KIT SUPERCONDUCTING UNDULATOR AND MAGNET DEVELOPMENTS - OVERVIEW AND STATE OF THE ART R&D ON HTS TECHNOLOGY

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Abstract

Undulators are widely used in synchrotron storage rings and free-electron laser facilities. With the advent of low-temperature superconductors (LTS), a new generation of superconducting undulators (SCUs) emerged, including the recent new THz LTS undulator for FLUTE. At KIT, state-of-the-art magnetic and cryogenic measurement capabilities — provided by the Magnet and Cryogenics Facilities (MCF) and the Accelerator Technology Platform (ATP) — form a foundation for the development and characterization of these systems.

Building on this experience, KIT is now advancing magnets and undulators based on high-temperature superconductors (HTS), aiming for compact, sustainable, energy- and resource-efficient solutions. These activities are driven by in-house research and providing the full value chain of HTS technology from tape development via structuring to prototypes and tests in real-world environments at KIT.

In this contribution, we provide an overview of our current developments and the supporting experimental infrastructure.

INTRODUCTION

Undulators are key components in modern synchrotron storage rings and free-electron laser facilities, enabling the generation of highly brilliant and tunable radiation for a wide range of applications. While permanent magnet undulators are widely used, SCUs enable significantly higher magnetic fields on the symmetry axis for comparable geometric constraints, allowing for shorter period lengths and enhanced photon energies [1]. With the commercial availability of LTS, SCU technology has matured and demonstrated its potential in various accelerator facilities [2–5]. At the Institute for Beam Physics and Technology (KIT-IBPT), extensive expertise in the development and operation of conduction-cooled LTS undulators has been established over the past decades [6], including recent developments such as a THz undulator for FLUTE (Ferninfrarot Linac- und Test-Experiment) [7, 8]. A key stone for this development are the MCF which allow a precise measurement of the magnetic properties and therefore a direct approach to the quality of the undulator. In close collaboration with our industrial partner Bilfinger, this work has also led to the successful industrialization of SCU technology [6]. Building on this experience, current research at KIT-IBPT focuses on the development of magnets and undulators based on HTS, aiming at compact, sustainable, and energy- and resource-efficient solutions.

In the following sections, a short motivation for HTS is given, followed by the HTS undulator research and is concluded by the HTS magnets. Lastly, the MCF and its possibilities are outlined.

FROM LTS TO HTS: MOTIVATION AND OPPORTUNITIES

LTS materials such as NbTi and Nb_3Sn have enabled the successful development of SCUs with high magnetic performance and reliable operation [9]. However, their operation at temperatures around 4 K requires complex and energy-intensive cryogenic systems. While conduction cooling has significantly simplified operation by eliminating the need for liquid helium, the overall cooling effort remains substantial. In addition, intrinsic geometric limitations arise from the finite cross-section and mechanical properties of LTS wires, restricting the minimum achievable bending radius and thus limiting undulator period lengths to approximately 8 mm and above. These constraints hinder further miniaturization and performance scaling of SC IDs. HTS conductors, often available as tapes, allow for novel design approaches that can overcome these geometric limitations and enable shorter period lengths. Their higher critical temperatures enable operation at elevated temperatures or, alternatively, significantly higher current densities and magnetic fields at 4 K. This opens up new possibilities for more compact designs, enhanced field strengths, and improved energy efficiency, contributing to more sustainable and resource-saving accelerator technologies. Beyond accelerator applications, HTS materials are widely regarded as a key enabling technology for next-generation high-field systems.

HTS UNDULATOR R&D AT KIT

The use of HTS enables fundamentally new approaches to undulator design, see Fig. 1, particularly when employing **structured HTS tapes**. At KIT, high-intensity laser pulses are used to define a meander-shaped current path within the SC layer, resulting in a quasi-sinusoidal magnetic field distribution along the beam axis [10]. Based on this concept, two main design approaches are currently pursued [11, 12]. In a first concept, a single 15 m long HTS tape is structured and wound around a stainless-steel yoke to form a continuous, jointless current path. In a second approach, 25 cm short

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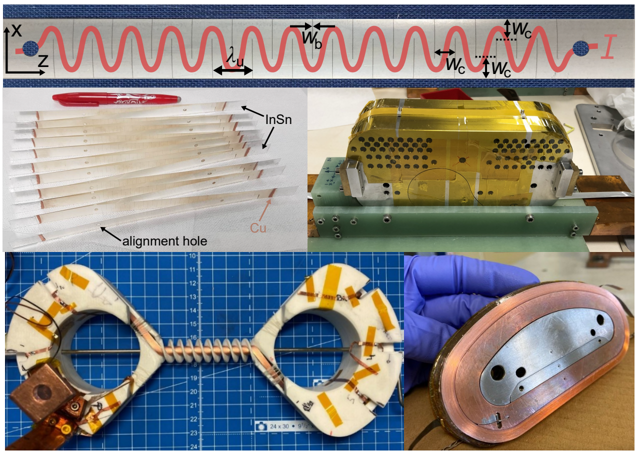

Figure 1: Undulator developments at KIT-IBPT. On top, in red, the quasi-sinusoidal path through a structured tape. Based on this, the zigzag and the jointless concept are shown. At the bottom, the helical undulator and the racetrack coil, both developed in collaboration with CERN, are shown.

structured HTS tapes are connected to each other via a soldering contact at the ends in an alternating zigzag configuration, allowing for increased flexibility in handling, material usage, and potential replacement of individual segments. Subsequently, initial power tests and first field measurements were conducted in liquid helium.

Vertical racetrack coil Operating in high-field regimes pushes superconductors close to their critical limits, making the risk of a quench omnipresent, and protection remains challenging. A no-insulation (NI) winding approach has been pursued in a KIT-CERN collaboration within the CompactLight project [13] for HTS undulator coils with a 13 mm period length and vertical racetrack design. The NI winding allows current to redistribute within the coil, preventing the spread or formation of a normal zone [14]. Tests at 4.2 K and 77 K achieved a magnetic flux density of approx. 2 T and operation at up to 300% of the expected critical current, with no degradation or damage to the superconductor.

Helical undulator In addition to planar designs, further concepts such as helical HTS undulators with 4 mm NI tape are being investigated, highlighting the versatility of HTS-based approaches [15]. The first HTS helical undulator demonstrator (10% of full winding, 77 K) with NI winding and copper terminals achieved stable operation. A full short model with five periods (13 mm period, 5 mm gap) is the next step, targeting >2 T at 4.2 K — an approximately 60 % increase over NbTi undulator technology.

HTS MAGNET DEVELOPMENT BEYOND UNDULATORS

In addition to superconducting undulators, high-temperature superconductors are being explored at KIT for a broad range of advanced magnet applications.

Periodic Quadrupole An ongoing research activity focuses on the design, fabrication, and testing of an HTS periodic quadrupole magnet based on simple pancake coils for laser–plasma accelerator applications [16]. The demonstrator, corresponding to one fourth of half a period of the periodic quadrupole and employing NI HTS tapes, was successfully operated at both 77 K and 4.2 K without degradation. Stable operation was achieved at 150 A (120 % of the critical current) at 77 K and up to 1 kA at 4.2 K, as shown in Fig. 2. Magnetic field measurements at 4.2 K showed excellent agreement with Opera simulations, with deviations below 1%, confirming the capability of the prototype to generate high magnetic field gradients. Future work will focus on improving the bridge connections to enable operation at even higher currents of approximately 1.3 kA.

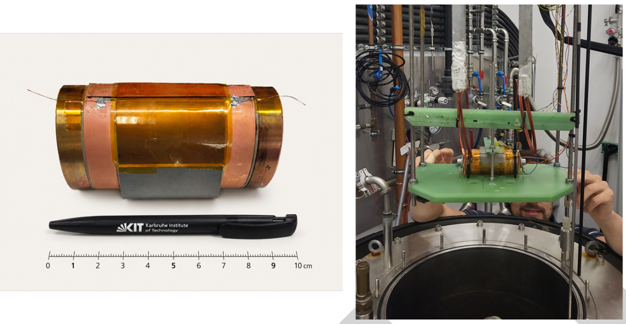

Figure 2: HTS periodic quadrupole prototype (left) and cryogenic measurement setup in CASPER I (right).

HiTSMAPIS & HTSCryo Currently, there are two projects for novel HTS magnet concepts funded by the German Federal Ministry for Research, Technology and Space. The HiTSMAPIS project advances HTS magnet technology through combined simulation and experimental R&D, focusing on compact, energy-efficient, and resource-saving magnet systems for future photon and ion sources. A particular emphasis is placed on understanding transient effects in HTS coils, including NI ReBCO-based windings, through dedicated modelling and experimental validation.

The HTSCryo project focuses on advancing HTS magnet technologies for next-generation particle accelerators. The aim is to achieve high magnetic fields at elevated operating temperatures, thereby reducing reliance on liquid helium and improving overall energy efficiency. A key aspect is the development of HTS demonstrators ranging from small-scale test coils to accelerator-relevant geometries, supported by iterative simulation and experimental validation.

Both projects contribute to the development of sustainable, scalable, and energy-efficient magnet technologies for future accelerator facilities.

MAGNET AND CRYOGENICS FACILITIES

A key enabler for the development of SCUs at KIT is the availability of dedicated magnetic and cryogenic measurement infrastructure. These systems are essential for characterizing the magnetic performance of prototypes with mT resolution at 4 K with µm spatial resolution to provide feedback to the iterative design and manufacturing process. Without this experimental capability, continuous development and optimization of SC devices would not be possible.

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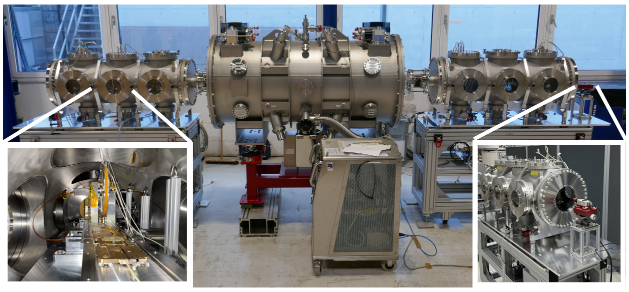

Figure 3: Mobile Measurement system with the latest wiggler for Diamond Light Source, UK. Bottom left: sledge and instrumentation. Bottom right: laser interferometer.

Figure 4: COMPASS teststand and worlds first operational prototype for 10 kA CMRC current lead.

Five systems build the foundation. These are the permanently installed CASPER I and CASPER II (Characterization Setup for Field Error Reduction), two mobile systems for the on-site measurements and COMPASS (Compact Accelerator System).

CASPER I is a vertical liquid helium bath cryostat-based measurement facility designed for undulator coils up to 500 mm [17]. It allows current-carrying capacity tests and high-precision local magnetic field measurements by Hall probes mounted onto a slide.

CASPER II extends these capabilities towards larger (up to 2 m SC coils) and more flexible device geometries [18]. It is a horizontal, cryogen-free, conduction-cooled environment equipped for local and integral field measurement at 4 K. Additionally, CASPER I and II are equipped with an in-house developed quench detection system from the Institute of Data Processing and Electronics (KIT-IPE). Both systems have been continuously improved and have been in operation for over 15 years.

In addition to stationary facilities, comparable **mobile systems** have been developed to allow in-situ characterization of SC devices in the final cryostat [19]. The smaller system only allows integral field measurements, whereas the upgraded system provides both local and integral field measurements. It is the first of its kind worldwide and was successfully tested in 2025 for the new Diamond wiggler, see Fig. 3.

The **COMPASS** teststand, shown in Fig. 4, is a dedicated experimental facility at the Institute for Refrigeration and Cryogenics (KIT-ITTK) [20]. It enables the testing and characterization of SC magnet systems, including compact accelerator undulators, at currents from several hundreds amperes up to 10 kA.

A key focus of the COMPASS teststand is the investigation of mixed-refrigerant-cooled current leads. Typically, state-of-the-art current leads transport electrical current from ambient to cryogenic temperatures, using a series combination of a normal conducting, metallic part and HTS materials below 80 K for low-loss operation. Due to resistive losses in the normal conducting part, the current lead contributes significantly to the heat on the cryogenic system [21]

In case of a mixed-refrigerant-cooled current lead, the resistive part is cooled by a cryogenic mixed-refrigerant cycle (CMRC). By providing cooling power along the entire length of the resistive part in a closed-loop setup, the heat load on the cryogenic system, as well as the overall power demand for cooling, is significantly reduced [22].

CONCLUSION AND OUTLOOK

HTS undulators and magnets developed at KIT demonstrate the potential to overcome the limitations of traditional LTS systems, achieving compact, sustainable, and energy-efficient solutions. Key milestones include stable operation at magnetic flux densities up to 2 T and successful powering beyond critical current limits, validated by experimental results aligning closely with simulations.

The unique combination of in-house design, fabrication, and dedicated magnetic and cryogenic measurement infrastructure provides a strong basis for continuous development and optimization. Future work will focus on enhancing performance and reliability, including improving component connections for higher current operation and scaling prototypes to full-scale models. These advances aim to establish HTS technology as the cornerstone for next-generation accelerator systems.

ACKNOWLEDGEMENT

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REFERENCES

[1] J. Bahrdt and E. Gluskin, “Cryogenic permanent magnet and superconducting undulators”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 907, pp. 149–168, 2018. `doi:10.1016/j.nima.2018.03.069`

[2] S. Casalbuoni *et al.*, “Field Quality of 1.5 m Long Conduction Cooled Superconducting Undulator Coils with 20 mm Period Length”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1395–1398. `doi:10.18429/JACoW-IPAC2017-TUPAB035`

[3] S. Casalbuoni *et al.* “Superconducting Undulators: From Development towards a Commercial Product”, *Synchrotron Radiat. News*, vol. 31, pp. 24–28, 2018. `doi:10.1080/08940886.2018.1460171`

PREPRINT

[4] K. Zhang *et al.*, “Review and prospects of world-wide superconducting undulator development for synchrotrons and FELs”, *Supercond. Sci. Technol.*, vol. 35, no. 9, pp. 093001, 2022. `doi:doi:10.1088/1361-6668/ac782a`

[5] S. Casalbuoni *et al.* “Superconducting undulator activities at the European X-ray Free-Electron Laser Facility”, *Frontiers in Physics*, vol. 11, p. 1204073, 2023. `doi:10.3389/fphy.2023.1204073`

[6] B. Krasch *et al.*, “KIT Superconducting Undulator Development Story of a successful industrial collaboration & future prospects”, *IOP Publishing*, vol. 3010, pp. 012026, 2025. `doi:10.1088/1742-6596/3010/1/012026`

[7] J. Gethmann *et al.*, “Prospects for photon science and beam dynamics studies of a THz undulator at FLUTE”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 2046–2048. `doi:10.18429/JACoW-IPAC2023-TUPL134`

[8] A. Grau *et al.*, “A THz superconducting undulator for flute - Design parameters and layout”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 1226–1229. `doi:10.18429/JACoW-IPAC2023-MOPM108`

[9] S. Prestemon *et al.*, “NbTi and Nb3Sn Superconducting Undulator Designs”, *AIP Conference Proceedings*, vol. 705, pp. 294–300, 2024. `doi:doi:10.1063/1.1757792`

[10] B. Krasch *et al.*, “Measurement Setup and Magnetic Field Studies of a Compact Superconducting Undulator With Laser-Structured HTS Tapes”, *IEEE Trans. Appl. Supercond.*, vol. 34, no. 5, pp. 1–4, 2024. `doi:10.1109/TASC.2024.3355320`

[11] B. Krasch *et al.*, “Design study of a compact superconducting undulator based on laser-structured HTS tapes”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 3781–3784. `doi:10.18429/JACoW-IPAC2024-THPS22`

[12] B. Krasch *et al.*, “HTS Undulator Design Study and First Results: Two promising magnet concepts”, *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, pp. 1–6, 2025. `doi:10.1109/TASC.2025.35294132`

[13] G. D’Auria *et al.*, “The CompactLight Design Study”, *Eur. Phys. J. Spec. Top.*, vol. 233, pp. 1–-208, 2024. `doi:10.1140/epjs/s11734-023-01076-0`

[14] S. Richter *et al.*, “High-Temperature Superconducting Undulator Prototype Coils for Compact Free-Electron Lasers”, *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, pp. 1-7, 2023. `doi:10.1109/TASC.2023.3242625`

[15] S. Richter *et al.*, “Design and Manufacturing of an HTS Helical Undulator Demonstrator for Compact FELs”, *IEEE Trans. Appl. Supercond.*, vol. 34(3), pp. 1–7, 2024. `doi:10.1109/tasc.2024.3356449`

[16] S. Fatehi *et al.*, “Fabrication and Powering Test of a High-Temperature Superconducting Periodic Quadrupole Driving a Short-Length Transport Line for Laser-Plasma Accelerators”, *IEEE Trans. Appl. Supercond.*, vol. 34, no. 3, pp. 1–7, 2024. `doi:/tasc.2024.3356449`

[17] E. Mashkina *et al.*, “CASPER - A magnetic measurement facility for superconducting undulators”, *IOP Publishing*, vol. 97, p. 012020, 2008. `doi:10.1088/1742-6596/97/1/012020`

[18] A. Grau *et al.*, “Instrumentation for Local and Integral Field Measurements of Superconducting Undulator Coils”, *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 2312-1215, 2011. `doi:10.1109/tasc.2010.2092748`

[19] Y.-R. E. Tan. *et al.*, “Design and commissioning of the first superconducting undulator for the BioSAXS beamline at the Australian Synchrotron”, *J. Synchrotron Radiat.*, vol. 23, pp. 908–918, 2025. `doi:10.1107/S1600577525003418`

[20] J. Arnsberg *et al.*, “Design of a high-current cryogenic test stand for compact accelerator systems”, *International Institute of Refrigeration (IIR)*, 2023. `doi:10.18462/IIR.ICR.2023.0290`

[21] Y. S. Choi and M. S. Kim, “Performance test of current lead cooled by a cryocooler in low temperature superconducting magnet system”, *Physica C: Superconductivity*, vol. 494, pp. 355–359, 2013. `doi:10.1016/j.physc.2013.04.085`

[22] E. Shabagin, “Development of a CMRC cooled 10 kA current lead for HTS applications”, Dissertation, Karlsruhe Institute of Technology, Germany, 2022. `doi:10.5445/IR/1000144514)`

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