SUNDAE2 AT EuXFEL: A TEST STAND TO CHARACTERIZE THE MAGNETIC FIELD OF SUPERCONDUCTING UNDULATORS

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Abstract

European XFEL foresees a superconducting undulator (SCU) afterburner in the SASE2 hard X-ray beamline. It consists of six 5m-long undulator modules with a 5 mm vacuum gap, where each module contains two 2m-long coils and one phase shifter. Prior to installation, the magnetic field must be mapped appropriately. Two magnetic measurement test stands named SUNDAE 1 and 2 (Superconducting UNDulAtor Experiment) are being developed at European XFEL. While SUNDAE1 will be a vertical test stand to measure SCU coils up to two meters with Hall probes in a liquid or superfluid helium bath, SUNDAE2 will measure the SCU coils assembled in the final cryostat. This contribution presents the development status of SUNDAE2 and its main requirements.

INTRODUCTION

European XFEL envisages the development of superconducting undulators (SCUs) technology as part of the facility development program. An SCU afterburner is proposed for the hard X-ray undulator beamline SASE2. This afterburner is composed of one pre-series prototype named S-PRESSO and five SCU modules [1,2]. The successful implementation of the SCUs has compelling benefits: First and foremost, it opens the possibility of lasing above 30 keV, which enables new types of experiments and opens the access to new scientific applications of FEL radiation. Also, SCUs can cover approximately the same photon energy range available from the presently installed PMUs (electron beam energy of 17.5 GeV), considering a continuous-wave (CW) operation mode.

The magnetic field characterization is an essential step in the design of high-quality undulators for storage rings and free-electron laser applications. Local field measurements (i.e., point-by-point) are commonly performed by Hall probes, while the flipping coil and moving wire systems are well known for field integral measurements. The pulsed wire method is an alternative method to map the local field. Although the pulsed wire technique is still not competitive with Hall probes in terms of accuracy, it has the potential to reconstruct space resolved magnetic fields for small-gap short-period long undulators (for which Hall probe-based measurements may be more difficult due to space constraints).

We are developing a test stand facility named SUNDAE2 (**S**uperconducting **UND**ul**A**tor **E**xperiment) to measure the SCU modules' magnetic field in the final cryostat. SUNDAE2 will be installed at DESY campus. It will operate three magnetic measurement techniques: two wire-based techniques (pulsed wire moving wire systems) and the Hall probe. This contribution presents the main features of the SCUs we aim to measure and the first steps taken towards developing SUNDAE2[1].

S-PRESSO MAIN PARAMETERS

S-PRESSO will be the first module to be delivered and characterized. It will be 5m-long, as the presently installed permanent magnet undulators. The magnetic period will be 18 mm and the on-axis peak magnetic field 1.82 T ($K = 3.06$). The maximum first and second field integrals allowed for both transversal field components are 4×10^{-6} Tm and 1×10^{-4} Tm^2, respectively. The vacuum gap of S-PRESSO will be 5 mm.

VACUUM CHAMBERS OF SUNDAE2

SUNDAE2 will be composed of three main vacuum chambers connected to each other. Each chamber consists of a welded vacuum tank with CF flanges and mounted equipment (e.g., blank flanges, electrical feed throughs, viewports, etc.). Figure 1 shows the design of the vacuum chambers of SUNDAE2. The main features of each vacuum chamber (named Chamber 1, Chamber 2, and Chamber 3 for convenience) are shown in Table 1.

Table 1: Main Dimensions of Chambers 1, 2, and 3

Parameter	**Ch. 1**	**Ch. 2**	**Ch. 3**
Longitudinal length (m)	2.8	1.0	1.3
Transversal length in x (m)	0.6	0.1	0.6
Transversal length in y (m)	0.6	0.1	0.6
Tube diameter (mm)	306	38	306

Vacuum and ion pumps will be connected to the lower flanges of Chambers 1 and 3 shown in Fig. 1. All the required electrical feed throughs will be placed on the opposite side of the lateral viewports of Chambers 1 and 3 illustrated in Fig. 1. Support structures (not shown in Fig. 1) will keep

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[1] SUNDAE1 will be a vertical test stand capable of performing magnetic measurements and training of superconducting coils up to 2 m [3,4].

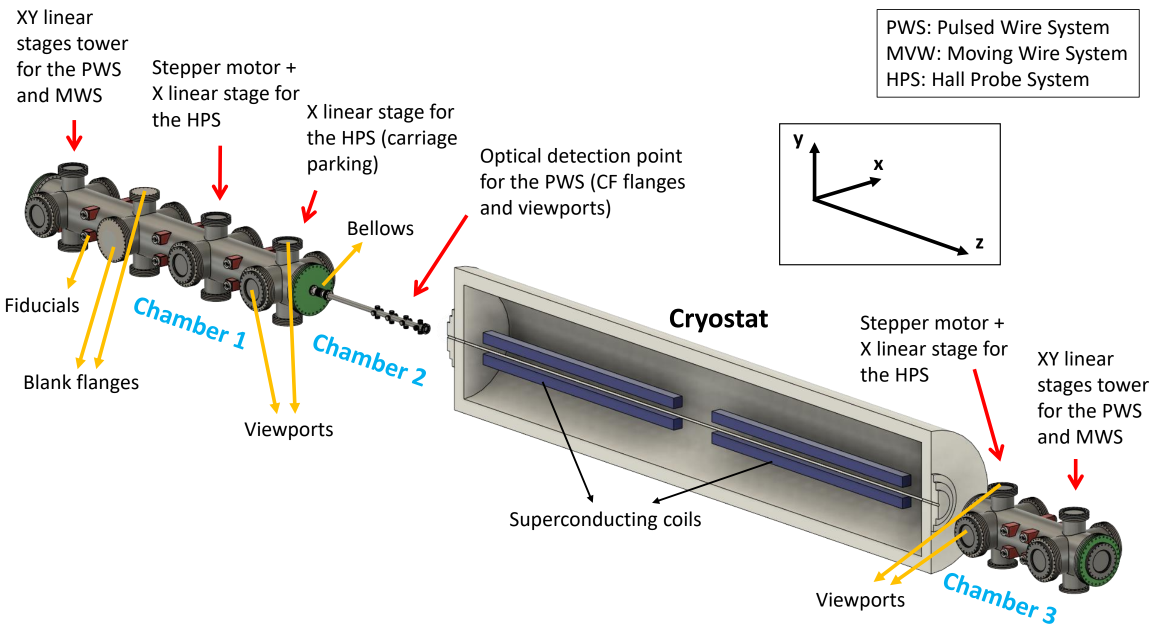

Figure 1: Sketch of vacuum chambers of the test stand SUNDAE2 (**S**uperconducting **UND**ul**A**tor **E**xperiment) planned to perform SCU magnetic field measurements.

the chambers' axes aligned with the SCU's beam chamber center, which must be 1.4 m above the floor. Chambers 1 and 3 will have fiducials placed on their sides for alignment. All chambers will operate under Ultra High Vacuum conditions (i.e., pressure smaller than 1×10^{-7} mbar). The relative magnetic permeability of the vacuum chambers and components must be smaller than 1.01, and the integral leak rate of all chambers has to be smaller than 1×10^{-10} mbar l/s.

WIRE-BASED MEASUREMENT SYSTEMS OF SUNDAE2

Pulsed Wire System

The pulsed wire method [5] is a promising solution for mapping the local magnetic field in small gap long devices. Although several improvements have increased the performance of the pulsed wire method since then [6–12], the technique has to be demonstrated to reconstruct the magnetic field for long undulators with a short period, particularly when the dispersion effect dominates.

For the pulsed wire system, we plan to use a wire of 10.5 m, which is long enough to cover the 5 m-long undulator and avoid any potential issues with the wave reflection. A wire tension of approximately 20 N has been estimated to keep the sag within the undulator region smaller than 100 µm. Considering a Beryllium Copper (BeCu) wire, its diameter should be larger than 150 µm to avoid going beyond its tensile yield strength. The tension will be produced by a movable carriage set into a rail and attached by springs to a fixed carriage. Both carriages and the rail will be held by brackets attached to a tower of linear stages that allow movement in the transversal xy plane. The travel range of the stages are 70 mm for the x-axis and 30 mm for the y-axis m. The linear stage towers will be sitting in leveling plates welded inside the vacuum chamber. The control system architecture will be based on EtherCAT (Ethernet for Control Automation Technology). The linear stages have three purposes: 1) to place the wire in the correct position to perform the measurement with the pulsed wire technique; 2) to move the wire in and out of the center to let space for the Hall probe carriage to move; 3) to perform magnetic field integral measurement with the moving wire technique (see *Moving Wire System* section).

The wire motion detection will combine the laser Thorlabs CPS532 and the photodetector Thorlabs PDA100A2. A low-pass filter Thorlabs EF110 is placed between the photodetector output terminal and the oscilloscope Lecroy HDO6104A-MS (12-bit ADC, 10 GS/s). A sensitivity of approximately 50 mV/µm has been demonstrated with these components [13]. Details of the pulse generator under development is also presented in [13]. The laser and photodetector will be placed out-of-vacuum, closed to the viewports shown in Fig. 1 (see Chamber 2). The longitudinal position of the optical detection spot may affect the measurement results [14]. Therefore, Chamber 2 has four spots where the laser and photodetector can be placed to measure the x and y magnetic field components.

Magnetic Field Reconstruction Program From Warren's criterion for dispersion to dominate [5], one realizes that dispersion will dominate our case and, therefore, some of the available correction techniques in the literature [9, 11] must be applied. We have developed a program in Matlab that creates a dummy magnetic field, simulates the wire displacement for different pulse shapes (considering wire dispersion, finite pulse width, and sag), executes corrections (some of them demonstrated in [9]), and reconstructs the magnetic field [15].

In the pulsed wire technique, the wire displacement is sampled. The magnetic field samples as a function of the longitudinal position can be numerically calculated by either the first or the second forward finite divided difference of the field integral, depending upon whether the pulse width provides the first or the second field integral. Inevitably, the finite divided differences technique introduces errors in the magnetic field — the so-called *discretization error*. The program corrects the discretization error effects on the wavenumber domain by multiplying the Fourier Transform of the wire displacement samples by $-i\kappa\Delta z/(e^{-i\kappa\Delta z}-1)$ for short pulses and and $-(\kappa\Delta z)^2/(e^{-2i\kappa\Delta z}-2e^{-i\kappa\Delta z}+1)$ for long pulses, where κ is the wavenumber in rad/m and Δz is the sampling space in m [15].

The study presented in [15] evaluated the uncertainties of the technique and how they affect the accuracy and precision of the pulsed wire method to obtain the relative local K parameter. For $\Delta K/K$, an accuracy and precision of the order of 1×10^{-3} and 1×10^{-5}, respectively, were estimated. Although the accuracy of the pulsed wire method is not comparable with the one obtained from Hall probes, the precision (needed to determine the magnetic field quality) is appropriate. For instance, an error of 1.5×10^{-3} for $\Delta K/K$ has been judged acceptable in terms of degradation of the FEL performances for an undulator with a period length of 15 mm [16].

If necessary, the sag can be corrected numerically in the space domain, since the vertical component of the magnetic field is $B_y(y)=B_0\cosh(2\pi y/\lambda_u)$, with B_0 being the on-axis field amplitude.

Moving Wire System

The xy tower of linear stages described for the pulsed wire will also perform field integral measurements. The same wire can be translated horizontally by ±2 mm and vertically by ±1 mm. By following the known equations of the method [17] and considering a wire translation of 1 mm, the maximum first and second field integral (4×10^{-6} Tm and 1×10^{-4} Tm^2) allowed for the undulators would induce an integrated voltage in a 10.5 m-long single wire of 4 nVs and 10 nVs, respectively. The main instrument under consideration to measure such a small induced signal is the Metrolab FDI2056, which has an integrated voltage resolution of 1×10^{-14} Vs and an accuracy of ±10 ppm [18].

HALL PROBE-BASED MEASUREMENT SYSTEM

Cryogenic Hall probes from Arepoc model HHP-VP and HHP-VU will be placed on a movable carriage (sledge). The sledge will travel through the SCU beam vacuum stepwisely. The Keithley 2450 will supply the constant current of 10 mA. The Keithley DAQ6510 will read out the Hall voltage. Similar instruments were used for the calibration of these Hall probes with a physical property measurement system (PPMS) at the Karlsruhe Institute of Technology. Each Hall probe was calibrated from a field range between ±5 T for 4.2 K, 30 K, and 77 K. The absolute calibration error is below 0.1 mT.

The details of the sledge's positioning and movement are still under study. The sledge's design is strongly linked to the SCU vacuum chamber profile, which the design is ongoing. The small gap long SCU vacuum chamber imposes obstacles to measure its longitudinal position and to fix rods/ropes to the sledge. The most appropriate method to measure the sledge's position is by using an interferometer solution. For this, a retroreflector must be placed on the back (and/or front) surface of the sledge, which has to be smaller than 5 mm and has part of the surface allocated for the rod/rope connection. In addition, any motors placed in the vacuum chambers of SUNDAE2 must be placed such that the light from the interferomenter's laser head is not blocked. If that is not feasible, additional mirrors have to be included to provide the proper path for the laser beam.

SUMMARY AND OUTLOOK

The magnetic field test stand facility SUNDAE2 is under development at European XFEL to measure the modules that will compose the SCU afterburner in SASE2. This contribution describes the development status and the plans for SUNDAE2 in terms of the measuring methods — named, the pulsed wire, the moving wire, and the Hall probe techniques — and vacuum requirements. Before measuring S-PRESSO, we aim to use SUNDAE2 to perform room-temperature measurements of the permanent magnet undulators with 40 mm period length used at European XFEL in the two hard X-rays undulator lines [19].

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