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LETTER

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Letters

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Letter

Feasible voltage-tap based quench detection in a Ag/Bi-2212 coil enabled by fast 3D normal zone propagation

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Abstract

Small insert solenoids have been built using a commercial Ag/Bi-2212 multifilamentary round wire, insulated with a new thin TiO_2–polymer coating insulation (thickness of ~20 μm versus ~100 μm for a commonly used mullite braided sleeve insulation), and characterized in a background magnetic field up to 14 T at 4.2 K to explore the high-field performance and quench detection of Bi-2212 magnets. The coil has no visible leakage and no electrical shorts after reaction, and it carries 280 A mm^{-2} in a background field of 14 T and generates an additional 1.7 T. A notable result is that, despite normal zones propagating slowly along the conductor, the hot spot temperature upon detection increases only from 40 K to 60 K when the resistive quench detection voltage threshold increases from 0.1 V to 1 V for all operating current density investigated, showing that quench detection using voltage taps is feasible for this coil. This is in strong contrast to a coil we have previously built to the same specifications but from wires insulated with mullite braided sleeve insulation, for which the hot spot temperature upon detection increases from ~80 K to ~140 K while increasing the detection voltage threshold from 0.1 V to 1 V, and thus for which quench detection using voltage taps presents significant risks, consistent with the common belief that the effectiveness of quench detection using voltage taps for superconducting magnets built using high-temperature superconductors is seriously compromised by their slow normal zone propagation. This striking difference is ascribed to the fast transverse quench propagation enabled by thin insulation and the improved thermal coupling between conductor turns. This work demonstrates that quench detection for high-temperature superconducting magnets highly depends on the design and construction of the coils such as the insulation materials used and this dependence should be factored into the overall magnet design.

Keywords: HTS magnets, Bi-2212, quench detection and protection

(Some figures may appear in colour only in the online journal)

Introduction

Quench protection is one of the key issues in the design of a superconducting magnet system, and indeed deserves much attention for a spectrum of powerful magnets made possible by high-temperature superconductors (HTSs) (REBCO, Bi-2223, and Bi-2212), which are becoming commercially available in long-length with superior current-carrying capability in strong magnetic fields up to 20–50 T at temperatures ranging from 4.2 K to 30 K. Due to their high critical transition temperature, these conductors are stable against disturbances such as epoxy cracking and conductor motion that cause Nb-Ti and Nb_3Sn magnets to quench. However, they also exhibit normal zone propagation velocity at several cm s^{-1}, two orders of magnitude lower than those for Nb-Ti and Nb_3Sn. Therefore, a big concern is that the simple and widely used voltage tap quench detection is significantly compromised, because unless the quench detection voltage threshold is reduced to difficult-to-use several mV or several tens of mV, a hot spot cannot be detected before the hot spot temperature rises to a dangerous level, likely above 100 K, to increase the resistivity of the conductor by one to two orders of magnitude to compensate the reduction in the normal zone propagation speed and the length of the conductor in the normal state. Consequently, a smaller amount of time is available for forcing magnet current to go to zero, the second important task of quench protection that is also compromised by the slow normal zone propagation. When a quench occurs, it can be fatal to HTS magnet systems [1].

We previously measured the hot spot temperature upon quench detection in a Bi-2212 coil fabricated from wires insulated with mullite sleeves and used it to measure the effectiveness of measuring the resistive normal zone voltage for quench detection [2]. The results showed that the effectiveness of quench detection using voltage taps is indeed compromised and the voltage development relies on the 1D growth of the normal zone along the wire. Therefore, such coils will likely be restricted to working at low operating critical current density to increase time for quench protection to several seconds or longer. This is undesirable because engineering current density J_E of up to 600–1000 A mm^{-1} at 20 T is becoming available in REBCO-coated conductors and Bi-2212 round wires [3, 4]. The purpose of this paper is to apply the same measurement to a coil made with Bi-2212 wires insulated with a new and much thinner TiO_2 coating insulation (thickness of ~20 μm versus ~100 μm for the common mullite braided sleeve insulation) and to evaluate its impact on promoting 3D quench propagation and on quench detection using voltage taps. We will show by comparison to mullite-insulated coil that voltage tap quench detection is effective for such a coil and has good engineering value.

Experimental details

Solenoids were hexagonally wound from commercial Ag/Bi-2212 multifilamentary round wires onto a pre-oxidized Inconel 600 mandrel according to the specifications listed in table 1. The wire (PMM140416) used was manufactured by Oxford Superconducting Technology, New Jersey, using a powder-in-tube (PIT) technique [5], and it had an architecture of 85 × 18 (18 bundles, within each of which there were 85 filaments; see [2] for more details regarding the wire fabrication and specifications). TiO_2–polymer insulation coating was applied to a 135 m long piece of such wire by nGimat Inc., with a green ceramic basecoat 21.2 μm thick on average and a polymer-only topcoat 2 μm thick on average. The properties of the TO_2–polymer insulation were examined in [6].

Table 1. Specifications of the solenoid.

Parameter	Value
Fabrication route	Wind-and-react
Conductor	Ag/Bi-2212 PIT wire
Bare strand diameter (mm)	1.2
Filament architecture	85 × 18 filaments
Wire superconductor/Ag/AgMg ratios	0.25/0.5/0.25
Insulation	TiO_2–polymer coating
Insulation thickness (μm)	23.2
Total number of layers	6
Total number of turns	270
Inner diameter (mm)	25.4
Outer diameter (mm)	38.8
Height (mm)	57.5
Total length of conductor used (m)	25
Central-field constant (mT A^{-1})	5.4
Inductance (mH)	0.8762

After being wound (figure 1(a)), the coil went through a degassing heat treatment at 400 °C for 20 h in flowing O_2 (flow rate = 1000 sccm) to burn off organic compounds within the insulation. The color of the insulation changed from gray to black after this heat treatment. The coil was then reacted in 1 bar flowing oxygen by heating it from room temperature to 820 °C at 160 °C h^{-1}, holding at 820 °C for 2 h, heating again from 820 °C to 891 °C at 48 °C h^{-1}, holding at 891 °C for 0.2 h, cooling to 881 °C at 10 °C h^{-1}, further cooling to 835 °C at 2.5 °C h^{-1}, holding at 835 °C for 48 h, and then quickly cooling to room temperature. After the reaction, the reacted coil was instrumented with heaters, voltage taps, and type-E thermocouples, and then vacuum-impregnated using CTD-101k and cured by heating it at 110 °C for 5 h with a post-cure of 16 h at 125 °C (figure 1(d)). After being cooled down to 4.2 K, the transport critical current I_c of the coil was determined in a background field up to 14 T using the standard four-point method with an electric field criterion of 1 μV cm^{-1}.

After critical current measurement, the coil was subjected to a heater-induced quench experiment to determine the quench characteristics such as the minimum quench energy and normal zone propagation velocity. To simulate quenches, quenches were initiated at layer 6 (the outermost layer, turn 24) using an epoxy heater (figure 2) made from graphite-based electrically conductive epoxy ECOBOND 60L, previously used by Ghosh *et al* [7] and us [2]. To start a quench, rectangular current pulses of variable duration of 100–300 ms were supplied by a 200 W KEPCO power supply (KEPCO Bipolar 50–4D, ±50 V/±4 A). Heat was deposited on the strand by passing a current pulse through the heater, using the superconducting strand as the current return path. This heater was 1 cm long and was used to trigger a normal zone of small sizes. To observe voltage growth and to determine the propagation speed and the size of the hot zone, the coil was instrumented with voltage taps across the conductor section covered by the heater, several sections at the quench turn, the neighboring turns, at each of the six layers, across the halves

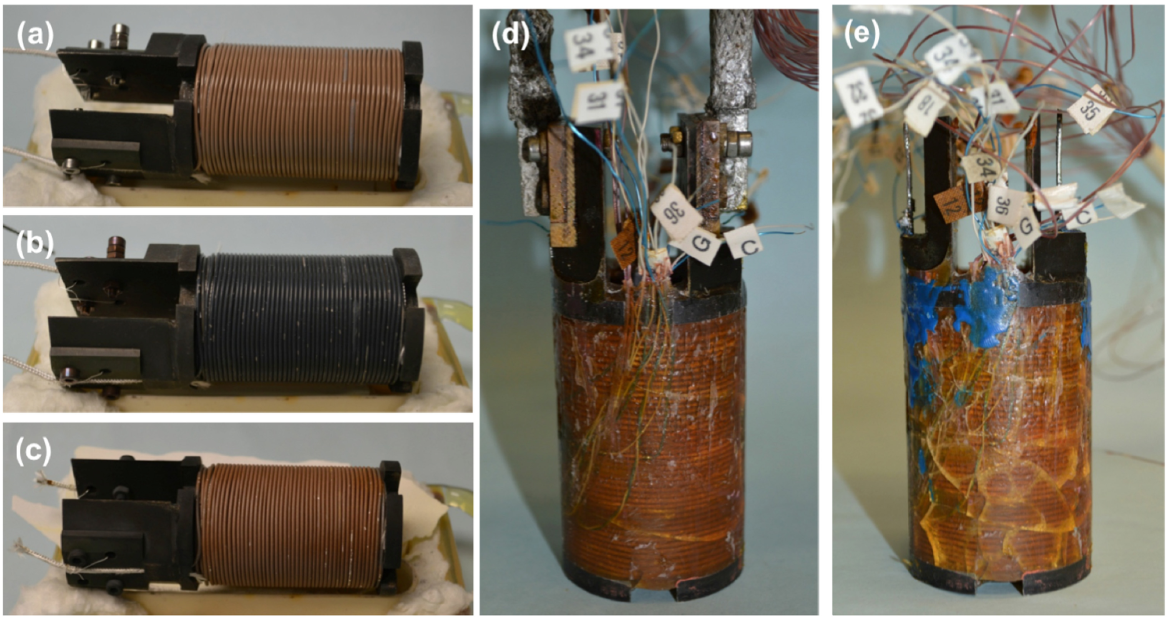

Figure 1. Photos of the solenoid fabricated: (a) after winding, (b) after an organic insulation burnoff heat treatment, (c) after a standard partial melt processing in 1 bar flowing O_2, (d) after instrumentation and epoxy impregnation, and (e) after high-field tests.

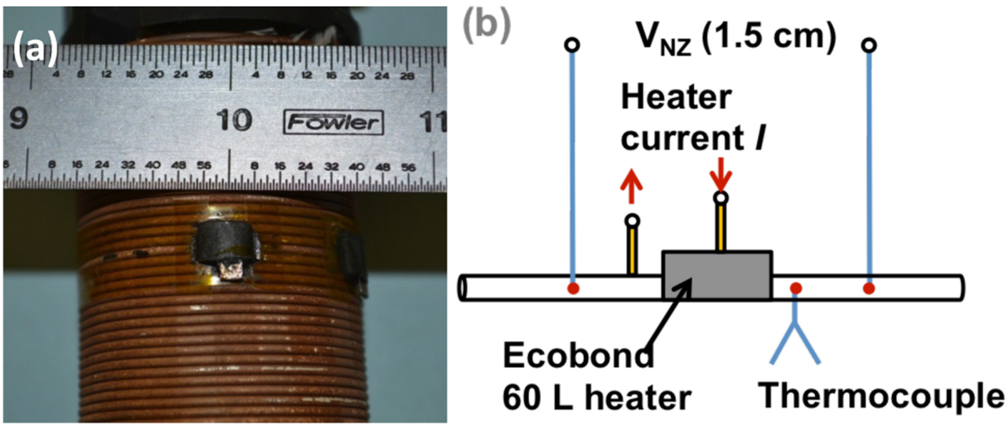

Figure 2. (a) A photo and (b) a schematic of the epoxy heater used. The heater was thermally and electrically insulated from conductor turns with which it had physical contact using Kapton films except the quench turn. Besides the voltage tap and the thermocouple shown in (b), there were several voltage taps and thermocouples for monitoring normal zone development, which were mounted on the quench turn in a manner similar to that used. Reproduced with permission from [8], copyright 2016 IOP Publishing Ltd.

of layer 6, and at the coil terminals, and voltage signals were recorded using a National Instruments SCXI/PCI-6289 data acquisition system with a sampling rate of 1 kHz and a voltage resolution up to 0.1 μV. For a typical quench test, the coil was maintained at 4.2 K and in a background field of 7 T, 9 T, and 11 T, and energized to an operating current I_o of 100 A, 150 A, 200 A, and 300 A at 50 A s^{-1} and dwelled for 3 s before a heat pulse was applied. The heat pulse was applied with increasing amplitude until the conductor was quenched. The minimum quench energy is defined as the minimum heater energy, which was calculated as a product of the current and the voltage and the duration of the rectangular heat pulse, required for quenching the conductor. The coil was protected by triggering a trip of the power supply and forcing its current to go to nearly zero within 0.1 s of a bucked signal ($V_{layer123}$–$V_{layer456}$, the voltage differential between layers 1 to 3 and layers 4 to 6) exceeding a detection criterion.

Results

I_c–B

Figure 3 shows the magnetic field dependence of the wire engineering critical current densities J_E of the short sample and the coil, tested in a background field up to 14 T at 4.2 K. Figure 3 also shows the $J_E(B)$ of a Bi-2212 insert coil made by Oxford Instruments (OI) using similar strands (insulated with mullite sleeve insulation) [9]. The coil I_c is below the short sample I_c; this is characteristic of Bi-2212 coils (such as OI Bi-2212 coils) reacted using partial melt processing at 1 bar in flowing O_2, since I_c degrades with increasing wire length with increasing de-densification of the Bi-2212 filaments associated with the silver creep driven by internal gas pressures [10]. This degradation can be removed by a recently developed overpressure partial melt processing [3]. However,

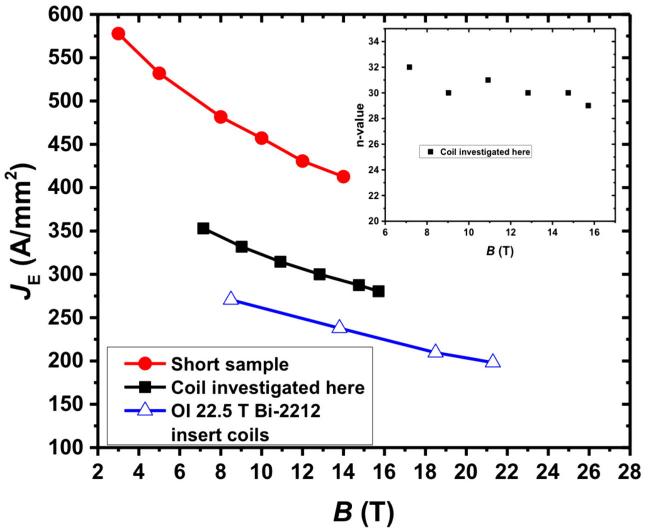

Figure 3. Magnetic field dependence of the wire critical current density for the short witness sample (8 cm, reacted with ends open), the coil, and a coil fabricated by Oxford Instruments that generated 22.5 T in a background field of 20 T. The total field in the coil bore was used and it was calculated using a finite element code (COMSOL 4.2). The inset shows the *n*-value of the coil investigated here as a function of magnetic field.

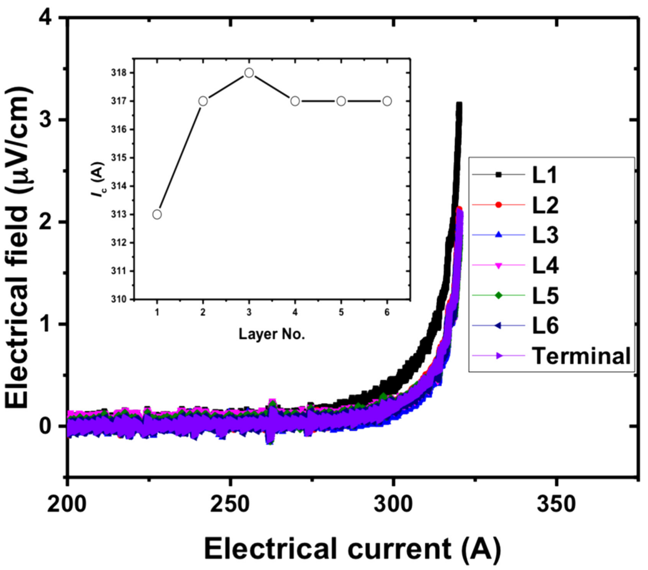

Figure 4. *V–I* curves of each of the six layers and terminal voltage of the coil at 4.2 K and in a background field of 14 T, showing uniform superconducting transitions. The inset shows the critical current of each layer.

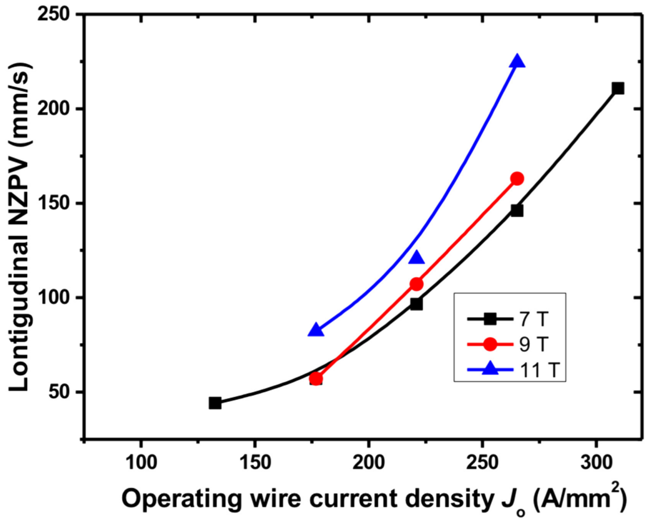

Figure 5. Longitudinal normal zone propagation velocity (NZPV) along the conductor as a function of magnetic field and operating critical current density J_o ($J_o = I_o/A$, where I_o is the transport current and A the cross-sectional area of the entire wire). Note that it was determined from the $V(t)$ of the conductor sections on the quench turn and had an uncertainty of approximately $\pm 15\%$.

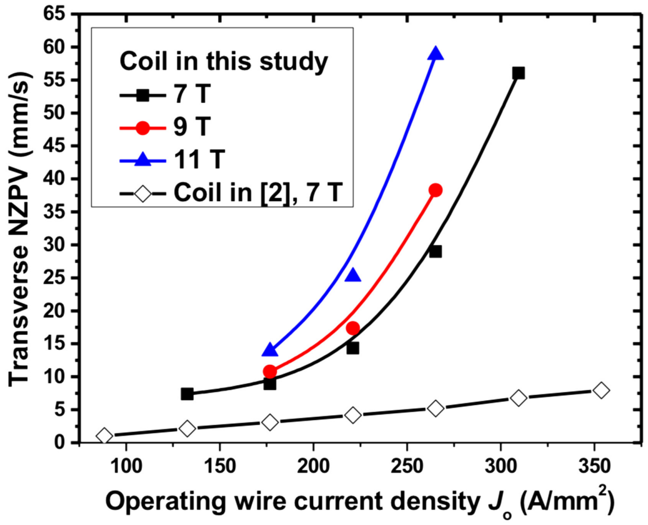

Figure 6. Transverse normal zone propagation velocity (NZPV) as a function of magnetic field and operating critical current density J_o for the coil investigated here and another coil built to the same specifications but insulated with a thicker mullite braided sleeve (wall thickness = 100 μm). Note that the transverse NZPV shown here is the radial NZPV determined from layer voltages and may have an uncertainty of $\pm 10\%$.

our coil $J_E(B)$ is higher than that of the OI coils, showing that at least the TiO_2 insulation is chemically compatible with Bi-2212 wires and does not significantly reduce their critical current density, consistent with earlier findings [11]. Figure 4 shows the *V–I* curves of the coil in a background field of 14 T at 4.2 K. The coil had no electrical shorts and showed rather uniform I_c of 313–318 A across the six layers (the lowest I_c of 313 A was found in the innermost layer), indicating the usefulness of such insulation coating for long wires and coils.

Normal zone propagation velocity

Figure 5 shows the normal zone propagation speed along the conductor and figure 6 shows the normal zone propagation speed across layers and turns. The longitudinal normal zone propagation velocity ranges from 5 cm s^{-1} to 23 cm s^{-1}, increasing with increasing magnetic field and increasing operating critical current density. The highest longitudinal normal zone propagation velocity measured is 23 cm s^{-1}, in a background field of 11 T. This value is high compared to the

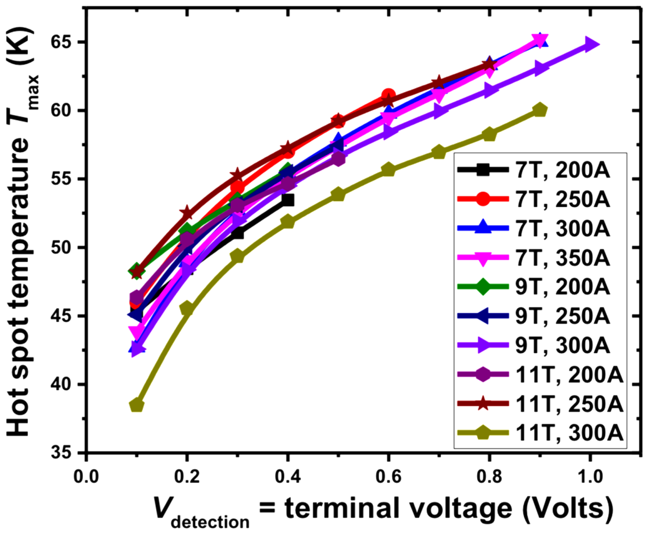

Figure 7. Hot spot temperature upon quench detection as a function of the voltage detection threshold at 4.2 K and in a background field of 7 T, 9 T, and 11 T (need analysis at 9 T and 11 T). The legend marks both the background field and the operating current I_o at which the quench experiments were performed. I_o was maintained to be constant (however, in some cases, I_o dropped by 5%–10% with the saturation of power supply voltage).

data in [2] but considering that most of the data in [2] were obtained in liquid helium and our sample is a fully impregnated coil and therefore the helium cooling effects on slowing down normal zone propagation are depressed, this discrepancy is reasonable. Figure 6 shows the transverse normal zone propagation velocity in a background field of 7 T, 9 T, and 11 T, in comparison to that in a coil built with the same specifications but with wires insulated with a thick mullite sleeve insulation. The transverse normal zone propagation in our coil is noticeably larger than that in the mullite-insulated coil, with the highest value determined around 6 cm s^{-1}, nearly a third of the longitudinal normal zone propagation velocity determined at the same conditions.

Dependence of hot spot temperature on quench detection voltage threshold

Figure 7 shows the hot spot temperature upon quench detection as a function of the voltage detection threshold at 4.2 K and in a background field of 7 T, 9 T, and 11 T. The hot spot temperature was determined by cross-examining the resistance of the hot zone section (1 cm) with the temperature dependence of the resistance of the entire wire [12]. The temperature is surprisingly low, and interestingly, it shows a small dependence on the voltage threshold to 1.0 V and on transport current.

Discussion

The importance of figure 7 and the impact of using thin insulation are better appreciated by comparing it to behaviors found in another coil we built recently to the same specifications but with the wires insulated with a thick mullite sleeve [2]. For the mullite coil, the hot spot temperature increased from ∼40 K to ∼140 K when the resistive voltage quench detection threshold was increased from 0.1 V to 1 V, and such dependence also quantitatively depends on the operating current density (figure 8). Therefore for the mullite coil, a low detection threshold (around 0.2 V or less) shall be used to keep the hot spot temperature low to allocate adequate time for quench protection (forcing the magnet current to go to zero) because the maximum allowable hot spot temperature cannot exceed 450 K [8]. However, such a low detection threshold can easily be confused with the often-seen voltage spikes caused by the mechanical motions of the coil such as stick-and-slip. Therefore for the mullite coil, the effectiveness of quench detection using voltage taps is severely compromised, consistent with the usual concern that quench detection in coils made from high-temperature superconductors can no longer rely on voltage taps [13, 14] and more advanced but more complex and perhaps also currently less reliable methods such as fiber optics [15] or acoustic emission [16, 17] need to be developed. As a result, the coils will be restricted to working at low operating current density regions as it becomes increasingly more dangerous to work at high operating current density regions, despite the fact that wire J_E of up to 1000 A mm^{-2} is becoming available in REBCO-coated conductors [4] and Bi-2212 round wires [3].

The feasibility of using simple voltage taps for quench detection demonstrated in the coil investigated here can be largely ascribed to the fast 3D normal zone propagation enabled by the thin insulation. This can be clearly seen by comparing the voltage signals from the two coils at 4.2 K and the same background field and similar operating currents (figure 8). After a quench, the normal zone quickly spread to adjacent layers for the TiO_2 coil while for the mullite coil, the normal zone stayed at layer 6 as a localized hot spot (no more than 20 cm long when the resistive voltage reached 0.1 V), even though its normal zone propagation speed should be slightly higher with higher operating current density.

The direct implication is that the quench detection and thus the design for coils constructed from high-temperature superconductors to work at 4.2 K strongly depend on the construction details such as the thermoconductivity of the insulation used and its thickness. Methods and magnet designs that promote strong thermal coupling between layers and turns are preferred. Examples include the thin TiO_2 coating reported here, ultrathin polyimide coating for REBCO [18], non-insulation winding for REBCO [19], and thin polyimide film for Bi-2223 [20]. Magnet designs that thermally isolate layers and turns would face significant challenges for quench detection using voltage taps and thus need to resort to other advanced methods. Examples include the canted cosine-theta dipole constructed from Bi-2212 [21] and REBCO, the fusion magnets constructed from high-current cable-in-conduit-like REBCO cables [22], and Bi-2223 NMR or MRI magnets constructed with thick Kapton-insulated Bi-2223. Moreover, it also means that the next generation of high critical current Bi-2212 coils, constructed using overpressure

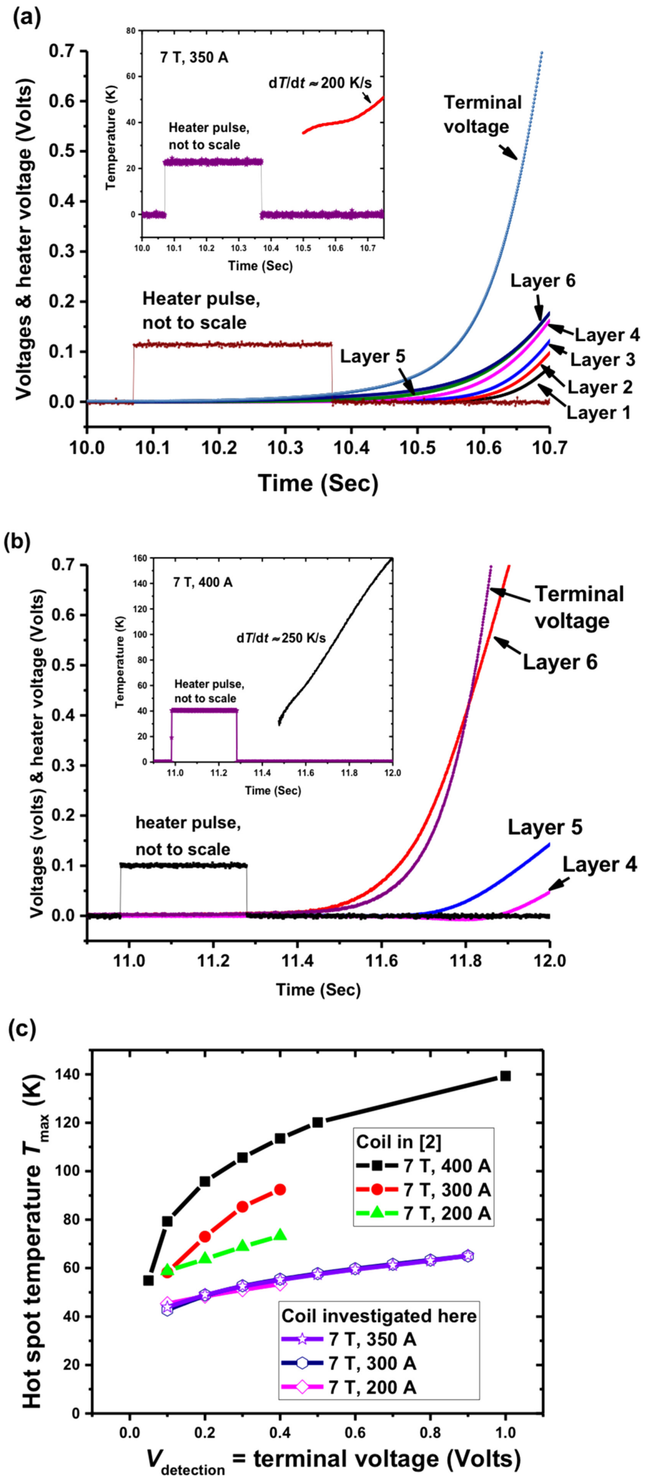

Figure 8. Voltage signals of coils after a quench initiated by the quench heater: (a) the coil investigated here at 4.2 K and in a background field of 7 T with a transport current of 350 A, (b) the mullite coil investigated in [2] at 4.2 K and in a background field of 7 T with a transport current of 400 A, and (c) comparison of the hot spot temperature as a function of the voltage detection threshold at 4.2 K and in a background field of 7 T at several operating transport currents between these two coils. The insets of (a) and (b) show the corresponding hot spot temperature as a function of time with the heat pulse also shown. Note that for the mullite coil, the hot spot temperature upon detection shows strong dependence on both the detection criterion and the operating transport current.

partial melt processing, will face significant challenges in terms of quench detection, because turns become more thermally isolated with increasing gaps between strands with 4%–5% shrinkage of wire diameters during reaction (such gaps will be filled with epoxy after reaction). Methods will need to be found to shrink the wire before winding and fortunately, this is consistent with the requirement of precise and predictable winding for NMR experiments.

Our results clearly demonstrate that there is a viable path forward in terms of quench detection through simple and reliable voltage taps by using thin TiO_2 insulation coating and closely packed winding for high-field Bi-2212 magnet technology. However, it is also likely that the feasibility of using voltage taps in our coil is partly due to the reasonably fast normal zone propagation along Bi-2212 in the range of 5 cm s^{-1} to 25 cm s^{-1}. Thus it is uncertain whether voltage tap quench detection will remain effective for Bi-2223 and REBCO high-field magnets, because measurements have shown that the normal zone propagation velocity of Bi-2223 and REBCO-coated conductors is lower than 5 cm s^{-1} at 4.2 K, even with operating current density of 580 A mm^{-2} [23].

Conclusion

We show that voltage-tap based quench detection is feasible in a solenoid constructed using a commercial Ag/Bi-2212 round wire insulated with a new thin TiO_2 coating insulation. The feasibility is due to the fast 3D normal zone propagation enabled by the thin insulation and the improved thermal coupling between adjacent turns and between adjacent layers. We argue that our test provides a strong lesson in terms of the design and construction of coils using high-temperature superconductors in that quench detection and therefore overall magnet design strongly depend on the construction details such as the insulation materials used. Methods and magnet designs that promote thermal coupling between layers and between turns are strongly preferred. On the other hand, for high-field Bi-2212 coil technology, this work clearly demonstrates that there is a viable path forward in terms of quench detection through simple and reliable voltage taps by using thin TiO_2 insulation coating and closely packed winding.

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