Enhanced Quench Stability of Coils Employing Defect-Tolerant REBCO Conductors

Jian Rong , Harshit Kumar Singh , Shengchen Xue , Jithin Sai Sandra, Lingfeng Zhu,
Chirag Goel , *Member, IEEE*, Nghia Mai, Umesh Sambangi, and Venkat Selvamanickam , *Fellow, IEEE*

Abstract—RE-Ba-Cu-O (REBCO, where RE denotes rare earth elements) high temperature superconducting (HTS) tapes are susceptible to uncontrolled quench events due to their slow quench propagation velocity. The high specific heat of the materials and the large temperature margin with respect to the critical temperature (T_c) suppress rapid quench propagation, which in turn drives the formation of local hotspots once a quench is initiated. In addition, tape displacement during electromagnetic loading and thermal cycling could cause defects in a HTS coil, which could initiate quenches. To address these challenges, we have developed a novel slot-and-fill (slot-n-fill) tape architecture, in which slots are patterned through all structures of tapes and filled with conductive material. This design enhances current sharing across neighboring turns in a non-insulated coil and increases thermal conductivity across turns. In this work, defect-triggered quench experiments were performed at 77 K in Nitrogen vapor to evaluate quench and recovery behavior. The results demonstrate that slot-n-fill architecture significantly improves defect-tolerance in non-insulation coils, confirming its potential for enhance the robustness and reliability of REBCO-based superconducting magnet systems.

Index Terms—High-temperature superconductor, REBCO, slotted tape, defect-tolerance, quench stability, hotspot temperature.

I. INTRODUCTION

RARE-EARTH barium copper oxide (RE-Ba-Cu-O or REBCO, where RE denotes rare earth elements) high-temperature superconducting (HTS) tapes are essential components in next-generation magnet systems for applications such as fusion energy, high-energy physics, and advanced material science [1], [2], [3]. These tapes can carry high current in high background field but are prone to quenches due to their slow quench propagation velocity, which is about a thousand times slower than that of low temperature superconductors [4], [5], [6], [7], [8], [9].

In coils, mechanical effects such as tape displacement during electromagnetic loading and thermal cycling could introduce defects. Moreover, the architecture of REBCO tapes, with a superconducting film only 2-5 μm thick, increases sensitivity to non-uniformities that may exacerbate defects. Although defects in the superconducting film or coil structure can trigger quenches, the slow quench propagation velocity of HTS coil, caused by their high specific heat and large temperature margin with respect to T_c, leads to the formation of localized hotspots. In addition, the REBCO tapes' layered structure and high-resistivity buffer layer limits current sharing between adjacent turns in coil assemblies, further exacerbating hotspots [10], [11], [12].

To address these limitations, we developed the slot-and-fill (Slot-n-Fill) tape architecture, in which slots are patterned through all layers of tapes and filled with conductive materials [11]. This design significantly reduces the inter-turn contact resistivity and enhances current sharing. In our previous study [13], we tested quench stability behavior of coils employing both standard and slot-n-fill tapes under heat-pulse-triggered quench conditions. The results revealed that slot-n-fill architecture substantially enhanced quench stability in non-insulation (NI) coils.

Building on that work, this study evaluates the defect-triggered quench behavior of NI coils fabricated from both standard and slot-and-fill REBCO tapes. Defect-triggered quench experiments were performed at 77 K in nitrogen vapor under different discharging time constants to assess both quench development and recovery behavior. The results highlight that the slot-n-fill design enhances defect tolerance and improves the overall reliability and robustness of REBCO-based superconducting magnet systems.

II. EXPERIMENTAL APPROACH

A. NI Coil Samples

In this study, we made two kinds of NI coils employing standard and slot-n-fill commercial REBCO tapes with a width of 4.0 mm. The tape structure includes copper layer ($20 \ \mu m \times 2$), silver layer ($2 \ \mu m \times 2$), Hastelloy layer ($50 \ \mu m \times 1$), Buffer layer ($0.3 \ \mu m \times 1$), REBCO layer ($2 \ \mu m \times 1$). The slots pattern in slot-n-fill architecture follows a 2-2-2 slot pattern, as shown in Fig. 1 (**left**), with two dashed lines of slots parallel to the edges of tape. The slots are laser-etched through all layers of the tape and filled with conductive material (silver and copper) to facilitate current shunting to the substrate and stabilizer and
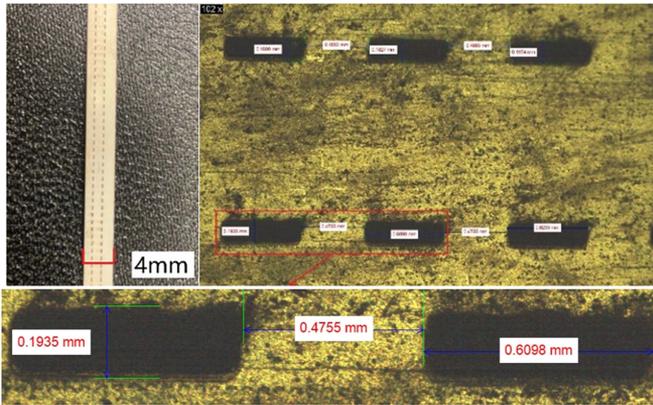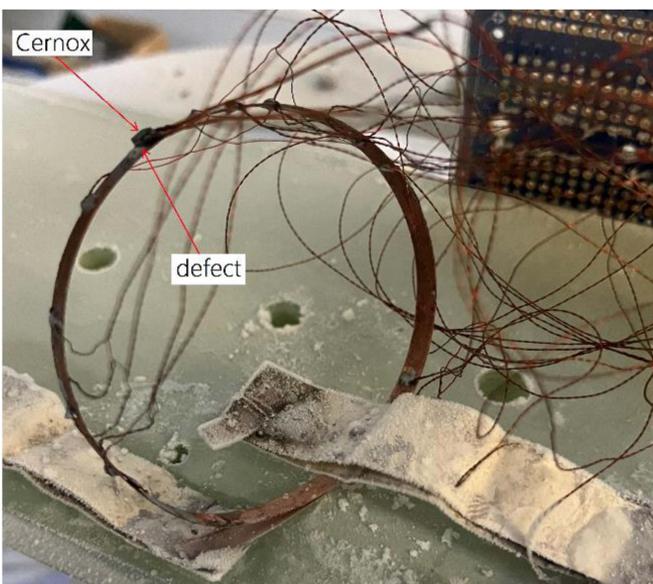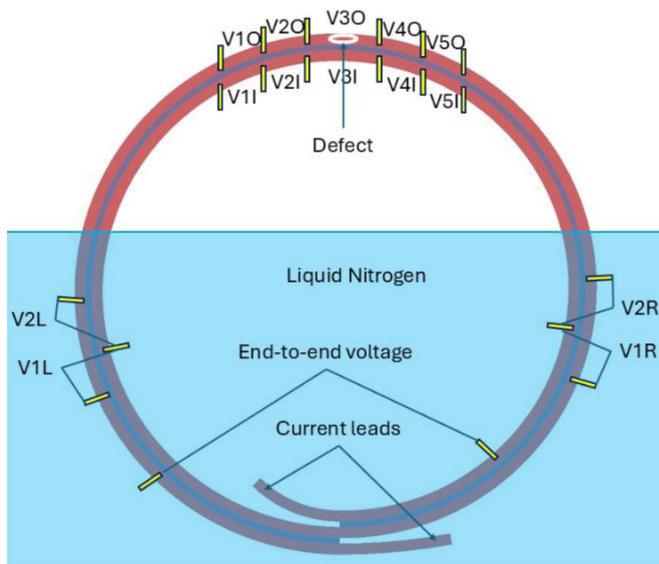
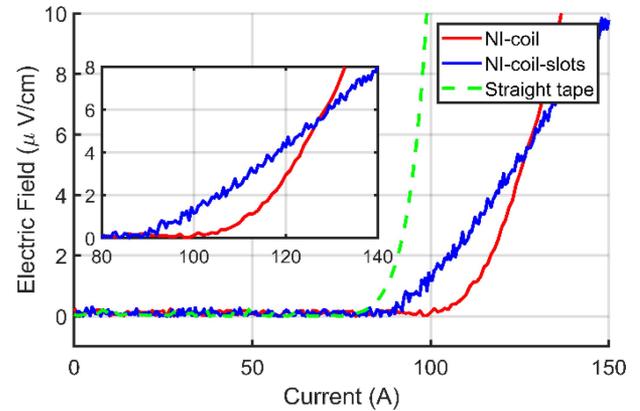Fig. 1. Slot pattern of slot-n-fill architecture.

Fig. 3. Electric field–current curves for no-insulation (NI) coils employing standard REBCO tape (NI-coil) and slot-n-fill REBCO tape (NI-coil-slots).

Fig. 2. Schematic of NI coil samples with defect (top), photograph of the NI coil with defect for quench stability testing (bottom).

enhance current sharing across turns in NI coils. Each slot is a rectangular hole (0.6 mm × 0.19 mm), with a 0.48 mm gap between adjacent slots, as shown in Fig. 3(right). The slots caused a critical current drop which was approximately equal to the proportion of slot width in a 4-mm-width tape [10], [11], as shown in Fig. 1 **(right)**.

The NI coils were fabricated by co-winding In52Sn48 strips with either standard or slot-n-fill REBCO tapes, the thickness of In52Sn48 strip was 0.5 mm, and the coils were soldered in an oven with maximum temperature of 140°C. The NI coils were wound with two turns around a 4.0 cm diameter core, using approximately 30.0 cm of tape for each coil. After soldering, the core was removed.

In this study, quenches were triggered by an artificial defect, of 1.0 mm diameter circular area, where the REBCO layer is damaged by laser, as shown in Fig. 2. Current leads were soldered to the terminals of coils connecting to REBCO sides with an overlap length of 12 mm. To minimize the effects of Joule heating from the current leads and observe quench propagation, the current leads (bottom zone) were immersed in liquid nitrogen, while the defect region of the sample was exposed to nitrogen vapor, as shown in Fig. 2.

Voltage taps were attached in the defect zone (labelled as 'voltages in defect zone' in the following section) to monitor quench behavior and on both sides of the current leads (labelled as 'voltages in current lead zone' in the following section) to observe current-sharing behavior during a quench, as shown in Fig. 2.

B. Quench Testing System

The quench measurement system is designed to assess the quench stability of the samples under controlled conditions. Voltage data is acquired using an NI-PXIe-4309 data acquisition system at a sampling rate of 1000 Hz, returning data every 1 milli second. A Cernox temperature sensor monitors the defect zone, ensuring a temperature of 77 K before quench initiation. The TDK-GEN8-600 power supply delivers the transport current to the sample.

To prevent transients, that come from quench or other unexpected status, damaged NI coil during testing, two voltage protection methods were used:

Hardware protection: The TDK GEN8-600 power supply's voltage limitation features were used. Initially, the voltage (V0) was read via the power supply, once transport current reached the set value. Then, the voltage limit of the power supply was set to V0 + 0.1 V. If the voltage read via the power supply exceeded this voltage limit, the power supply would reduce the current to maintain the voltage within the limit. Once the voltage limit was set, protection was enforced through hardware alone, without the need for continuous voltage monitoring by the test program.

Software protection: A Keithley 2182A measured the end-to-end voltage across the sample continuously. Once the end-to-end voltage reached a threshold of 50 mV, the TDK power supply was immediately shut down via software. In this test, 50 mV threshold can balance effective quench protection with the need to log meaningful quench behavior data.

These dual protection methods safeguard the sample during high-current quench tests, ensuring reliable and safe data acquisition. In general, the hardware protection is more sensitive than software protection, since the voltage reading for software protection is inside the testing loop, while the voltage used for hardware protection is read at the power supply itself. However, if software protection needs to be triggered earlier than hardware protection for current gradient control, then the voltage threshold for hardware protection should be set at a value higher than that for software protection.

C. Measurement Protocol

In this study, we assumed that NI-coils are used in a magnet system with a discharging time constant of 2 seconds. A defect is assumed to appear suddenly during normal operation. There is a delay time between defect's appearance and quench detection. Once the quench is detected, the magnet system begins discharging, with the current variation over time described by the formula [14]:

$$I\left(t\right) = I_0 e^{-t/\tau}$$

Where I_0 is the operation current, and τ is time constant. This model simulates the current decay during a quench event, allowing us to evaluate the quench behavior and recovery dynamics under realistic operating conditions.

In NI coils, once quench in a turn is triggered by a sudden defect, part of current would be shared to adjacent turns, reducing current flowing through stabilizer. This minimizes Joule heating and hotspot temperature during discharging cycle, thereby protecting the coil from damage.

III. Result

The initial critical current of the 4 mm-wide REBCO tape used for fabricating NI coils is approximately 160 A. After slotting, the critical current decreases to 145 A. Introducing an artificial defect further reduces the critical current by approximately 30%. As shown in Fig. 3, the critical current values of NI-coil-slots (made by slot-n-fill REBCO tape) with defect and

NI-coil (made by standard tape) with defect are 100 A and 115 A, respectively.

Fig. 3 presents the electric field–current curves for the NI coils, indicating a decrease in the n-value for the NI-coil compared to the straight tape, with a further reduction observed in the NI-coil-slots. In a straight tape, when current exceeds critical current, a portion of current, which is excess part than critical current, is carried by stabilizer. While, in a NI coil, the excess current will flow radially across turns from one current lead to another, due to high current sharing performance across turns. Moreover, the slots filled with silver and copper in the NI-coil-slots reduce the inter-turn resistance compared to NI-coil without slots, as evidenced by the shallower slope of linear portion in Fig. 3. Consequently, the NI-coil-slots exhibit higher current sharing performance across turns than NI-coil without slots. Therefore, the observed decrease in n-value does not reflect an actual degradation in the intrinsic n-value of the REBCO tape itself. Rather, the radial current flowing across turns mitigates the voltage rise, giving the appearance of an n-value decrease. This effect is more pronounced in the NI-coil-slots than NI-coil due to better current sharing efficiency across turns of slot-n-fill architecture.

During testing, an initial transport current of 16 A was applied, well below the critical current of coils to prevent quench-induced damage before data acquisition. The transport current was then increased to 144 A and maintained for delay times of 0.5 s or 2.0 s. At the end of the delay time, the current began to decrease with a time constant of 2.0 s, until reaching zero.

As shown in Fig. 4(a) (c), when the current abruptly increased to 144 A and held during the delay time, voltage spikes were observed in both defect zone and current leads zone. Voltage jumps in defect zone caused by a defect-triggered quench, while voltage jumps in current leads zone caused by current sharing across turns. At the moment of current reaching 144 A, voltages in both current lead and defect zones reached the highest value and then gradually stabilized during delay time. At the end of delay time, voltage of V3O and V4O in the defect zone of outer turn, as well as V1L and V2L in current lead zone, as shown in Fig. 2, were reversed due to discharging and induction of coil. After delay time, the amplitude of voltages in both defect and current lead zone reduced progressively and eventually dropped to zero when the transport current becomes lower than critical current of the coil.

For the 2.0 second delay time configuration, as shown in Fig. 4(b) (d), after the transport current stabilized at 144 A, voltages presented in current lead zone across turns, caused by a defect-triggered quench, indicated current sharing between turns. The voltages in both defect zone and current leads zone of NI-coil-slots were around 30 μV, which is significantly lower than that in the NI-coil with a voltage value of 160 μV. Although hotspot temperature was not measured directly, the lower voltages suggest a lower hotspot temperature during discharging process [15], [16], [17]. This indicates that the slot-n-fill architecture enhances defect tolerance of NI coils due to improved current sharing performance. The slots, filled with highly conductive material such as silver and copper, facilitate this improvement.
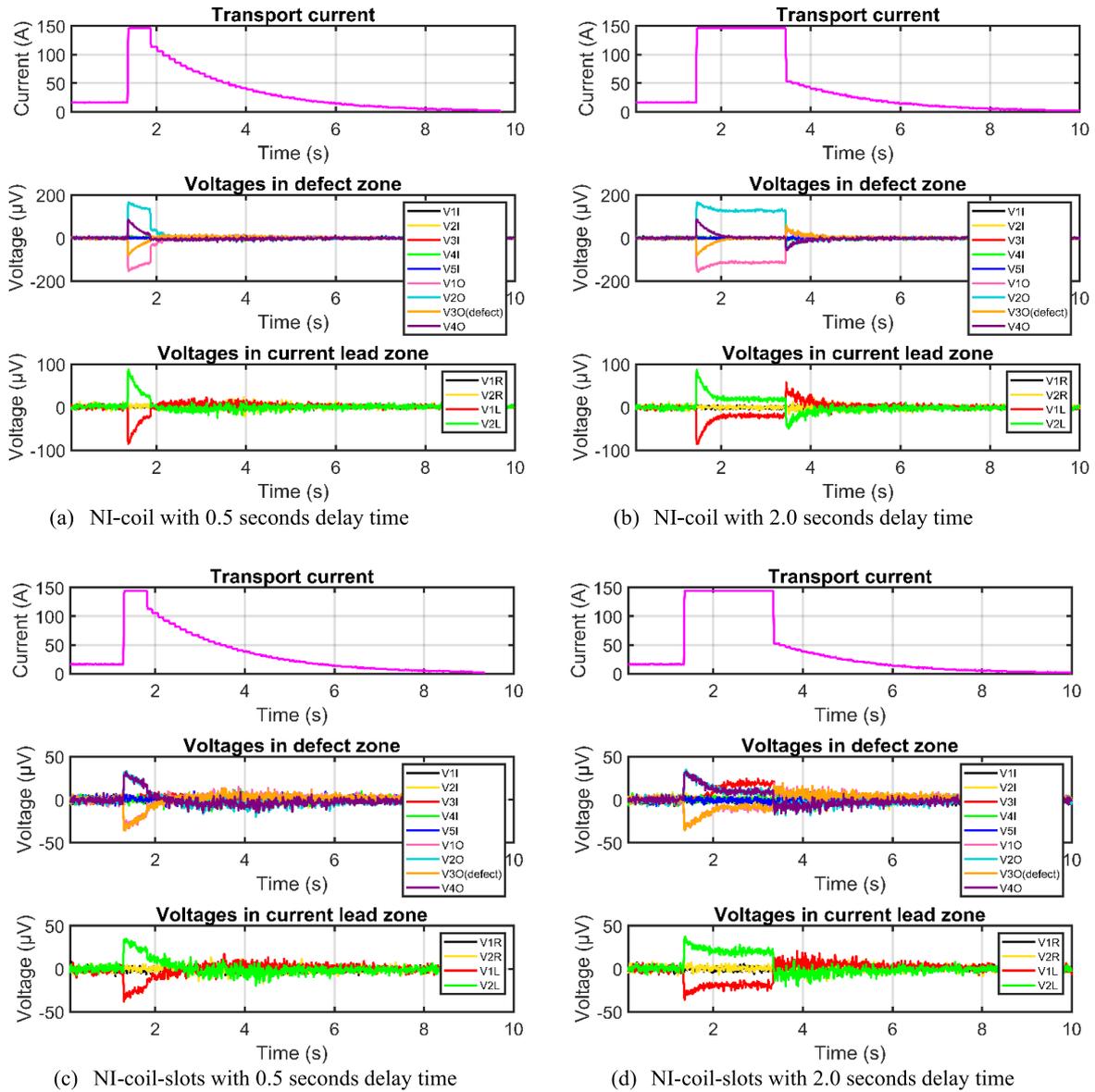
Fig. 4.   Quench behavior of NI-coil and NI-coil-slots with both 0.5- and 2.0-seconds delay time.

Additional tests were made at higher transport current: 160 A and 180 A, which is significantly higher than critical current of REBCO tapes. In both configurations, the quench recovered without critical current degradation, which demonstrates that the current-sharing capability of the coils provides an overcurrent protection, allowing them to handle transient overcurrent conditions without sustaining permanent damage.

IV. CONCLUSION

This study investigated the defect-triggered quench behavior and defect tolerance of non-insulated (NI) coils fabricated from both standard and slot-n-fill REBCO tapes. The NI coil with slots (NI-coil-slots) exhibited significantly lower voltages in both the defect and current lead zones compared to the standard NI coil, indicating reduced hotspot temperatures during the discharge

process and enhanced defect tolerance. This improvement stems from the superior current-sharing performance enabled by the conductive materials filling the slots in the slot-n-fill architecture, which enable efficient current sharing transfer from REBCO film to the stabilizer and adjacent turns. These results confirm that the slot-n-fill design substantially enhances the defect tolerance of NI coils, improving their reliability for superconducting magnet applications, even though the slots reduced the critical current.

REFERENCES

[1] Z. S. Hartwig et al., "The SPARC toroidal field model coil program," *IEEE Trans. Appl. Supercond.*, vol. 34, no. 2, Mar. 2024, Art. no. 0600316, doi: 10.1109/TASC.2023.3332613.

[2] A. P. Malozemoff et al., "Progress in high temperature superconductor coated conductors and their applications," *Supercond. Sci. Technol.*, vol. 21, no. 3, 2008, Art. no. 034005, doi: 10.1088/0953-2048/21/034005.

[3] P. Bruzzone et al., "High temperature superconductors for fusion magnets," *Nucl. Fusion*, vol. 58, no. 10, 2018, Art. no. 103001, doi: 10.1088/1741-4326/aad835.

[4] A. D. Berger, "Stability of superconducting cables with twisted stacked YBCO coated conductors," Plasma Sci. Fusion Center Report PSFC/RR-11-15, Massachusetts Inst. Technol., Cambridge, MA, USA, 2011. [Online]. Available: https://library.psfc.mit.edu/catalog/reports/2010/11rr/11rr015/11rr015_full.pdf

[5] M. Marchevsky, "Quench detection and protection for high-temperature superconductor accelerator magnets," *Instruments*, vol. 5, no. 3, 2021, Art. no. 27, doi: 10.3390/instruments5030027.

[6] S. Hahn et al., "45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet," *Nature*, vol. 570, pp. 496–499, 2019, doi: 10.1038/s41586-019-1293-1.

[7] N. Bykovskiy et al., "Experimental study of stability, quench propagation and detection methods on 15 kA sub-scale HTS fusion conductors in SULTAN," *Supercond. Sci. Technol.*, vol. 36, no. 3, 2023, Art. no. 034002, doi: 10.1088/1361-6668/acb17b.

[8] J. Schwartz, "Quench in high temperature superconductor magnets," in *Proc. Workshop Accel. Magnet, Superconductor, Design Optim. (WAMSDO)*, 2014, doi: 10.5170/CERN-2013-006.

[9] M. Paidpilli and V. Selvamanickam, "Development of RE-Ba-Cu-O superconductors in the US for ultra-high field magnets," *Supercond. Sci. Technol.*, vol. 35, no. 4, 2022, Art. no. 043001, doi: 10.1088/1361-6668/ac5162.

[10] S. Xue et al., "Current sharing in double-sided REBCO tapes," *Supercond. Sci. Technol.*, vol. 37, no. 7, 2024, Art. no. 075006, doi: 10.1088/1361-6668/ad4e76.

[11] S. Xue et al., "Current sharing and mechanical properties of slot-n-fill REBCO tapes," *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, Aug. 2025, Art. no. 8400505, doi: 10.1109/TASC.2025.3547318.

[12] M. Majoros, M. D. Sumption, M. Jiang, and E. W. Collings, "Current sharing in defected superconducting REBCO tape stack cables for HTS inserts in accelerator magnets: FEM modeling," *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, Aug. 2025, Art. no. 6602405, doi: 10.1109/TASC.2025.3530386.

[13] J. Rong et al., "Quench stability measurements with different REBCO tape architectures," *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, Aug. 2025, Art. no. 4701608, doi: 10.1109/TASC.2024.3524375.

[14] K. Wang, Z. Song, P. Fu, W. Tong, H. Li, and X. Zhang, "Structure optimization of fast discharge resistor system for quench protection system," *IEEE Access*, vol. 7, pp. 52122–52131, 2019, doi: 10.1109/ACCESS.2019.2911710.

[15] J. Rong et al., "Hotspot temperature calculation and quench analysis on ITER busbar," *Fusion Eng. Des.*, vol. 89, no. 12, pp. 2971–2974, 2014, doi: 10.1016/j.fusengdes.2014.08.013.

[16] H. Witte, W. B. Sampson, R. Weggel, R. Palmer, and R. Gupta, "Reduction of the hot spot temperature in HTS coils," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. no. 4601904, doi: 10.1109/TASC.2013.2281849.

[17] E. Härö, A. Stenvall, J. van Nugteren, and G. Kirby, "Hot spot temperature in an HTS coil: Simulations with MIITs and finite element method," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 2, Apr. 2015, Art. no. 4901107, doi: 10.1109/TASC.2015.2396945.