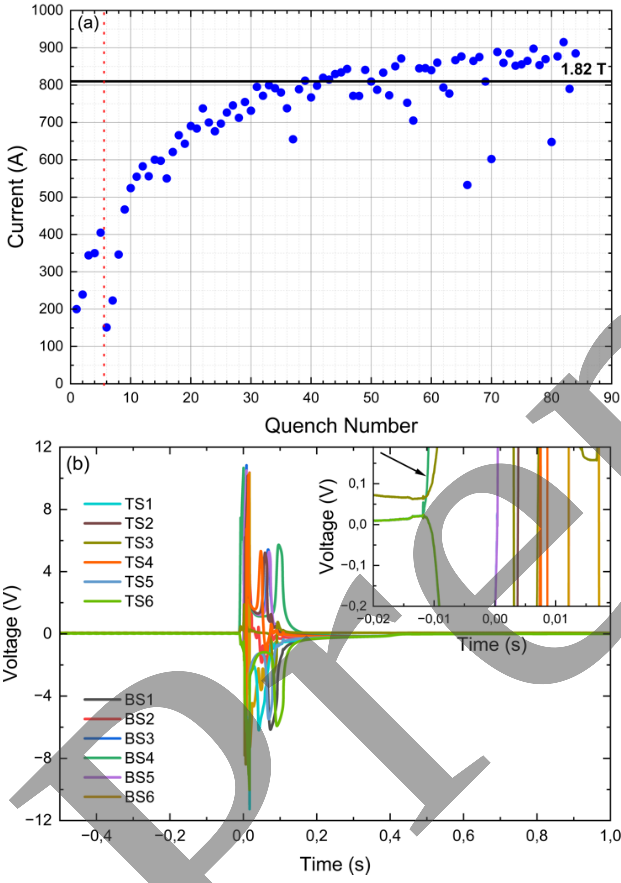

Figure 4: (a) Magnet A training curve. The black line marks the nominal current of 810 A for 1.82 T, and the red dashed line indicates a thermal cycle. (b) Voltage-tap signals during a quench at 884 A. The inset shows the onset of the event and identifies BS4 as the quench-origin section.

Figure 4 (a) summarizes the training of Magnet A. The horizontal black line marks the nominal operating current of 810 A, needed to reach to the nominal on-axis peak magnetic field of 1.82 T. Magnet A is subdivided into twelve series-connected coil sections, arranged as six for the top (TS1…TS6) and six for the bottom coil (BS1…BS6). Each subsection is equipped with a cold-diode block and a pair of voltage taps, providing localized protection and enabling section-by-section voltage monitoring during operation and quench events. The quench detector is triggered when the voltage imbalance between the top and bottom coils voltage is larger than 100 mV for longer than 10 ms.

Figure 4(b) shows the voltages of the different sections during a quench at 884 A and identifies BS4 as the quench-origin section. As seen in the inset, the BS4 signal rises first and creates the voltage imbalance that triggers the quench detector. The subsequent response of the remaining channels reflects quench propagation through magnet A.

Figure 5 shows the on-axis magnetic field profile of magnet A for two operating currents, namely a main-coil current of 810 A with AUX1 = 1.9 A and a main-coil current of 200 A with AUX1 = 1.4 A. At 810 A, the field amplitude reaches about ± 1.82 T, consistent with nominal operation, whereas at 200 A the amplitude around ± 0.8 T. More details on the field quality are provided in Ref. [7].

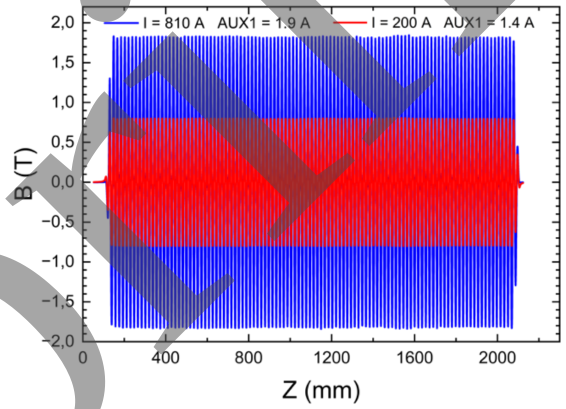

Figure 5: Magnetic field profile B of magnet A at a main coil current of 810 A and 200 A, AUX1 = 1.9 A and 1.4 A.

CONCLUSIONS AND OUTLOOK

The SUNDAE1 test facility has been successfully commissioned. Magnetic field measurements have been benchmarked with the S-PRESSO mock-up measurements performed at the KIT test facility CASPER I. One the 2 m long magnets of S-PRESSO have been successfully characterized (see also Ref. [7]), showing the capability of the system to precisely measure long coils. The 2 m long magnet A is ready for characterization in the horizontal test stand SUNDAE2 [8] and SUNDAE1 to characterize further SCU magnets.

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