HTS TECHNOLOGY DEVELOPMENT FOR ENERGY EFFICIENT MAGNETS IN PSI LARGE RESEARCH FACILITIES

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Abstract

Over the past decade, the Magnet Section at the Paul Scherrer Institute (PSI) has developed extensive expertise in superconducting magnet design, fabrication, assembly, and testing through PSI strategic projects and the CHART (Swiss Accelerator and Research Technology) MagDev program. This expertise provides a strong foundation for the energy transition of magnet systems in large research facilities. At PSI, this transition is supported by complementary initiatives: CHART, SMILE (Superconducting Magnets to Improve Large Research Facilities Efficiency), and the European project HTS4SRI. They enable the development of High-Temperature Superconductor (HTS) magnet technologies to improve performance while reducing electricity consumption and CO_2 emissions. This article outlines the proposed roadmap and presents the R&D directions. Key directions include HTS tape and cable technologies for DC and AC applications, conduction-cooled magnets, pulsating heat pipes for thermal management, efficient cryogenic powering, radiation-hard conductors for high-intensity target areas, and life-cycle assessment. An integrated framework for the design, manufacturing, and qualification of energy-efficient superconducting magnets is now being established. The long-term strategy is to progressively install efficient HTS magnets across PSI's large research facilities and supporting more sustainable accelerator technologies.

INTRODUCTION

Over the past decade, magnet technology for large research infrastructures at the Paul Scherrer Institute (PSI) has undergone a profound transformation. Initially focused on resistive magnets, developments have progressively shifted toward compact, energy-efficient solutions, and more recently toward approaches integrating sustainability considerations. This transition has been driven by major strategic projects such as the SLS 2.0 [1] and the IMPACT project, including the HIMB and TATTOOS beamlines [2] as well as by PSI's strong involvement in CHART (Swiss Accelerator Research and Technology consortium) and initiatives such as SMILE (Superconducting Magnets to Improve the Efficiency of Large research Facilities). This article presents the context and motivations behind the development, the key drivers enabling this transformation, and the outcomes in terms of infrastructure, coils, and magnets based on high-temperature superconducting technologies. Technologies related to the use of permanent magnets, as well as NbTi and Nb_3Sn superconductors, are addressed in separate articles [3, 4].

CONTEXT AND MOTIVATIONS

PSI Large Research Facilities

Large research infrastructures at the Paul Scherrer Institute are true engines of discovery, producing proton, neutron, muon, and photon beams that serve as probes of matter. Facilities such as the High Intensity of Proton Accelerator Complex (HIPA), the Swiss Light Source (SLS 2.0), and the two lines of the Free Electron Laser (SwissFEL) support fundamental research, materials science, and medical applications including proton therapy. These facilities are highly energy-intensive, with a large share of electricity consumed by accelerator magnets used to steer and control particle beams. At the Paul Scherrer Institute, the total annual energy consumption is approximately 140 GWh. The High-Intensity Proton Accelerator (HIPA) accounts for about 50% of this consumption, with around 26% attributed to magnets. Future projects such as the IMPACT project (HIMB and TATTOOS) will further intensify these needs, relying on more powerful magnets in demanding environments, which increases energy consumption with conventional technologies [5].

HTS Technology for PSI Magnets

PSI magnet section has progressively developed expertise in energy-efficient accelerator magnet technologies, particularly through high-temperature superconducting magnets. This evolution reflects a broader trend in which traditional requirements—performance, field quality, stability, and reliability—are now complemented by energy efficiency and sustainability, as illustrated in Fig. 1.

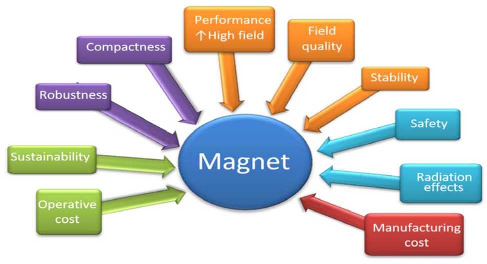

Figure 1: Accelerator magnet requirements combining core criteria—performance, field quality, stability, robustness—with emerging priorities such as energy efficiency, sustainability, operation cost, radiation tolerance.

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Accelerator magnets must therefore combine high performance and stable operation with reduced operating costs and CO_2 footprint. This transition requires selecting the most suitable material for each application. Permanent magnets are well suited to low, fixed-field, high-density, low-radiation environments, such as light sources. For fields above 2 T in high-radiation environments, such as proton accelerators, superconducting magnets are generally more appropriate. The choice between LTS and HTS depends on operating conditions, cooling needs, costs, and radiation effects on conductors and insulation. Table 1 summarizes the benefits and limitations of HTS technology compared with normal-conducting and LTS magnets.

Table 1: Benefits and limitations of conduction-cooled HTS magnets with respect to resistive and LTS ones.

Criterion	Benefit	Limitation
Field performance	High field in compact designs	Field quality is harder to optimize with HTS
Compactness	Reduced magnet size for a given performance	More complex mechanical integration
AC behaviour	Suitable for demanding DC or slowly varying applications	AC losses remain significant in time-varying fields
Thermal stability	Large temperature margin with HTS improves stability	Local heat deposition must still be managed
Safety (Protection)	High stability can lower quench risk	Quench detection and protection are more challenging for HTS
Cryogenics	Operation above 20–30 K eases cooling constraints compared with LTS	Requires efficient conduction-cooling design
Energy efficiency	Lower electricity consumption than resistive magnets	Cryocoolers still contribute to power use
CAPEX (capital cost) vs OPEX (operating costs)	Potential savings through reduced operation costs	HTS conductors and associated systems remain costly, with additional expenses from continuous magnets cooling.
Sustainability	Reduced energy use helps lower CO_2 footprint	Overall benefit depends on full life-cycle conditions
Stable operation	Large temperature margin and high thermal stability	Radiation heat loads, cooling instabilities, or transient disturbances can still trigger a quench inducing downtime

Beyond energy efficiency, magnet development must now be addressed within a broader sustainability framework. The planetary boundaries concept introduced by Johan Rockström [6] highlights that technologies, including superconducting magnets, create upstream pressures through raw-material extraction, water use, and manufacturing, while also delivering downstream benefits such as energy savings and societal value. For PSI, this means extending the traditional design criteria—operating conditions, cost, and radiation resistance—to include a rigorous methodology covering material selection, responsible manufacturing, efficient cryogenic operation, life-cycle assessment, and recyclability. The challenge is therefore to develop future efficient magnets (starting with demonstrators) that achieve high performance without compromising the environment.

PILLARS FOR ADVANCING HTS TECHNOLOGY AT PSI

The adoption of superconducting technology is driven by a dual objective: reducing operational energy consumption while enhancing magnet performance and compactness. This transition relies on three pillars: a long-term strategy for PSI facilities in operation and upgrades, the development of key technological building blocks supported by dedicated testing, integration and experimental infrastructure, and strategic programmes such as SLS 2.0, IMPACT, CHART, SMILE, and HTS4SRI. Together, these elements form a coherent framework for energy-efficient and sustainable magnet concepts. Ongoing PSI beam line upgrades and the progressive replacement of high-power HIPA magnets, create concrete opportunities for HTS implementation. Strong collaborations with CERN, research institutes, industry, and Park Innovaare [7] further support technology transfer from R&D to real applications.

Long-term Strategy

The key elements of the use of HTS technology for PSI efficient magnets include:

- reduction of electrical power consumption up to 50%
- use of cryocoolers in particular with inverter-driven compressors and cold heads,
- integration of pulsating heat pipes to improve thermal management and heat extraction,
- qualification of radiation-hard conductors,
- development of low-loss power delivery to HTS magnets by integrating cryogenic power converters directly inside the cryogenic environment,
- HTS magnets with variable-field capability for operation with changing beam energies,
- development of helium-free magnet demonstrators operating with subcooled nitrogen,
- integration of sustainability metrics, such as Life Cycle Assessment, into magnet design,

These features are well suited to constrained and evolving PSI beamlines, where radiation tolerance, operational flexibility, and reduced energy consumption are essential. The main long-term objective is to progressively

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replace high power-consuming resistive magnets in the HIPA beamlines with HTS magnets. These solutions are more compact, significantly more energy-efficient (with energy savings per magnet ranging from ~238 to 725 MWh/year), and in some cases capable of operating at higher magnetic fields. Over a typical 20-year operation period, the cumulative energy savings per magnet can reach 4.5 to 14.5 GWh, corresponding to a CO_2 reduction of approximately 180 to 590 tons. The table 2 summarizes the main characteristics of the possible candidates for replacement.

Table 2: Some Characteristics of Targeted HIPA Magnets to Be Replaced in The Next Decade.

Dipole	**AHC**	**AHM/N**	**AHB**	**AHD1/2**
Field (T)	1.56	1.50	1.80	1.20/1.15
Weight (To)	12.5	22	4.2	19
Power (kW)	128	67	189	32/74
Energy saved (MWh/y)	481	238	725	267

PSI Projects and R&D Programs

The production of two NbTi superconducting superbend dipoles for the second phase of the SLS 2.0 has been a major catalyst for developing superconducting magnet expertise at PSI [8]. These cryogen-free magnets are designed to operate in the 3–5 T range at 4 K and are currently being tested at PSI, where stable operation at 5.4 T and 4.2 K has been achieved. Their installation in the machine is planned for the end of 2026. Reliable operation of these superbends will provide an important basis for future HTS-based super bend*ing dipoles* in fourth-generation diffraction-limited synchrotron light sources. IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target Technology), a strategic PSI project currently underway, provides a major opportunity to develop HTS magnet technologies at PSI. As a major HIPA upgrade, IMPACT is structured around two pillars: High-Intensity Muon Beamlines (HIMB), aimed at in-creasing muon production for fundamental physics, and the Targeted Alpha Tumour Therapy and Other Oncological Solutions (TATTOOS) beamline, dedicated to medical isotope production for diagnostics and targeted therapies. The project includes the design, assembly, and testing of 34 magnets, including large-aperture solenoids, dipoles, a wobbler, and separators. Within this framework, super-conducting technology will be progressively introduced, with a 4 T HTS cable-based magnet planned for TATTOOS and targeted for installation around 2030.The construction of this 4 T HTS magnet for the TATTOOS beamline will be strongly facilitated by the HTS4SRI project (High Temperature Superconductors for Sustainable Research Infrastructure), funded by the European Union under the HORIZON-INFRA-2025-01-TECH-01 program, starting in September 2026 for four years. HTS4SRI is bringing together PSI, CERN, GSI, CEA, CIEMAT, UNI Milano, INFN, and Bruker. The central goal of the project is to establish a systematic framework in which conductor development, cryogenics, cryogenic power supplies, radiation-tolerant materials, and assembly processes are jointly optimized under sustainability criteria and energy efficiency. As proof of feasibility, HTS4SRI will be not limited to the construction of the 4 T dipole magnet for TATTOOS but also design, fabricate, and qualify large-aperture HTS quadrupole coils for SIS18 synchrotron and a compact combined-function magnet for CERN FCC-ee. These demonstrators will validate the methodology in diverse operational environments, including radiation exposure, the potential for more than 30% reduction in magnet-related electricity consumption compared with conventional resistive technologies

The CHART initiative was established in 2016 with SERI support to coordinate and strengthen accelerator research in Switzerland [9]. It brings together CERN, PSI, EPFL, ETH Zurich, and the University of Geneva, with a strong focus on technologies for the Future Circular Collider. Within CHART, PSI plays a central role in developing LTS and HTS high-field magnet technologies for FCC-hh and FCC-ee applications. PSI's activities include the design, fabrication, and testing of demonstrator magnets, supported by a complete value chain covering electro-magnetic and mechanical design, conductor and cable development, coil fabrication, assembly, and testing. CHART has also strengthened PSI's superconducting magnet infrastructure through the construction of the MagDev laboratory, while enhancing international collaborations and visibility. In addition, it supports the transfer of FCC-driven R&D toward future PSI applications, including HTS high-field solenoids for the P^3 experiment, 18 T split solenoid for DC operation at SINQ, and a compact HTS coil designed to generate 6 T on the sample inside the manipulator head of the SLS ACCESS 2.0 beamline.

SMILE (Superconducting Magnets to Improve the Efficiency of Large Research Facilities) is a PSI magnet section initiative launched in 2025, focused on magnet technology development related to the energy and environmental needs of PSI accelerators. Its objective is to stimulate the development of superconducting magnet technologies and associated systems by addressing not only magnet performance, but also energy efficiency, sustainability, radiation constraints, and system integration. The initiative is structured around three main activity areas. Figure 1 describes a conceptual diagram of SMILE with the tree poles of activities and the various collaborations. The first activity pole focuses on efficient DC superconducting magnets, with emphasis on irradiation effects, sustainability aspects, and PSI-relevant applications. The second addresses compact HTS magnets operating under variable magnetic fields with changes of above 1 T/s. This work focuses also on the development and study of low-losses HTS cables such as CORC with the use striated tapes, including both experimental and numerical activities.

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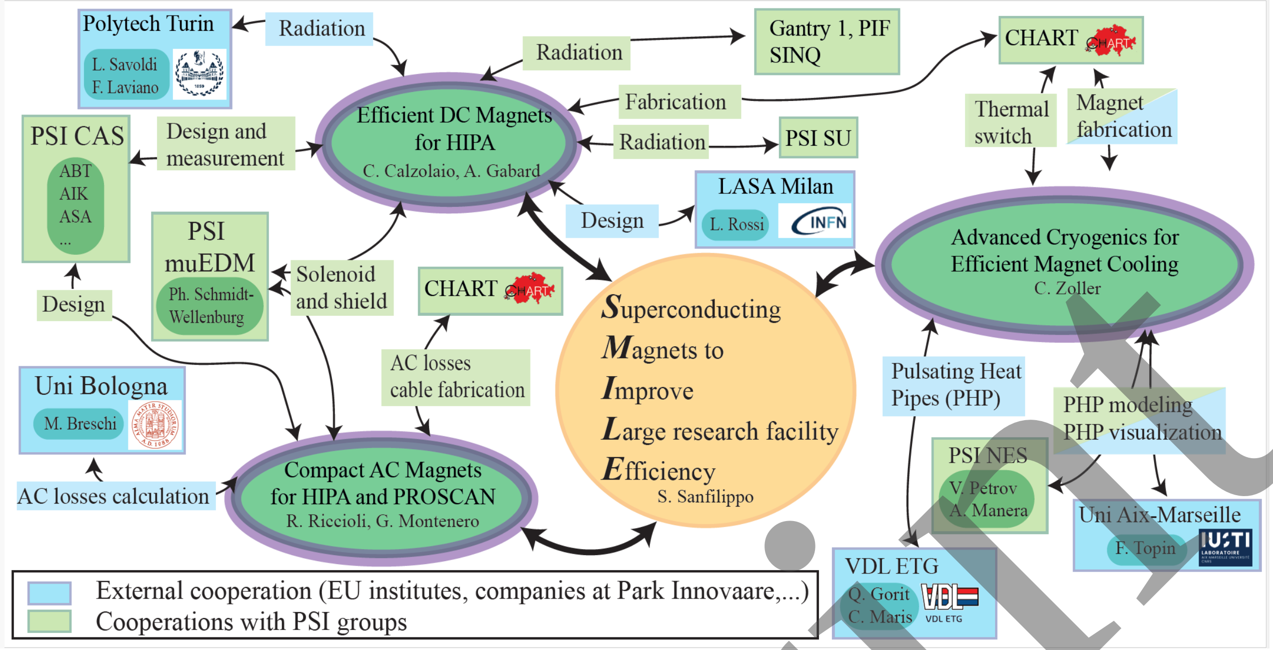

Figure 2: Conceptual diagram of the SMILE framework integrating design, fabrication, and testing of superconducting magnets for improved efficiency in large research facilities.

The third focuses on advanced cryogenics for efficient magnet cooling. SMILE is currently partially funded: the third pole has benefited from a fruitful collaboration with VDL ETG since 2024 enabling the development of Pulsating Heat Pipes using neon and nitrogen. Additional collaborations have been established with the Polytechnic University of Turin for radiation hardness studies and the University of Bologna for the development of numerical model of the electromagnetic behavior of the CORC cable. The synergies in expertise and experience within CHART are significant, particularly in magnet fabrication, including the development of cables from striated conductors and impregnation processes.

Technological Building Blocks and Infrastructure for Magnet Manufacturing and Tests

The development of HTS conductors and cable architectures is a key technological building block. Several directions are being pursued to cover a broad range of applications. Relevant directions included coated tapes, multi stacked-tapes, striated tapes [10], and CORC®-type cables (Conductor around a round core) for high-current and variable-field applications [11]. Non-insulated coil technology [12] is another major breakthrough, enabling current redistribution, improved mechanical and thermal stability, and intrinsic quench-protection capability. A key research focus is also the development of optimized magnet geometries to mitigate the strong Lorentz forces that limit performance at high magnetic fields. In this context, stress management by the structure itself plays a central role, as the electromagnetic loads are intercepted directly by the mechanical support structure rather than being fully transmitted to the superconducting conductor [4]. The Canted Cosine Theta geometry can be regarded as this concept pushed to its limit: each conductor turn is placed in an individual groove, allowing the surrounding structure to capture, support, and redistribute the stresses, thereby reducing conductor degradation and improving the robustness of high-field magnets [13].

HTS magnets enable operation in the 20–70 K range using cryogen-free cooling systems. For future PSI magnets, particular effort is devoted to efficient cooling solutions, since cryocoolers avoid large liquid-helium infrastructure and support compact, modular magnet systems. Two directions are pursued. First, one- or two-stage 4 K GM cryocoolers, already used in several PSI magnets, can be combined with dual-inverter compressors such as the E- 77A, operating at 6.5/7.5 kW at 50/60 Hz, to enable faster cooldown, reduced-speed operation, and lower energy consumption [14]. Second, in the context of SMILE, Pulsating Heat Pipes operating with He, N_2 or Ne are being developed as passive thermal links between HTS coils and cryocoolers, improving temperature uniformity, reducing hot spots, and supporting compact cryogen free magnets [15].

These building-block technologies only reach their full potential when supported by dedicated infrastructure, enabling their integration, validation, and scaling into reliable HTS magnet systems. PSI's laboratories provide a complete environment for HTS magnet development. Since 2020, the MagDev laboratory has been progressively developed with CHART support as a dedicated infrastructure for super-conducting magnet R&D at PSI. It covers the full value chain of new magnet concepts, including design, coil winding, Nb_3Sn reaction, soldering for no-insulation and insulated REBCO coils, impregnation, assembly and pre-load, instrumentation, precision metrology, and measurement analysis (see Fig. 3). MagDev is now a key PSI platform for developing and qualifying advanced

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Figure 3: Panoramic view of the MagDevlab dedicated to the superconducting magnet technology development.

Superconducting magnets, with CHART acting as a catalyst for expertise, infrastructure, and innovation.

A dedicated cryogenic test station for superconducting conductors, coils, and magnets has also been developed. It is composed of a cryogen-free setup cooled by cryocoolers, flexible operation from 4.5 K to 77 K, high-current powering up to 2kA, quench protection, and magnetic field qualification with-in a single platform. The station includes a cryostat with thermal shields, vacuum pumps, and multiple cryocoolers, enabling tests at 4.5 K and at intermediate temperatures up to 77 K and also in liquid-nitrogen bath. It supports characterization of superconducting materials and coils, including RRR, Tc, thermal conductivity, AC losses, Pulsating Heat Pipes qualification and high-field testing of HTS and LTS coils. Dedicated electronics provide temperature control, voltage measurements, and quench detection using CERN's uQDS system with customized detection algorithms. Magnetic qualification, including field integral and mapping, is performed with a 3D Hall probe with 0.1% accuracy. This platform is a key asset for the rapid characterization of conductors, coils, HTS and LTS magnets.

OVERVIEW OF HTS R&D DIRECTIONS

High Field and Efficient Magnets

HTS technology development at PSI is strongly driven by the REBCO Subscale Magnet program, developed within the High Field Magnet and CHART roadmap. This program provides a stepwise path to qualify HTS technologies for future FCC-hh magnets, covering conductor concepts, coil fabrication, field quality, AC losses, stress management by structure, and quench protection before scaling toward high-field short models ab3ove 14 T. Three demonstrators, RS1, RS2, and RS3, are planned within MagDev phase 3. RS1 is a 4 T double-aperture racetrack-coil magnet using insulated soldered REBCO stacked tape conductors [16] to assess stress-management concepts in a Nb_3Sn-like common-coil geometry. RS2 introduces a field-aligned common-coil design to reduce the conductor dimension exposed to time-varying fields, while RS3 will explore striated tape-around-core cables to suppress AC losses and field errors. An energy-saving HTS magnet development is pursued within the HTS4 project [17], part of the CHART framework and FCC-ee feasibility studies. HTS4 targets a low-power, cost-effective nested HTS magnet system for FCC-ee by replacing normal-conducting sextupole and quadrupole magnets with compact superconducting variants. Two CERN and PSI demonstrators explore complementary approaches: a canted-cosine-theta design based on insulated HTS tapes, and a partially insulated cosine-theta configuration. The expected benefit comes from eliminating ohmic losses and increasing the dipole filling factor, potentially reducing total FCC-ee energy consumption by about 20%. The project is reinforced by the development of a cryogenic power supplies by ETH Zürich within CHART framework. This concept places part of the power conversion inside the cryostat to reduce current-lead losses, targeting 5–6 W total cryogenic losses for a 250 A HTS system, compared with about 21 W for a conventional room-temperature supply [18].

CHART MagDev activities also investigate the promising uses of non-insulated (NI) HTS technology as a route toward compact, robust, high-field superconducting magnets. This approach is applied to the PSI positron-production experiment P^3 through the development of a cryogen-free 15 T NI REBCO solenoid designed for efficient particle capture in the SwissFEL beamline [19]. The solenoid was designed and manufactured at PSI. Figure 4 shows a coil demonstrator made of 4 pancakes (left) and the assembled HTS solenoid cooled using two cryo-coolers (center and right). The power tests at 21 K were stopped at 1 kA, corresponding to a magnetic field of about 10 T, before installation in the SwissFEL beamline in 2026. The performance limitations are now understood (mechanical failure of the soldered Field's metal bond between pancakes) and will be addressed during a second run in 2027.

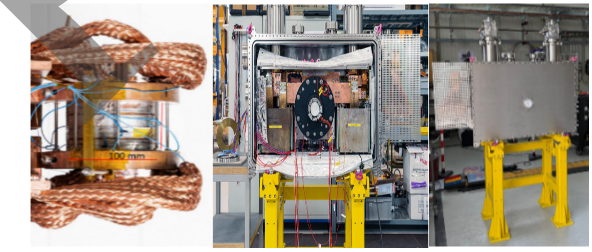

Figure 4: Non-insulated HTS capture solenoid for P^3: (left) REBCO NI coil stack demonstrator, (center) integration of the cold mass inside the cryostat, and (right) fully assembled conduction-cooled magnet system.

Study of Radiation Hardness of HTS at PSI

PSI offers complementary irradiation facilities, including PIF for proton irradiation with energies from 6 to 230 MeV, fluxes up to $\sim 2\times10^9$ protons$\cdot$s$^{-1}\cdot$cm^{-2} and possible measurements at room temperature or in liquid nitrogen; the PROSCAN Gantry 1 proton-therapy facility, with beams up to 230 MeV and doses larger than ~20 kGy per treatment and the SINQ neutron irradiation service, providing characterized neutron spectra for displacement-damage and activation studies. Several $YBa_2Cu_3O_7{-}\delta$ (YBCO) and $GdBa_2Cu_3O_7{-}\delta$ (GdBCO) samples were irradiated at room

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temperature using the above-mentioned facilities, after having been characterized in liquid nitrogen before irradiation. For the Gantry 1 experiment, a total dose of approximately 22.1 kGy was delivered within about 20 s, whereas at the Proton Irradiation Facility (PIF) a dose of about 56 kGy was delivered over a much longer irradiation time of 15 h. Despite the large dose-rate difference, no measurable change in critical current or critical temperature was observed at room temperature after irradiation. One Faraday Factory YBCO sample was also irradiated in liquid nitrogen at PIF for 15 h with a 230 MeV proton beam and a total fluence of 10^{18} p·m^{-2}. Only a marginal increase in the n-value was observed, about 4%, which requires repeated tests to confirm its significance. Since the sample was warmed to room temperature before post-irradiation characterization, partial recovery may have masked irradiation-induced effects. In parallel, an HTS magnet demonstrator is being developed within SMILE to bridge material studies and real operating conditions. It consists of a dry-wound coil made of 190 turns of 4 mm Faraday Factory REBCO tape, mounted on a copper support and integrated into an aluminium cryostat with shielding. The system is cooled by an RDE-412D4 cryocooler, providing about 1.25 W at 4 K, and will operate between 10 K and 40 K, mainly around 20 K. Installation near the PSI proton cyclotron is planned in 2026, with irradiation over about 4000 hours at an expected dose rate of 3×10^{-4} Gy/s. Radiation monitoring and regular critical-current measurements, combined with modelling of radiation-induced damage in HTS tapes with Politecnico di Torino, will support lifetime predictions for superconducting magnets in high-radiation environments [20].

CONCLUSION

PSI is entering a transition where accelerator magnets must combine performance with energy efficiency, sustainability, and radiation tolerance. HTS magnets offer compact high-field solutions, improved thermal stability, and reduced power consumption, although challenges remain in field quality, AC losses, protection, cryogenics, cost, and radiation effects. Through challenging projects and programs, a dedicated infrastructure and international collaborations, PSI has built a value chain from conductor and cable development to coils and demonstrators. A roadmap based on insulated and non-insulated HTS technologies supports both high-field magnets and compact HTS magnets operating around 1.5–3 T, with high efficiency, radiation environment and operation above 20 K. These activities establish HTS as a realistic pathway toward sustainable magnets for current and future PSI beamlines.

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