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KIT Superconducting Undulator Development Story of a successful industrial collaboration & future prospects

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Abstract. Undulators are X-ray sources widely used in synchrotron storage rings and free-electron laser facilities. With the commercial availability of low-temperature superconductors, a new type of undulator was born, the superconducting undulator (SCU). In this context, the industrial cooperation between the Karlsruhe Institute of Technology and Bilfinger Nuclear & Energy Transition GmbH started more than 15 years ago. The SCU15 was the first of its kind SCU providing light to a beamline. The SCU20 followed and is still in operation at the Karlsruhe Research Accelerator. The successful realisation of such SCUs has required the simultaneous development of appropriate magnetic and cryogenic facilities.

1 Introduction

Insertion devices (IDs), such as undulators, are crucial for free-electron laser (FEL) facilities and advanced synchrotron radiation sources, as they generate photon beams with high brilliance and with a broad spectral range. Currently, the most prevalent undulator technology is the permanent magnet undulator (PMU). However, superconducting undulators (SCUs) have been developed through the application of low-temperature superconducting (LTS) materials. As the current standard, NbTi wire is wound around coils. However, Nb_3Sn wires are increasingly being used for higher magnetic field generation, where coil handling and winding is more complex and error-prone as special heat treatment is required [1]. It has long been known that theoretically SCUs with the same geometry, such as magnetic gap or period length, have a higher magnetic peak field on the symmetry axis than cryogenic PMUs [2,3]. This fact has also been demonstrated experimentally [4]. This technology therefore holds great potential not only for current accelerators and beamlines, but also for future storage rings and linear accelerators such as FELs and laser plasma accelerators (LPAs), see references [35,36] and section 2.4. A secondary advantage of the SCU is that, unlike cryogenic PMUs, there is no risk of performance degradation due to radiation damage to the magnet, i. e. demagnetization or magnetic structure damage [5–9]. The research and development of SCU technology has been pursued at the Institute for Beam Physics and Technology (IBPT) at the Karlsruhe Institute of Technology (KIT) for over 20 years. SCUs have been used in continuous operation at the Karlsruhe Research Accelerator (KARA) for 10 years now [3]. The conversion of a research idea into a commercial product was realised in cooperation with an industrial partner. The fusion of IBPT

Table 1: **Insertion devices (IDs).** The range of applications for IDs extends from THz to X-rays.

	SCU15	SCU20	HEX70 SCW	ANSTO SCU16	S-PRESSO	SCUF	DLS SCW	S-PRESSO Mock-Up	ANSTO SCW
period length	15	20	70	16	18	65	48	18	48
full periods	100.5	74.5	29	98	108*2	20	22.5	14	40
max. field on axis (T)	0.73	1.19	4.3	1.1	1.82	0.88	4.2	2.02	4.6
K-value (approx.)	1.0	2.2	28.1	1.6	3.1	5.3	18.8	3.4	20.6
location	KARA KIT, DE	KARA KIT, DE	NSLS II BNL, US	AS AUS	EuXFEL DE	FLUTE KIT, DE	DLS UK	EuXFEL DE	AS AUS
status	delivered 2014	delivered 2017	delivered 2022	delivered 2022	in production	in production	in production	cold tested	in production
beam stay clear (mm)	7 (15)	7 (15)	8	6	5	35	8	5	6

research and Bilfinger Nuclear & Energy Transition GmbH (Bilfinger) industrial know-how created a coherent partnership with the goal to develop and sell full-scale SCUs without cryogenic refrigerants for current and next generation low-emittance light sources.

The standard design parameters for each SCU presented in Table 1 are NbTi wound coils and cryogen-free conduction cooled operation at 4 K, using Gifford-McMahon cryocoolers. This cooling method has the advantage of being user-friendly and particularly attractive for facilities without helium recovery, as only water and electricity are required for operation. The scientific objective in the development of such SCUs has always been to achieve good field quality in order to maximise the spectral response. To achieve this, two conditions had to be met. First, the undulators had to be manufactured with the necessary mechanical precision and accuracy, so Bilfinger developed, improved and perfected new manufacturing processes. Second, the IBPT has designed, operated and is continuously developing appropriate measurement technologies and adequately equipped measurement facilities to characterise undulators in terms of their performance and magnetic properties. The results obtained were then fed back into the next iteration to optimise the manufacturing process and improve the magnetic characteristics. In addition, the IBPT offers the opportunity to install and test the undulator during the operational phase with KARA. This provides a deeper insight into standard operation and therefore allows a much better assessment of the entire SCU technology.

In the following we highlight the different perceptions of the three partners involved: the research institute IBPT, which develops SCUs, the company Bilfinger, which manufactures and produces the devices, and the Australian Nuclear Science & Technology Organisation (ANSTO), which ordered and operates the product as the end customer.

2 R&D on future accelerator technology at KIT

The research and development of SCUs began at IBPT more than 20 years ago. The further development of this technology requires high-precision magnetic measuring systems capable of resolving magnetic field changes in the mT range at 4 K with µm spatial resolution. These are the stationary installed CASPER I [10] and CASPER II [11] (**Ch**aracterization **S**etu**p** for Field **E**rror **R**eduction) facilities, continuously improved and in operation for over 10 years, and one new mobile measurement system [12] used for on-site measurements.

2.1 Magnet and Cryogenic Facilities

At CASPER I [10], short undulator coils up to 500 mm can be tested and trained in a vertical liquid helium bath cryostat. The local magnetic field is measured by Hall probes mounted on a sledge, which is moved along the beam axis of the undulator via a linear stage. The local accuracy of 2 µm is determined by the readout of a linear encoder. In addition at CASPER II [11], SC coils up to 2 m in length can be characterised at 4 K in a horizontal, cryogen-free, conduction cooled environment by local and integral magnetic field measurement techniques, see also Figure 1. The local measurements are performed by Hall probes on a sledge which is pulled along the coils while guided by two precisely machined rails. The position of the sledge is measured with sub-µm precision by a laser interferometer. A moving wire (CuBe,

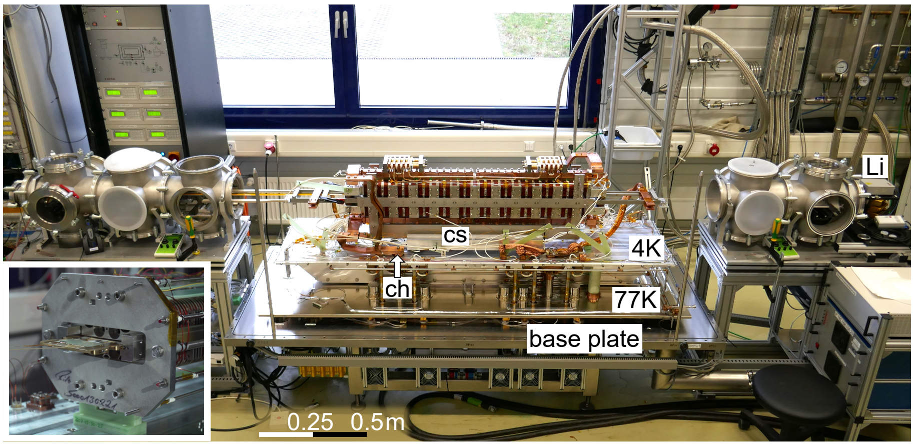

Figure 1: **CASPER II setup.** Open cryostat with the **base plate**, followed by a 77 K cold shield and the 4 K table to which the coils (HEX70 wiggler [13]) are mounted via a special coil support (**cs**). Cold heads (**ch**) with each 1.5 W at 4 K are in use. On the left and right are vacuum chambers containing the measurement instrumentation. The laser interferometer (**Li**) is on the right side. The inset shows the sledge. A scale bar is shown at the bottom of the Figure.

125 µm diameter) method [14] provides the first and second field integrals with further optimisation by using attached field correction coils. More information on the accuracy of CASPER II can be found in [15, 16]. A power supply with up to 1500 A is available at CASPER I and II. Additionally, both systems are equipped with an in-house developed quench detector system from the Institute of Data Processing and Electronics (KIT-IPE). The Physical Property Measurement System (PPMS, `https://qdusa.com/products/ppms.html`) 9 T from Quantum Design at the Institute for Technical Physics (KIT-ITEP) enables a direct in-house calibration with an accuracy of 100 µT for the Hall sensors used. Thus, no further correction factors to calibrate the Hall sensors are necessary. CASPER I & II are constantly improved to meet new requirements. For example, the height of the sledge could be reduced to 5 mm (including the Hall sensor) and the width to 104 mm, see Figure 1 bottom left corner. Further reduction to 4 mm in height (see Figure 2) and 65 mm in width will allow for even smaller beam pipe gaps. The adjustment of the interferometer at CASPER II by two mirrors was also replaced by a hexapod to make it simpler and more stable.

The variety of performed characterisations of different types of SC magnets [14, 17–23], ranging from in-house systems over applications at national and international research institutions, such as CERN, to companies, and the associated publications in scientific journals underline the possibilities of these measuring facilities at IBPT. CASPER I & II form the basis and foundation without which the technology transfer would not have been possible.

2.2 Mobile measurement systems

At IBPT we develop high-sensitive, and also mobile magnetic field measurement setups to precisely evaluate cryogenic IDs in the final cryostat. Measurement techniques for local and integral magnetic field studies are implemented for multipurpose use with any type of magnetic system. The setups are designed comparable to the stationary CASPER I & II to reach the same or better accuracy and reproducibility, see [15,16]. In 2022, the first mobile (moving wire) system was developed, assembled, tested and referenced at IBPT [12]. A more detailed investigation of the SCU16 at the Australian Synchrotron (AS) in Clayton, specifically, can be found in reference [24]. The reproducibility of the 1st and 2nd field integrals was 5x10^{-6} using the moving wire technique (CuBe wire with 125 µm diameter). Currently an upgraded system combining both local and integral magnetic field measurement techniques is assembled, see Figure 2. This new system will be used for quality assurance of the new wiggler for the Diamond Light Source during the site acceptance test. In 2025, the system shall be used for the second wiggler ordered by AS. In parallel, new measurement techniques such as constant current and pulsed wire methods are tested and evaluated to continuously upgrade and improve the mobile measurement devices.

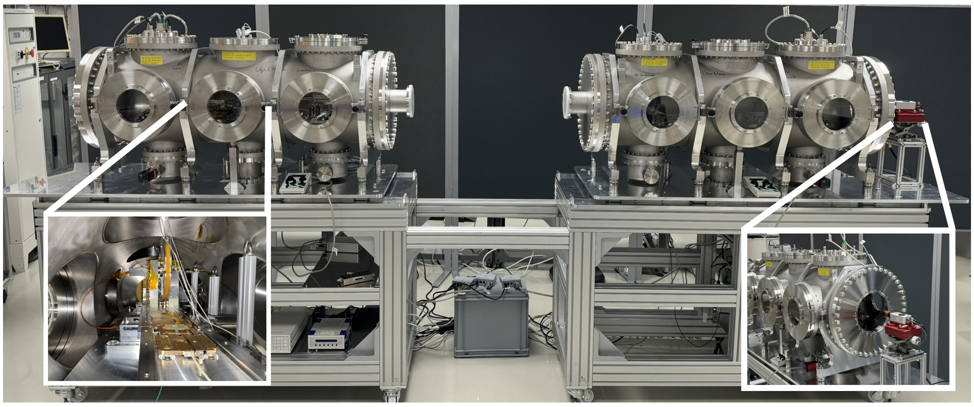

Figure 2: **Newly designed and assembled mobile measurement system.** On the right and left side are the vacuum chambers displayed which are mounted to the final cryostat on site of the end costumer. Bottom left-hand corner: sledge and (cf. Fig. 1) the associated instrumentation for pulling, guiding and reading the Hall sensor. Bottom right-hand corner: laser interferometer.

2.3 Transparency requirements for undulators operating in a storage ring
For accelerator operations the SCUs should be transparent, so that the electron orbit in a storage ring experiences only negligible disturbances during magnet field tuning. Preferentially, users should tune the field while at the beamline. The downtime after a quench should also be very short. Besides an excellent magnetic field quality, a good cooling concept, reliable quench safety, high systemic technical requirements for automation and synchronisation are needed. With respect to these crucial aspects the realisation of such SCUs is possible due to the available infrastructure in the Accelerator Technology Platform at KIT with its various institutes, laboratories and workshops. The associated expertise in the fields of cryogenic technology, ultra-high vacuum, solid state physics, measurement technology, electronics, but also modelling and simulation includes the aforementioned Hall sample calibration at KIT-ITEP and quench detection systems from KIT-IPE. The KARA storage ring with the associated beamlines made it possible to develop, advance and integrate the SCU technology in an accelerator environment under real-world operations [25]. The continuous further development of SCUs also opens up a spectrum of completely new research topics, as the following section will show.

2.4 Additional R&D and new research areas using synergy
At KIT we push exclusive R&D on compact, sustainable, energy- and resource-saving SC magnets and SCUs, based on high-temperature (HTS) technology. One promising approach is the development of SCUs by stacking 30 non-insulated, laser-structured, 12 mm HTS tapes to realise smaller period lengths ≤ 8 mm [26–29]. Another approach is a helical undulator with 4 mm non-insulated HTS tapes for compact FELs [30]. First cooling tests in liquid demonstrated suitable properties for both designs. As an example, one design showed current densities of up to 60.000 $\mathrm{A/mm^2}$. Non-insulated, so called not stabilised, HTS tapes can have the advantage of quench-free operation, i.e. well above I_c. In addition, the realisation of thermal transitions for cryogenic vacuum chambers [31], SC magnets for a short-length electron transport line for LPAs [32–34], SC transverse-gradient undulators for laser wakefield accelerator-driven FELs [35, 36] or the R&D on THz undulators for the European XFEL [37] and for FLUTE (Far Infrared Linac and Test Experiment) [38] are carried out. Since the emitted synchrotron radiation for protons of the Future Circular Collider for vacuum beam screens is similar to electrons at KARA, CERN selected the KIT accelerator test facility. Several prototypes were manufactured and installed in the beam screen test-bench experiment at KARA [39]. The development of SCUs with the possibility to change the period length during operations is also studied [40, 41]. The responsible and efficient use of energy and materials is an important topic for the current and future R&D on SCUs and their sustainable operation. The new HTS SCU concepts have the potential for reducing the energy consumption for cooling. The KIT Test field for Energy Efficiency and Grid Stability in Large-Scale Research Infrastructures (KITTEN) is a unique union of two research infrastructures, KARA and the Energy Lab, which supports research from the component to the system level [42]. This year, in 2024, a KIT-led project, the Research Facility 2.0, has also started to address the sustainability of particle accelerator [43].

3 Bilfinger's full-scale conduction cooled SC undulators portfolio

All IDs need to be transparent for the electron beam of the accelerator they are operating in. Therefore, stringent requirements are usually set for the 1st and 2nd field integrals concerning all operating currents. The magnetic design of all Bilfinger's recent IDs is point-symmetric, with a $\frac{1}{4}$ - $\frac{3}{4}$ end field adaption to achieve a straight trajectory around the target orbit inside the device. The design approach iterates the number of turns in the last three winding grooves of the ID's coils. The last step of optimisation of the trajectory, both in design and in operation, is achieved with so-called auxiliary coils in the last grooves. These auxiliary coils are wound with a small, typically 0.25 mm, SC wire to maintain the operating currents within a few amperes. The main coils' multifilamentary NbTi SC wire is of 0.68 mm x 1.08 mm rectangular cross section, therefore operating currents range from 300 A to above 1000 A. A typical design result for the 2nd field integral is shown in Figure 3 (a). In the course of the winding former manufacturing

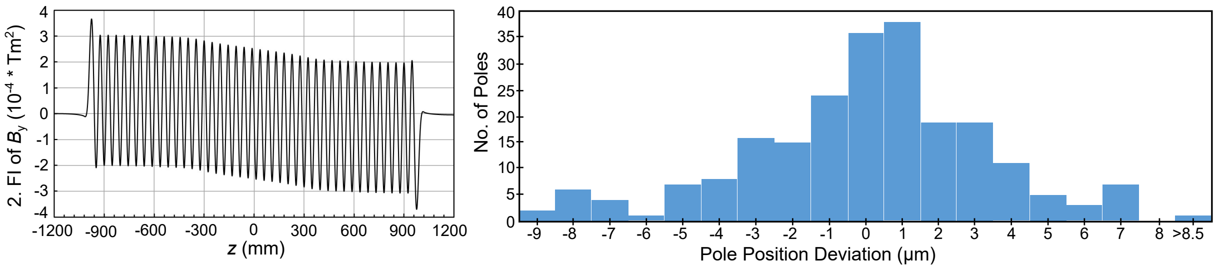

Figure 3: **(a) Computed 2nd field integral for a 40 full-period wiggler. (b) Distribution of the pole position deviation from the target position of a 2 m long undulator coil.** Each category provides the count number within an interval of ± 0.5 µm.

optimisation, improved methods have been found to mechanically machine the winding formers from one piece each, even if slightly longer than 2 m. The positions of the winding former's iron poles are crucial to achieve low field and phase errors. The technological development from 2012 with the SCU20 compared to 2024 with the SCU16 shows that the standard deviation for the pole width has decreased from 17 µm to 2 µm, and for the groove width from 32 µm to 2 µm. With the present manufacturing method, the deviations from the target positions are typically within ± 10 µm, as measured by a coordinate-measuring machine. An example of the position accuracy achieved within a 222 pole winding former is shown in Figure 3 (b). After coil winding, the SC wires have to be fixed to withstand the high Lorentz force densities during operation, therefore, the coils are vacuum-pressure impregnated. The process optimised during the last years is profiting from a resin-mixing plant that allows preparing two-component resin mixtures from independently pre-heated and evacuated storage vessels on demand, reducing the risk of premature gelling of the resin during the mould filling process.

Experience from the SCU16 BioSAXS (Biological Small Angle X-Ray Scattering) beamline [44] and the need for high mechanical accuracies in the EuXFEL project S-PRESSO [45] gave the impact to re-design the mechanical structure around the SC coils (see Table 1). Stiff plates provide the moment of inertia to counter-act bending of the ∼4.5 m long cold mass of S-PRESSO. As a side effect, the new mechanical structure also allows a more accurate positioning of the cold electron beam chamber inside the gap of the magnets. This is of particular importance, whenever the beam chamber has to act as the guiding element for cold local magnetic measurements inside the ID.

Thorough design, manufacturing and assembly of all cryogenic components of an ID is essential for reliable and efficient operation. Based on the experience of IDs being or having been operational at KIT, BNL, and ANSTO, the cryogenic design has been improved towards a more standardised and modular approach. Identical cryocooler, thermal bus, and current lead sub-assemblies are now foreseen for all IDs presently under design or manufacture. The design uses finite element software packages like ANSYS and nonlinear, isotropic or orthotropic materials' data for the simulations. An example of electron beam tube temperatures during operation with heat loads from thermal conduction and beam induced losses is shown in Figure 4 (a). The temperature of the beam tube inside the 4 K magnet is typically below 20 K. This modular cryogenic design and assembly approach helps reducing operational risks and time for assembly. As a result of this cryogenic concept, the cooldown of these SC systems is just a start-button-operation, no handling of cryogens is required, and there is no need for any cryogen-relief safety elements.

4 Experience of an end customer: SCU16 at the Australian Synchrotron (AS)

The AS [46] is a 3 GeV user facility operated by ANSTO since 2005. Based on the long-term operation of SCU20 at KARA, the BioSAXS beamline selected an SCU with a photon energy of 12.4 keV at the fifth harmonic to be designed and built by the company Bilfinger [24]. The SCU16 is a vertical racetrack undulator with a period length of 16 mm, a magnet length of 1.6 m and the longest SCU to be installed in a light source (cf. Table 1). The maximum B-field on axis is 1.084 T at $K = 1.62$ with a magnetic gap of 8.0 mm and a vacuum chamber height of 6 mm. First field measurements with the CASPER II system were performed at KIT prior to installation. In 2022, the SCU16 was installed and commissioned at AS. It took less than 4 days to cool down the entire system with an insulation vacuum of 10^{-6} mbar. In addition, only up to 10 quench cycles were required to restore the magnetic field after installation in the storage ring. The maximum ramp rate for the main current is 4.5 A/s, which means that the maximum field can be reached within 3 min. In the case of a quench, the temperature at the magnets/diode sensors rises to 20 K and it takes 25 min to reach the operational temperature again. With the mobile measurement system developed at KIT, the field quality was checked on site using the moving wire method and it was shown that the transport had no influence on the field quality. There is a maximum orbit deviation of less than 100 µm with a maximum disturbance of less than 5 µm with orbit feedback enabled. The overall change in horizontal and vertical betatron tunes was $v_{x,y}$= +0.0010, +0.0018 and is similar to other in vacuum undulators at the AS [47]. The spectrum of the SCU is displayed in Figure 4 (b). It can be

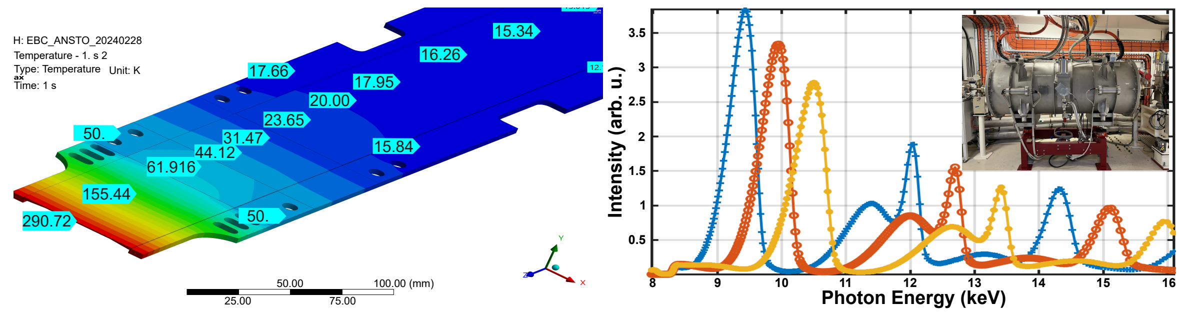

Figure 4: **Results for the SCU16.** (a) Local beam chamber temperatures during operation computed with ANSYS are shown from 15 K to room temperature. (b) Spectrum at 1.05 T (blue), 1.00 T (red), and 0.95 T (yellow) (inset: SCU16 installed at AS). For more details we refer to reference [24].

summarised that the cooling system operates well below the design temperatures, providing more than adequate performance for the BioSAXS beamline (> 10^{12} ph/s on sample) with quench recovery time of under 30 min.

5 Conclusion & outlook

Despite SCUs having a shorter development history than CPMUs, the strong collaboration between KIT and its industrial partner Bilfinger has advanced their development to a commercial product. Today, Bilfinger is the only company in producing full-scale SCUs based on conduction cooling and liquid cryogenics free. This was possible because we have continuously worked on improving and optimising magnet and cryogenic facilities at KIT-IBPT to enable precise and accurate field measurements. Due to its conduction cooling and horizontal orientation, CASPER II is ideally suited for the testing of the here presented SCUs. Furthermore, Bilfinger has continuously optimised its manufacturing processes to ensure the desired precision of SCUs. Ultimately, the end customers and photon science experiments benefit from this technology transfer. Building on the knowledge gained, the IBPT is not only further developing advanced measurement technologies for current and future IDs used in X-ray light sources, but also driving forward developments of SC THz undulators and HTS systems including SCUs, magnets for compact transport and injection lines, and many more.

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