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Conceptual Design of a Liquid Helium Vertical Test-Stand for 2m long Superconducting Undulator Coils

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Conceptual Design of a Liquid Helium Vertical Test-Stand for 2m long Superconducting Undulator Coils

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Abstract. Superconducting Undulators (SCUs) can produce higher photon flux and cover a wider photon energy range compared to permanent magnet undulators (PMUs) with the same vacuum gap and period length.
To build the know-how to implement superconducting undulators for future upgrades of the European XFEL facility, the test stand SUNDAE1 for the characterization of SCU is being developed. The purpose of SUNDAE1 is the training, tuning and development of new SCU coils by means of precise magnetic field measurements.
The experimental setup will allow the characterization of magnets up to 2m in length. These magnets will be immersed in a Helium bath at 4K or 2K temperature.
In this article, we describe the experimental setup and highlight its expected performances.

1. Introduction

Superconducting undulator technology enables achieving stronger magnetic peak fields than permanent magnet technology, considering the same period length and vacuum gap in the undulator [1, 2].
In the recent years, SCUs have been succesfully employed in synchrotron radiation sources [3, 4]. Similarly to what has been demonstrated for synchrotrons, the use of SCUs can potentially improve the performance and flexibility of advanced FELs. In particular by working at short undulator periods superconducting magnet technology would allow reaching higher photon energies while keeping a wide range of tunability of the setpoint. That is why the implementation of SCUs is being considered by several FEL projects world-wide [5, 6].
The advancement of SCU technology has a strategic importance also for the future development of the European XFEL facility. The extension of the energy range of the radiation towards higher values would fully exploit the high electron energy beam capability of the accelerator [7]. Moreover, this development can be considered complementary to the study on the upgrade of the XFEL linac for continuous wave (CW) operation [8]. CW operation at European XFEL

is considered possible only with reduced electron beam energy. Specifically the electron beam energy will be limited to about 7 GeV, while the present maximum value is 17.5 GeV. The replacement of the existing PMUs beamline with SCUs having shorter undulator periods would enable the 7 GeV linac to cover the same photon energy range as the present accelerator.
For all those reasons, a project for the realization of a SCU afterburner for the SASE2 line is being set-up. The main parameters and specifications for a pre-series prototype module (S-PRESSO) of such afterburner have been presented in [9].
Numerical simulations [10, 11] show that ensuring high precision manufacturing of the coils and their relative alignment are important aspects for the development of the prototype module.
An early and fast characterization of the stand alone coil, before installation in the final cryostat, would allow a prompt evaluation of the magnet properties, as routinely pursued in other facilities world-wide [12, 13]. Magnetic correction procedures, such as shimming [14] or discard of the coil could possibly be applied early enough to guarantee proper performances of the final cryomodule.
Consequently the test stand SUNDAE1 (Superconducting UNDulAtor Experiment 1) for the characterization of SCU has been proposed. Such test-stand will be located in the DESY campus. The purpose of SUNDAE1 is the training, tuning and characterization of new SCU coils by means of magnetic field measurements.
A second test-stand, named SUNDAE2, for the characterization of the final afterburner cryomodules, is also under construction in the same experimental area. In this second test-stand the characterization of the module using the pulse-wire technique is also foreseen [15, 16].
In this article we will describe the present design concept of SUNDAE1 and comment on the expected performances in terms of magnetic field characterization.

2. Conceptual Design of SUNDAE1

Figure 1 shows the schematic drawing of SUNDAE1. The coils of the SCUs will be immersed in a liquid or superfluid Helium bath. Two Hall probes will be installed on a sledge driven by a Linear Motion System (LMS). The sledge will be able to move between the two coils constituting a SCU. Its thickness is 4 mm, thus allowing the characterization of coils having a magnetic gap down to 6 mm. The range of the scan of the sledge is 2.3 m. Coils having maximum length of 2 m and 15 cm field tails on each side of them can be therefore characterized by the Hall probes.

2.1. Magnetic Field Characterization

In [9] the design-parameters of the coils of S-PRESSO have been presented. The measurement of variations of the magnetic field profile $\Delta B/B \ll 10^{-3}$ requires a resolution of the absolute value of the magnetic field better than 1.8 mT. Moreover, in order to be able to resolve errors on the manufacturing of the poole/groove width of the coil of the order of 10 μm, a resolution of the Hall-probe position of roughly 1 μm is wished.
The orientation of the Hall-probes shown in Fig. 1 allows the characterization of the y-component of the magnetic field of the coils, B_y. The resolution of the measurement of the magnetic field is of the order of few μT but its accuracy is limited by the error on the calibration of the Hall probe.
The cryogenic Hall-probes that will be used in SUNDAE1 have been calibrated in a physical properties measurement system of the Institute at KIT. The Hall-probe read-out voltage, HV, versus the magnetic field, B_y, was recorded under fixed temperatures (4.2 K, 30 K, and 77 K) in the range from -5 T to +5 T. The measured data have been divided in regions. For each region a polynomial fit of the data B_y versus HV has been performed. Such measurements allowed the estimation of the calibration error, which is in the order of 0.1 mT.
Fulfilling the requirement on the precision of the positioning of the Hall-probe is not trivial due to a number of systematic effects acting on the system both inside and outside the cryostat. Outside the cryostat, environmental temperature variations of few degrees and background vibrations are expected. Inside the cryostat, a systematic variation of the length of the rod while scanning

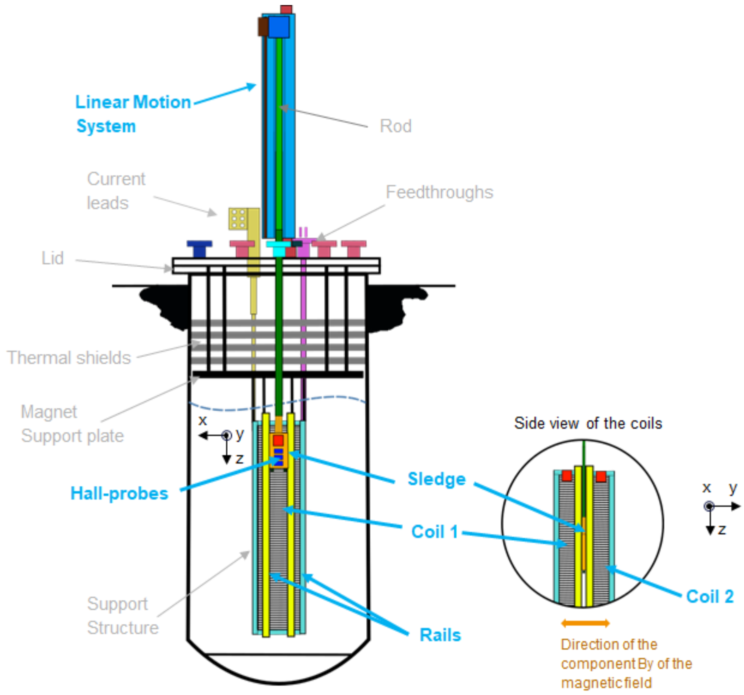

Figure 1. Scheme of SUNDAE1. The SCUs are immersed in a liquid or superfluid Helium bath. Two Hall probes will be installed on a sledge placed at the edge of a rod connected to a Linear Motion System (LMS). The movement of the sledge is constrained by two rails parallel to the longitudinal axis of the SCU. The coils are supported by a structure anchored on a plate of the Lid. Several thermal shields guarantee low heat load from the surroundings to the cryogenic vessel. The magnet is connected to the power supply outside the cryostat through current leads. Several feedthroughs at the Lid allow the connection of diagnostics sensors (temperature sensors, voltage taps, Hall probes etc.) to the outside of the cryostat.

the magnetic field will be present. The rod supporting the sledge and Hall-probe is indeed partially immersed in liquid Helium. The fraction of the rod that is immersed in liquid Helium depends on the z location of the Hall-probe. The elongation or contraction of the rod by few mm during the scan due to the different temperature gradient influences the z position of the Hall-probe with respect to the SCU.
The LMS will be equipped with a single axis vertical translator with 2400 mm of travel-range. The system is presently under development by the company Hositrad and has been specified to have resolution, accuracy and repeatability better or equal to 1 μm. The encoder of the LMS is beeing designed to account for temperature fluctuations and vibrations outside the cryostat.
The systematic error caused by the contraction/elongation of the rod inside the cryostat is more complex to be managed. Initially we foresee to correct the data analysis of the measured data by making use of the signal read by two Hall probes and by modeling the effect of the contraction of the rod analytically. More details on the data analysis will be included in future publications. Later on we plan to implement the direct measurement of the position of the sledge by using an interferometer. This solution requires an upgrade of the experimental setup and will therefore be implemented in the mid term future.
The installation of an interferometer is the most reliable method to measure with high resolution of the position of the Hall-probe. In this concept (illustrated in Fig. 2), the rod holding the sledge is replaced by two hollow tubes containing independent in-vacuum interferometers. The

interferometers are constituted by optical fibers, sensor heads and retro-reflectors. The sensor heads are interfaced with a pico-scale interferometer. The setup allows the simultaneous online monitoring of the length of the first and second hollow tubes and therefore online measurement of the position of the sledge. This solution presents many technical challenges, such as the fact that the space for the retroreflectors is quite limited and guaranteeing the mechanical stability of the setup is not trivial. The technical design is presently under study.

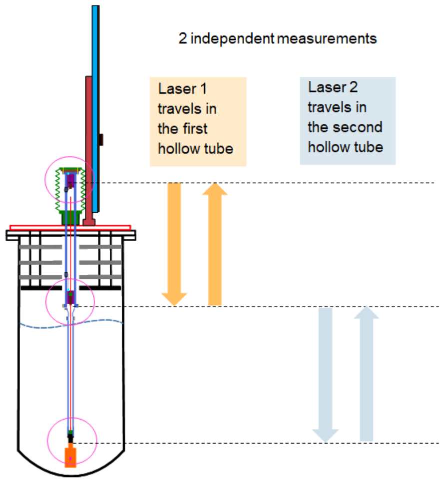

Figure 2. Sketch of the concept for the interferometric measurement of the sledge position. The rods holding the sledge are replaced by two hollow tubes containing independent interferometers.

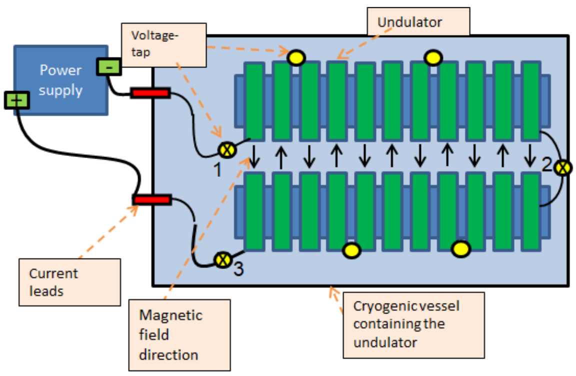

Figure 3. Simplified scheme of the distribution of the voltage taps. The voltage taps marked with crosses are used by the quench detection system, the other ones are used to identify the "hot-regions".

2.2. Quench Events and Magnet Training

Beside its application for the final magnetic characterization of the SCUs, SUNDAE1 will also be used for the training of coils. Quench events happening when the coil is initially brought into operation have to be managed in a safe way. We define quench event as the transition from the superconducting to the normal conducting state of a superconducting magnet [18].
A quench event leads to the appearance of voltage, temperature increase, differential thermal expansion and electro-magnetic forces, as well as cryogen pressure increase and expulsion within

the cryostat. During a quench event, the magnetic energy stored in the magnet, and the power provided by the power supply, are converted into heat in a percentage that can go from a small fraction to its totality.
In order not to damage the superconducting coil, the power supply of the coil has to be switched off immediately after the detection of a quench event. For this reason, the power supply is connected to quench detection system.
For the detection of the quench event, the three voltage taps marked with crosses in Fig. 3 are used. The voltage difference between points 1 and 2 (ΔV_{12}) and the one between points 2 and 3 (ΔV_{23}) are monitored and the reference value $\Delta V_{ref} = \Delta V_{12} - \Delta V_{23}$ is calculated. A quench event is detected if the signal ΔV_{ref} exceeds a given threshold within a specific time-interval, e.g. 100 mV within 10 ms. We have chosen to use power supplies and quench detection system produced by the company JEMA. The system can detect voltage thresholds as low as 1 mV in 1 ms.
When a quench-event occurs, the power-supply of the undulator is switched off and the stored magnetic energy is sent to a dump resistor.
At SUNDAE1, the maximum allowed voltage of the power supply during the discharge is 1 kV. Three different dump resistors having resistance 2.5 Ω, 1.25 Ω and 0.66 Ω will be available in order to minimize the decay time for different nominal current and inductance values of the coils (see Table 1).

During the magnet training procedure, the input current of the coil is increased slowly and

Table 1. Decay time of the current after a quench for a coil having inductance L = 1 H, different nominal current and corresponding optimized dump resistors. The following symbols are used: I is nominal current of the coil, L is the inductance of the coil, R is the resistance of the dump resistor, $\tau = L/R$ is the decay time to half the nominal current value and 5τ is the current decay time to less than 1 % nominal current value.

$I[A]$	$R[\Omega]$	$\tau[s]$	5τ [s]
400	2.5	0.4	2
800	1.25	0.8	4
1500	0.660	1.5	7.5

quench events due to imperfections of the physical setup are triggered. In absence of errors in the design of the magnet and in the experimental setup for the test, after a quench event the system ends up in a more stable state, thus allowing to increase further the input current. At the end of the training procedure, the magnet has reached its nominal current value [19].
During the training process, it is useful to dispose of diagnostics able to detect the hot-regions in the coil. The "hot-regions" are the regions of the magnet where the quench event has originated and, therefore, the temperature has reached higher values.
Hot-regions can be detected by monitoring voltage signals along the coil. For this reason, voltage taps are distributed along the SCU coil and the voltage difference between different portions of the magnet during a quench is monitored [20]. Spikes in the voltage readout identify the hot-regions. At SUNDAE1, 40 voltage taps will be available for hot-region diagnostics (see Fig. 3). For a 2m-long magnet with 18 mm period length, this roughly corresponds to one voltage tap every six periods. The voltage taps will be connected to imc CRONOSflex units with 40 simultaneously readable channels and a sampling rate per channel of roughly 50 kS/s.

3. Conclusion and Outlook

The advancement of SCU technology has a strategic importance for the future development of the European XFEL facility. In particular, the realization of an afterburner for the SASE2 line of the facility has been foreseen. The characterization of the magnetic field of the novel SCUs is a key step to understand and evaluate the technology prior to the installation in the beamline. The test-stand SUNDAE1 will allow the training and characterization of one stand alone coil in a liquid or superfluid Helium bath. In this contribution, we have shown the conceptual design of the test-stand and we have described the specifications of the main parameters. The setup is presently undergoing its technical design and procurement phase. The commissioning of cryogenics and diagnostics is foreseen to start in 2023.

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