Quench Stability Measurements With Different REBCO Tape Architectures

Jian Rong, Lingfeng Zhu, Shengchen Xue, Harshit Kumar Singh, Nghia Mai, Bhabesh Sarangi, Goran Majkic, and Venkat Selvamanickam

***Abstract*—RE-Ba-Cu-O (REBCO, where RE denotes rare earth elements) superconductor tapes are prone to uncontrolled quench damage especially because of the tape architecture which consists of a monolithic, 2–5-μm-thick film. Moreover, commercial REBCO tapes are not very uniform; defective regions are susceptible to become hot spots when currents of several hundred amperes are transported through the very thin films. In this work, we have been developing new REBCO tape architectures such as double-sided tapes where REBCO films are deposited on both sides of the tape, and slot-and-fill (Slot-n-Fill) where slots are created in the insulating buffer stack and filled with a conductive material to shunt current to the substrate. These architectures have been shown to promote current sharing by lowering the contact resistivity between tape strands. The primary objective of this work is to evaluate the quench characteristics of these defect-tolerant REBCO tape architectures. The different architectures result in different thermal conductivity and resistivity at normal state, which cause different quench characteristics, such as minimum quench energy (MQE), normal zone propagation velocity (NZPV), and hotspot temperature. In this work, the minimum quench energy and quench propagation behavior of tapes with different architectures, as well as coils fabricated from these tapes, are measured. The quench stability measurement was conducted at 77 K in nitrogen vapor.**

***Index Terms*—Double-side tape, high-temperature superconductor, hotspot temperature, quench stability, REBCO, slotted tape.**

I. Introduction

RARE-EARTH barium copper oxide (RE-Ba-Cu-O or REBCO, where RE represents rare earth elements) superconductor tapes are widely used in various fields such as fusion energy, high-energy physics, and material science due to their high quench stability margin, critical field, and current-carrying capacity [1], [2], [3]. REBCO high-temperature superconductor (HTS) tapes are particularly favored for their performance at higher temperatures and high magnetic fields. However, their quench propagation velocity is typically three orders of magnitude lower than that of low-temperature superconductors [4].

The architecture of REBCO tapes consists of multiple layers with thicknesses ranging from 2 to 50 micrometers, contributing to significant non-uniformity in commercial tapes. This non-uniformity increases the susceptibility to damage from hot spots during operation. Furthermore, the electrical conductivity of REBCO tapes is highly anisotropic, and the buffer layer's high resistivity hampers current sharing between tapes in a coil assembly, further exacerbating the risk of the quench.

To mitigate these challenges, our research focuses on developing novel REBCO tape architectures. We have investigated designs such as double-sided tapes, where REBCO films are deposited on both sides of the tape, and slot-and-filled (Slot-n-Fill), where slots are strategically introduced into the insulating buffer layer and filled with a conductive material to enhance current shunting to the substrate. These innovative architectures have demonstrated potential in improving current sharing by reducing the contact resistivity between tape strands [5], [6].

We conduct a series of measurements to assess the quench stability of tapes with different architectures, as well as coils fabricated from these tapes, at 77 K in nitrogen vapor. These measurements provide critical insights into the quench stability performance of these advanced superconductor tape designs under operational conditions, both in individual tapes and in coil configurations.

II. Experimental Approach

A. Double-Side Tape Samples

In this study, we compared the quench stability performance of double-sided tape with and without slots, as well as single-sided tape. To ensure accurate comparisons, all samples were designed with the same cross-sectional area.

The **double-sided tape** sample was prepared by soldering two standard REBCO tapes back-to-back using In52Sn48 solder strips at 140 °C in an air-atmosphere oven. For the **single-sided tape** sample, one standard REBCO tape was soldered to a heat-treated REBCO tape, which had been exposed to 250 °C for 30 minutes to reduce its critical current. Fig. 1 illustrates the sample structures, and Table I provides detailed parameters.

In this study, the quench is triggered by a heater, which is wound using a bare nickel wire and encapsulated with Stycast

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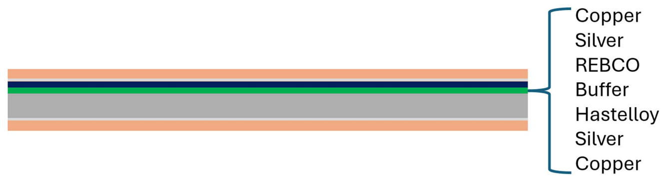


Fig. 1. The structure of REBCO tape.

TABLE I
THE PARAMETER OF THE REBCO TAPE

Layers	Thickness (μm)
Copper	20
Silver	2
REBCO	2
Buffer	0.3
Hastelloy	50

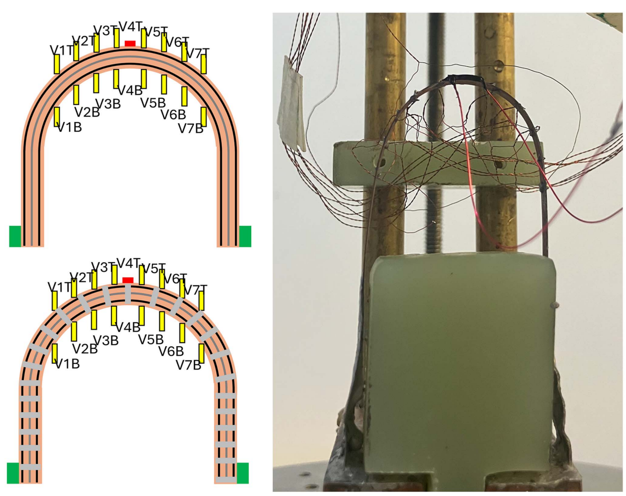


Fig. 2. (Left) Schematic of samples for quench measurement without slots and with slots (red block is heater, and green blocks are current leads), (Right) photograph of the tape wired for quench stability testing.

2850FT. The heater is attached to the top side of the center of the sample by Stycast 2850FT, as depicted in Fig. 2. The current leads are soldered to the terminals of top side of the sample separately. To minimize the effects of Joule heating from the current leads, the samples are shaped into an ‘n’ configuration, and the current leads are put in the liquid nitrogen, while the middle part of the samples is put in the nitrogen vapor, as illustrated in Fig. 2. In this setup, the current leads are immersed in liquid nitrogen, while the central region of the sample is exposed to nitrogen vapor.

Quench stability measurements are typically performed in environments with limited cooling efficiency, such as a vacuum or nitrogen vapor [7], [8], [9], to reflect the intrinsic quench stability of HTS tapes accurately. Our study performs these measurements in nitrogen vapor at 77 K.

Additionally, we developed Slot-n-fill tapes, where slots are laser-etched through all layers of the tape and filled with a conductive material (silver and copper) to facilitate current shunting to the substrate, enhancing current sharing [5]. The slot pattern follows a 2–2–2 design, as shown in Fig. 3 (left), with two dashed

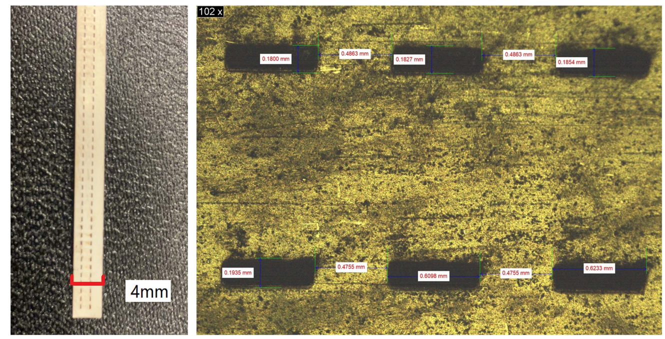


Fig. 3. Slot pattern in double sided tape, the slots are filled with silver and copper.

lines running parallel to the tape edges. Each black point in the slot pattern contains a rectangular hole, with slot dimensions of 0.6 mm × 0.18 mm and a 0.48 mm gap between adjacent slots, as illustrated in Fig. 3 (right). The slots caused a critical current drop ratio which was approximately equal to the proportion of slot width in a 4-mm-width tape.

B. Coil Samples Without Slots and With Slots Samples

Slots can effectively reduce hotspot temperatures in coils during quenching by enhancing current-sharing performance. In this study, we fabricate four coils with different configurations to measure quench stability. Each coil has a diameter of 5 cm and consists of two turns, with a single layer of tape in each turn.

- First Coil: Insulation Coil (**I-coil**): This coil is wound using single-sided REBCO tapes without slots. The insulation between turns is provided by Stycast 2850FT.
- Second Coil: No-Insulation Coil Without Slots (**NI-coil-no-slots**): This coil is wound with single-sided REBCO tapes without slots. In52Sn48 strips are inserted between turns and soldered at a temperature of 140 °C to improve electrical connectivity.
- Third Coil: No-Insulation Coil with 4 cm Slots (**NI-coil-4cm-slots**): This coil uses single-sided REBCO tapes with slots located in the central 4 cm zone, where heater is attached. The coil is assembled by inserting In52Sn48 strips between turns and soldering at 140 °C.
- Fourth Coil: No-Insulation Coil with Full-Length Slots (**NI-coil-slots**): This coil is wound with single-sided REBCO tapes featuring slots along the entire length of the tape. In52Sn48 strips are also used between turns and soldered at 140 °C.

As illustrated in Fig. 4, the heater is attached to the outer circle of the top center of the coil samples by Stycast 2850FT. The voltage taps are soldered in the heater zone (labeling as ‘voltages in the heater zone’ in the following section) to detect quench behavior and on both sides of the current leads (labeling as ‘voltages in the current leads zone’ in the following section) to monitor current-sharing behavior during a quench. Similar to the double-sided quench measurements, the effects of Joule heating from the current leads are minimized by immersing the leads in liquid nitrogen while exposing the central region of the sample to nitrogen vapor.

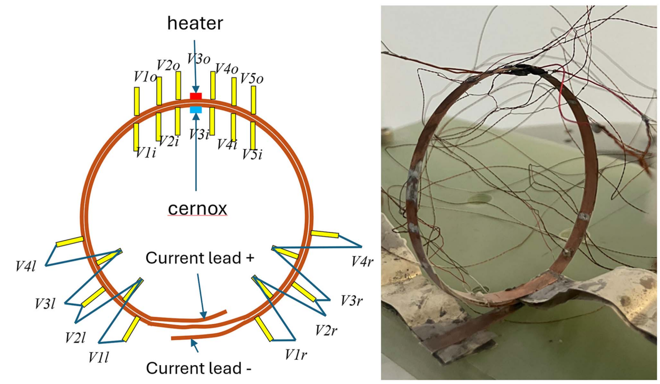


Fig. 4. Schematic and photograph of coil samples for quench testing (red block is heater, and green blocks are current leads).

C. Quench Measurement System

The quench measurement system is designed to assess the quench stability of the samples under controlled conditions. A Keithley 2461 source meter generates a heating pulse with a duration of 0.1 seconds, while the voltage data of the heater is acquired using an NI-PXIe-4309 data acquisition system. A Cernox temperature sensor is employed to monitor the temperature of the heater zone, ensuring it is at 77 K before the application of the heating pulse.

As depicted in Figs. 3 and 4, the samples are soldered to the current leads with an overlap length of 12 mm. The distance between the current leads and the nearest voltage tap on either side of the heater zone is greater than 6 cm. The NI-PXIe-4309 DAQ collects voltage data during quench measurements at a sampling rate of 100 Hz, returning data every 10 ms. The TDK-GEN8-600 power supply is used to deliver the transport current to the sample.

Measurements are conducted in nitrogen vapor, which has poor cooling performance, and under high transport currents. Consequently, effective quench protection is essential to prevent the sample from permanent damage. A protection voltage of 50 mV is set as the maximum allowable end-to-end voltage across the sample, and once this voltage threshold is reached, the current power supply is shut down. Our experimental system uses two protection methods to ensure sample safety during quench measurements:

1) Hardware Protection: The TDK GEN8-600 power supply's voltage limitation and protection features are utilized. Initially, the transport current is supplied and read the voltage (recorded as V0) via TDK power supply. Subsequently, the limit voltage is set to V0 + Vprot, where Vprot is set to approximately 50 mV. This configuration allows us to monitor quench propagation effectively. When the power supply voltage exceeds the set limit voltage, the current will be reduced to bring the voltage back within the allowable range.
2) Software Protection: A Keithley 2812A is employed to measure the end-to-end voltage across the sample. When the voltage reaches the Vprot threshold, the TDK power supply is shut down via software.

These dual protection methods ensure that the sample is safeguarded against damage during high-current quench measurements, enabling reliable and safe data acquisition.

D. Measurement Protocol and Data Analysis

The critical current (I_c) of the sample is measured after it is secured in the quench measurement setup at a temperature of 77 K under self-field conditions. The critical current is determined using the formula $E/E_c = (I/I_c)^n$ [10], where E represents the electric field across the sample, I is the transport current, and $E_c = 1\ \mu\mathrm{V/cm}$ serves as the electric field criterion for I_c.

The minimum quench energy (MQE) is generally defined as the minimum energy absorbed by the sample to initiate an unrecoverable quench [11], [12]. However, due to the partial absorption of heating pulse energy by the heater itself, precisely determining the energy absorbed by the sample can be challenging. In this study, MQE is defined as the minimum heating pulse energy, with all samples utilizing heaters of identical size and weight. The heater dimensions are 4 mm × 8 mm, and the weight is 120.5 ± 0.5 mg. The energy that triggers a quench is called quench energy, while the energy that could not trigger quench is called recovery energy. In this study, MQE is the minimum quench energy, when the difference between maximum recovery energy and minimum quench energy is lower than 10 mJ.

For single-sided tape, double-sided tape, and double-sided-slots tape configurations, if the energy of a 0.1-second duration heating pulse is slightly above the MQE, a quench is triggered. At this point, the sample in the heater zone enters a quench state. However, after 0.1 seconds, the energy dissipated through cooling exceeds the Joule heating produced by the sample, allowing it to gradually return to a superconducting state. Conversely, if the heating pulse energy is equal to or greater than the MQE, the quench is triggered, and the energy dissipated through cooling is insufficient to counteract the Joule heating. Consequently, the quench propagates along the sample toward the current leads, ultimately resulting in an unrecoverable quench.

In the I-coil configuration, the heating pulse can induce an unrecoverable quench, whereas, in the NI-coil-no-slots, NI-coil-slots, and NI-coil-4cm-slots configurations, it does not. In the I-coil, the insulation layer between turns mirrors the behavior observed in double-sided tape. When the heating pulse energy is equal to or exceeds the MQE, the quench propagates along the sample in the opposite direction of the heater. However, in the NI-coil configurations (NI-coil-no-slots, NI-coil-slots, and NI-coil-4cm-slots), when a quench is triggered, the REBCO tape in the heater zone transitions to a resistive state while the rest of the sample remains superconducting.

III. Result

A. Quench Stability Measurement of Tapes

The single-sided tape sample was prepared by soldering one standard ReBCO tape (bottom tape) to a heat-treated ReBCO tape (top tape) in a back-to-back configuration. The standard 4 mm-wide ReBCO tape had a critical current of 150 A, but after heat treatment at 250 °C for 30 minutes, its critical current was reduced to 20 A. The bottom tape was connected to the current power supply, while the top tape was not, limiting the maximum shared current capacity between the two sides to 20 A. This configuration caused the voltage curves for the top and bottom sides to align closely. As shown in Fig. 5(a) , the total critical current of the sample was 170 A, with the bottom tape contributing 150 A and the top tape 20 A.

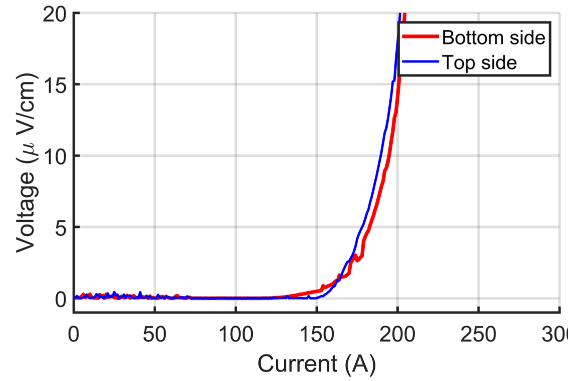
The double-side tape sample was made by soldering two standard ReBCO tapes in a back-to-back configuration, and the top side tape was soldered to the current leads. As shown in Fig. 5(b), the voltage of the top-side tape starts to rise at 150 A, indicating its critical current. The voltages of the top and bottom sides converge at 280 A, which is 20 A less than the sum of their individual critical currents. This reduction occurs because the current flows primarily through the top-side tape rather than being evenly shared between both tapes. Additionally, the resistance between the top and bottom tapes affects the voltage response and limits the overall critical current. The critical current of the bottom-side tape was measured at 130 A, with a maximum current-sharing capacity of 130 A between the tapes.

The double-sided slotted sample was fabricated by soldering two slotted tapes in a back-to-back configuration, with the top tape connected to the current leads. Each slotted tape had a critical current of 130 A. As shown in Fig. 5(c), the voltage of the top tape begins to rise at 130 A, indicating its critical current. The voltages of the top and bottom tapes converge at 250 A, which is 10 A below the combined critical currents of the individual tapes. This reduction is due to the primary current flow through the top tape, rather than an even distribution. In this slotted configuration, the enhanced current-sharing capability increased the maximum shared current capacity to 120 A.

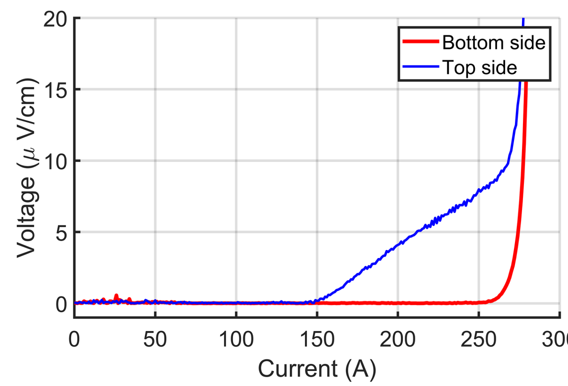
Fig. 5(d) shows the relationship between shared current and the voltage across the top tape (connected to the current leads), which caused the current sharing from the top tape to the bottom tape. Here, the shared current represents the current flowing in the bottom tape that originated from the top tape. At the sample voltage, the shared current in double-side-slots tape is higher than in double-side tape, which exhibits that the double-side-slots tape has better current sharing performance than the double-side tape.

The minimum quench energy (MQE) of single-sided tape, double-sided tape, and double-sided slotted tape was measured in nitrogen vapor at 77 K. As shown in Fig. 6, at low transport currents—where the shared current induced by the heating pulse is below 20 A—both single-sided and double-sided tapes effectively share the current, resulting in a higher MQE regardless of the sample type. However, at higher transport currents, where the shared current exceeds 20 A, the single-sided tape struggles with efficient current sharing, leading to a lower MQE compared to the double-sided tape. These findings demonstrate that double-sided tape has a higher MQE than single-sided tape, indicating superior quench stability in the double-sided configuration.

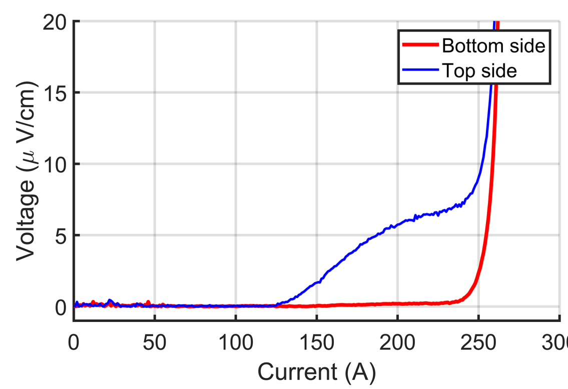
The MQE of the double-side-slots tape was assessed across various transport currents, ranging from 30% to 170% of the top side's critical current. The results reveal that the MQE of the double-side-slots tape is greater than that of the double-side tape



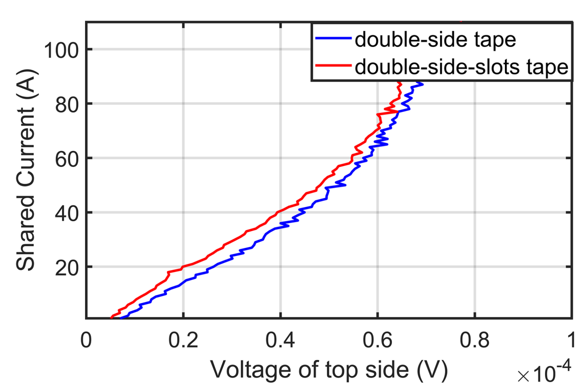
(a) Single-side tape



(b) Double-side tape



(c) Double-side-slots tape



(d) Current sharing performance of double-side tape and double-side-slots tape

Fig. 5. The critical current in different coils.

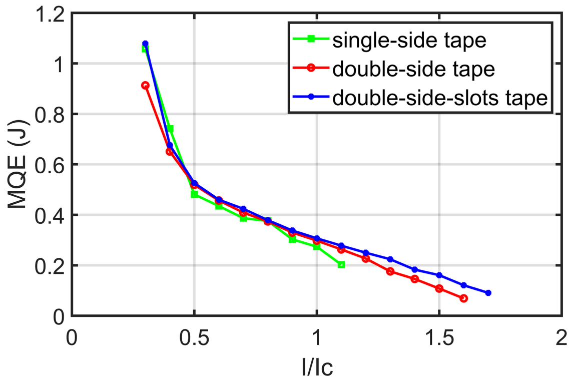


Fig. 6. MQE of single-side tape, double-side tape, and double-side-slots tape.

at equivalent critical current ratios. This implies that double-side-slots tape demands more energy to trigger an unrecoverable quench than double-side tape. Therefore, under these test conditions, double-side-slots tape demonstrates superior quench stability compared to double-side tape. This improvement in quench stability is attributed to the enhanced current-sharing performance via the slots in double-side-slots tape. The slots effectively facilitate more even current distribution between the top and bottom sides of the tape, preventing localized heating and boosting overall stability during high-current operations.

Typically, for single-sided tape, the transport current ranges from 30% to 90% of the critical current to initiate quench measurements. However, with double-sided tape configured such that the current input is from the top side, the current can exceed the critical current of the top side without causing a global quench. This occurs because the current is shared through the silver and copper components at the tape's edge to the bottom side, preventing widespread quenching even at very low voltages.

As depicted in Fig. 7, the transport current of double-side tape is 225 A, with a sharing current of 75 A, whereas the double-side-slots tape achieves a sharing current of 91 A at a transport current of 221 A. Due to the slots, even though the sharing current is higher in double-side-slots tape than in double-side tape, the baseline voltage of double-side-slots tape is lower than that of double-side tape before the heating pulse. In our measurements, the global unrecoverable quench is triggered by a heating pulse. Fig. 7 demonstrates the quench propagation behavior of double-side tape and double-side-slots tape when an MQE heating pulse is applied to the sample. In the double-side tape, the heating pulse is applied at 1.06 seconds, and with quench propagation, voltage protection is triggered at 2.44 seconds, resulting in a quench propagation time of approximately 1.38 seconds. In contrast, for the double-side-slots tape, the heating pulse is applied at 1.2 seconds, and voltage protections are triggered at 3.23 seconds, with a quench propagation time of around 2.03 seconds. To avoid damaging the sample, the hot spot temperatures are not directly measured, and the quench propagation time before triggering voltage protection serves as an indicator of the hot spot temperature. Consequently, the hot spot temperature of double-side-slots tape is likely lower than that of double-side tape. Based on these observations, double-side-slots tape exhibits better quench stability than double-side tape. The improved current sharing facilitated by the slots enhances voltage distribution uniformity and promotes more stable quench behaviors across both sides of the tape configuration.

B. The Quench Stability Measurement of Coils

The initial critical current of the 4-mm-wide REBCO tape used to fabricate the coils is approximately 150 A, while the critical current of the tape with slots is around 130 A. The coil fabrication was performed using a simple setup, which made it challenging to control the tension during soldering, leading to a reduction in the critical current of the coils. As shown in Fig. 8, the critical current values for the coils are as follows: the I-coil exhibits a critical current of 150 A, the NI-coil without slots has a critical current of 165 A, the NI-coil with 4 cm slots shows a critical current of 130 A, and the NI-coil with full slots exhibits a critical current of 110 A.

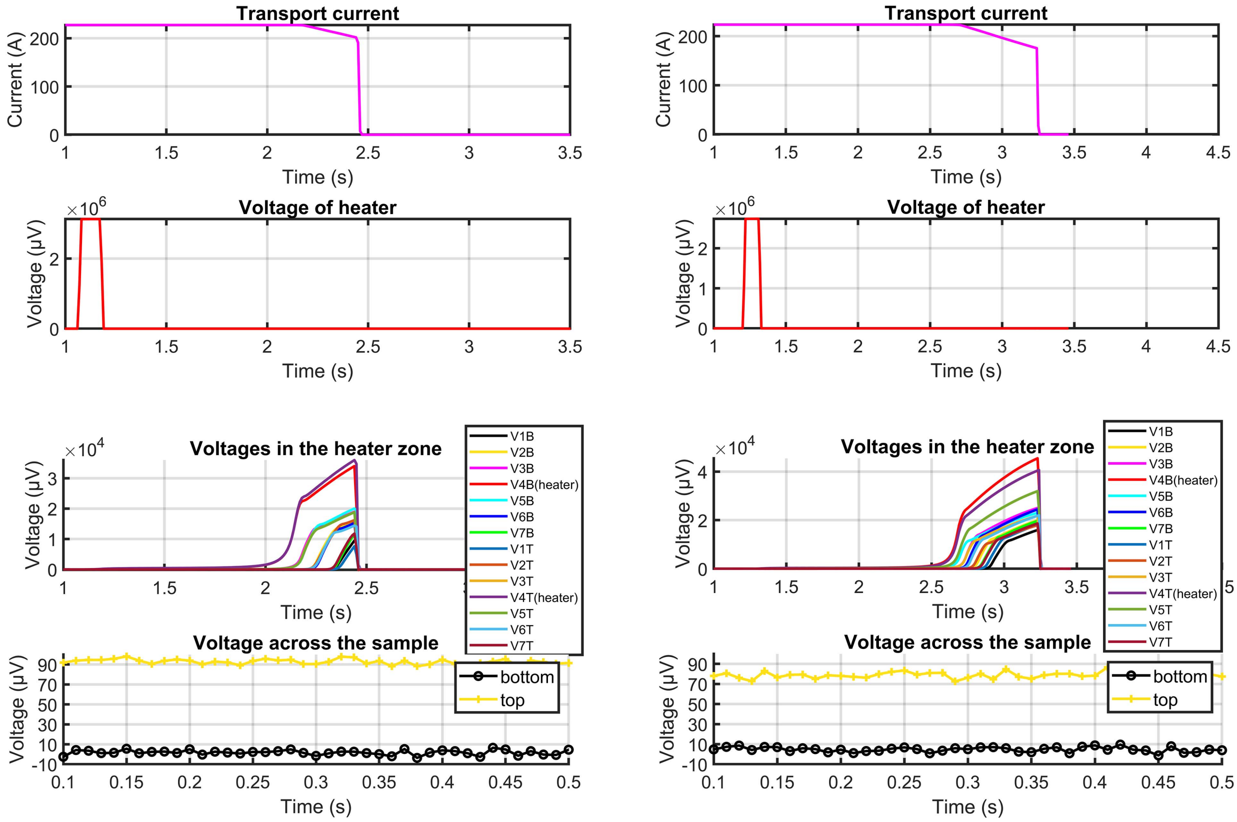
According to our measurements, an unrecoverable quench can be triggered by a heating pulse in the I-coil, allowing the MQE to be determined. In contrast, in the NI-coils, the unrecoverable global quench could not be triggered by the heating pulse, even when the pulse reached 1.5 J—a significant amount of energy for a coil with only two turns during MQE measurement. When an unrecoverable quench is triggered in the I-coil, the quench propagation behavior mirrors that observed in previous tape samples (Fig. 9), due to the absence of current sharing between turns.

Fig. 9 illustrates the quench propagation behavior of different coils at a transport current of 0.5 times critical current. The heating pulse for the I-coil is equivalent to an MQE of 0.33 J, while the heating pulse for the NI-coils, both with and without slots, is around 1.98 J, which is higher heating pulse, but an unrecoverable quench is not triggered.

In the I-coil, a heating pulse is applied at 1.23 seconds, with voltage protection triggering at 2.42 seconds, resulting in a quench propagation time of approximately 2.03 seconds. The maximum electric field in the heater zone reaches 22 mV/cm, indicating a potential for very high hot spot temperatures within the I-coil. The voltages in NI-coils are lower than I-coils, indicating better quench stability performance in NI-coils.

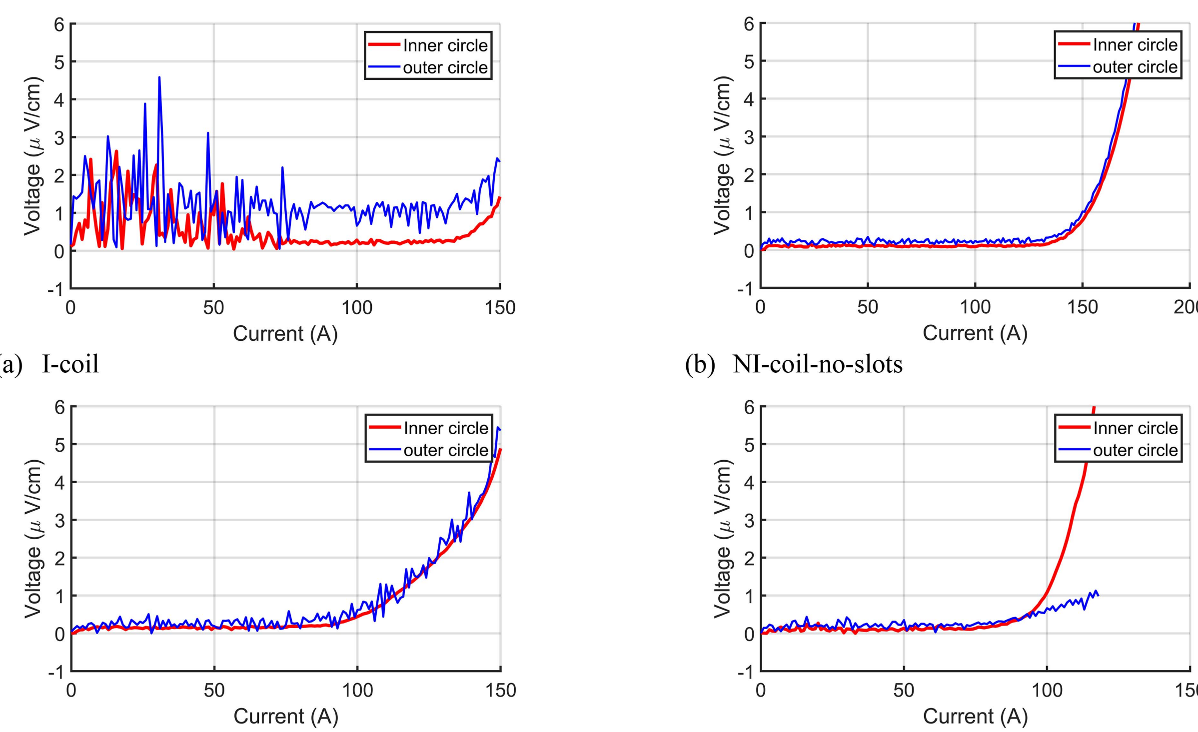
With a heating pulse of 1.98 J amplitude and 0.1 s duration, the maximum voltage in the current leads zone is approximately 30 μV for the NI-coil with full slots, around 50 μV for the NI-coil with 4 cm slots, and reaches 135 μV for the NI-coil without slots. This data indicates that the NI-coil with full slots has superior current-sharing performance compared to the NI-coil with 4 cm slots, and that both slotted NI-coils outperform the NI-coil without slots in terms of current sharing. The maximum electric field in the heater zone of the NI-coil without slots is around 460 μV, whereas in the NI-coils with 4 cm slots and full slots, it is only about 110 μV.

In the NI-coil without slots, the heating pulse is applied at 1.2 seconds, triggering a quench in the heater zone. Due to the current sharing between turns, most of the transport current flows through the green path shown in Fig. 5, from the positive current lead to the negative current lead. As a result, the Joule heating caused by the transport current is lower than the cooling energy. At 9 seconds, the NI-coil with 4 cm slots recovers to the



(a) Double-side tape (b) Double-side-slots tape

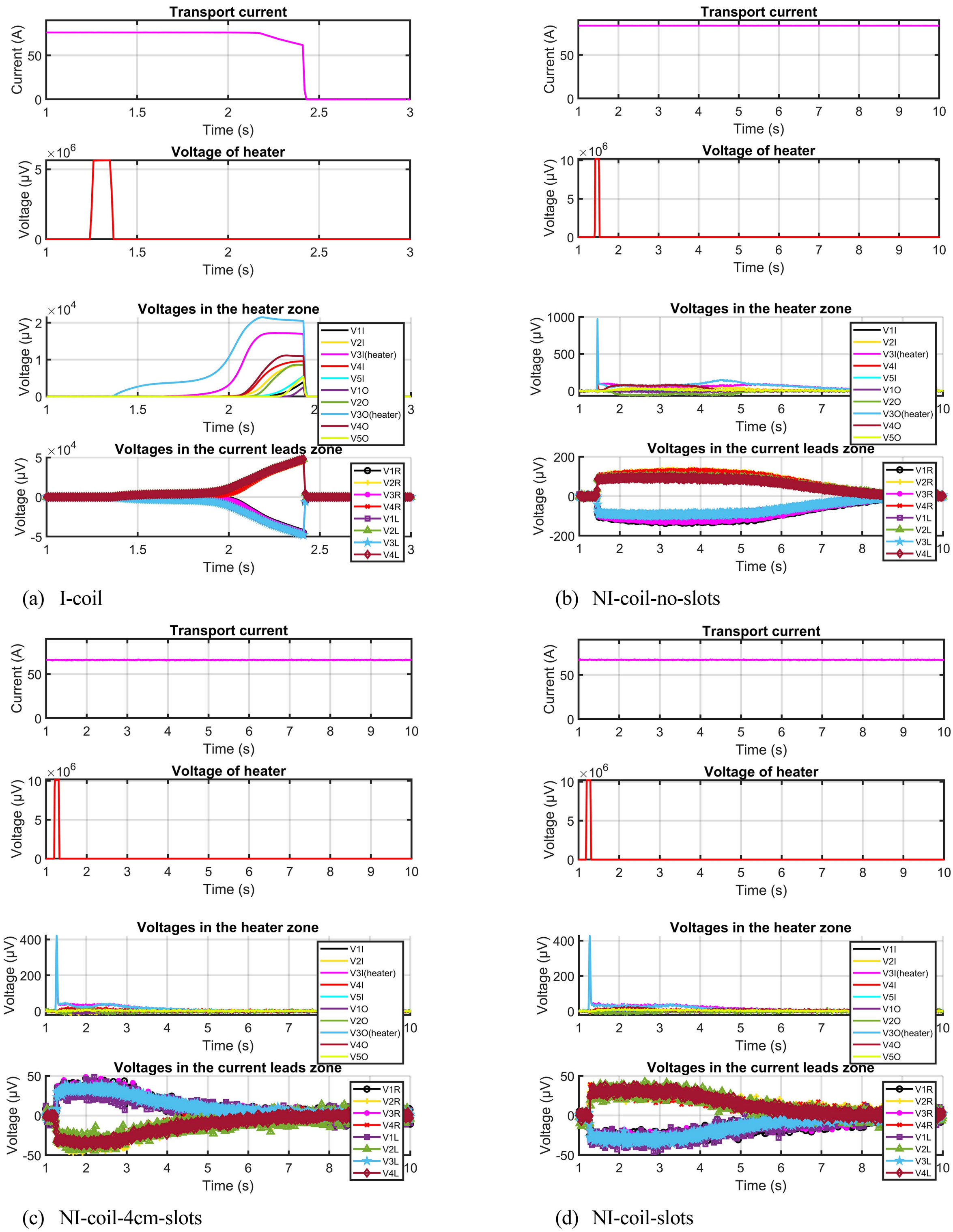
Fig. 7. The quench behavior of double-side tape at transport current of 1.5 $I_c = 225$A, and double-side-slots tape at transport current of 1.7 $I_c = 221$A.



(a) I-coil (b) NI-coil-no-slots

(c) NI-coil-4cm-slots (d) NI-coil-slots

Fig. 8. Current-voltage curves of four types of coils tested for quench stability in this work.



(a) I-coil

(b) NI-coil-no-slots

(c) NI-coil-4cm-slots

(d) NI-coil-slots

Fig. 9. The quench propagation behavior of different coil samples.

superconducting state, resulting in a recovery time of around 7.8 seconds. In contrast, the recovery times for the NI-coil with 4 cm slots and full slots are shorter than 5 seconds. This indicates that the hot spot temperature in the NI-coil without slots is higher than in the NI-coils with slots, demonstrating that slots effectively reduce the hot spot temperature of the coil.

IV. Conclusion

The investigation into the quench stability of various REBCO tape architectures—namely single-sided, double-sided, and double-sided with slots—has provided valuable insights into their thermal and electrical performance under high-current conditions. The double-sided tape exhibited significantly improved quench stability compared to single-sided tape, largely due to its enhanced current-sharing capabilities, which are primarily attributed to its higher critical current. Additionally, the incorporation of slots in the double-sided tape further improved current-sharing performance, resulting in a higher Minimum Quench Energy (MQE) and an extended quench propagation time before triggering voltage protection. These results indicate that Slot-n-Fill is an effective method for reducing hot spot temperatures, thereby enhancing the overall stability of the tape during high transport current operations.

The study also extended its analysis to coil configurations, where the benefits of Slot-n-Fill were again evident. Coils incorporating slots demonstrated better current-sharing behavior, translating into improved quench stability. The MQE of the insulated (I-coil) configuration was confirmed without current sharing between turns, while the no-insulation coil (NI-coil) resisted triggering an unrecoverable quench, indicating that the NI-coil has superior quench stability compared to the insulated coil.

Notably, when transport currents were maintained at the same ratio of critical current, the NI-coil with slots exhibited the lowest electric field in the heater zone, the longest recovery time, and the best current-sharing performance. This configuration, featuring slots along the entire length of the tape, demonstrated the most robust quench stability among the coils tested. The findings indicate that the hot spot temperature in the NI-coil without slots is higher than in the NI-coil with slots, thereby confirming that slots effectively reduce the hot spot temperature of the coil. This further underscores the advantages of the slotted architecture in enhancing quench stability.

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