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High-field quench behavior and dependence of hot spot temperature on quench detection voltage threshold in a Bi$_2$Sr$_2$CaCu$_2$O$_x$ coil

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Abstract:

Small insert solenoids have been built using a multifilamentary Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ round wire insulated with mullite sleeve (~100 µm in thickness), and characterized in background fields to explore the quench behaviors and limits of Bi$_2$Sr$_2$CaCu$_2$O$_x$ superconducting magnets, with an emphasis on assessing the impact of slow normal zone propagation on quench detection. Using heaters of various lengths to initiate a small normal zone, a coil was quenched safely more than 70 times without degradation, with the maximum coil temperature reaching 280 K. Coils withstood a resistive voltage of tens of mV for seconds without quenching, showing the high stability of these coils and suggesting that the quench detection voltage shall be greater than 50 mV to not to falsely trigger protection. The hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from ~40 K to ~80 K with increasing the operating wire current density $J_0$ from 89 A/mm$^2$ to 354 A/mm$^2$ whereas for the voltage to reach 1 V, it increases from ~60 K to ~140 K, showing the increasing negative impact of slow normal zone propagation on quench detection with increasing $J_0$ and the need to limit the quench detection voltage to < 1 V. These measurements, coupled with an analytical quench model, were used to access the impact of the maximum allowable detection voltage and temperature upon quench detection on the quench protection, assuming to limit the hot spot temperature to <300 K.
1. Introduction

The Ag/Bi$_2$Sr$_2$CaCu$_2$O$_{x}$ (Bi-2212) round wire has the capability to substantially transform the technology of high-field superconducting magnet. It has been shown to carry a critical current density $J_c$ of $10^3$ A/mm$^2$ at 4.2 K in fields up to 45 T, in lab-made monocoire wires [1,2] and then in commercial powder-in-tube (PIT) multifilamentary wires [3], both of which were heat treated using a partial melt process [1]. The potential of this conductor for high-field magnets has been enhanced with the recent development of an overpressure partial melt process [4], which further raises $J_c$ of Bi-2212 wire by removing porosity inherent in PIT wires [5] and eliminating conductor leakage and $J_c$ degradation [6-8] common in previously made Bi-2212 coils. Thus Bi-2212 round wire, now a magnet-grade superconductor carrying an engineering current density $J_e$ up to $720$ A/mm$^2$ at 4.2 K and 20 T [4], offers to construct a new class of powerful superconducting magnets that generate magnetic fields of >$20$ T, beyond limits of Nb$_3$Sn.

However, quench protection of Bi-2212 magnet systems remains a significant challenge. Quench protection of superconducting magnets, which must detect a non-recovery normal zone and force the magnet current to go to nearly zero within a few seconds or even some fractions of a second to prevent overheating of superconducting windings [9,10], is nontrivial even for superconducting magnet systems made from Nb-Ti and Nb$_3$Sn [11,12] for which abundant coil fabrication and operation experiences have been accumulated. It is especially challenging for superconducting magnet systems based on high temperature superconductors (HTS) [13,14] because measurements in short samples of both Bi-2212 [15,16] and (RE)Ba$_2$Cu$_3$O$_{7-x}$ (RE = rare earth) coated conductors [17] show that at 4.2 K normal zones propagate at an order of cm/s, instead of m/s for Nb-Ti and Nb$_3$Sn at 4.2 K, even in strong magnetic fields (Figure 1 summarizes propagation speed data of Ag/Bi-2212 round strands and coils available in the literature and measured for this study), limiting our ability to drive the resistive zone to occupy as large a fraction of the winding volume as possible for developing an internal resistance useful for active quench protection.

During a quench, conductor temperature rises quickly. Simple ballpark analysis by considering the heat balance of unit volume of winding $(1 - \lambda)J_c(T)^2 \rho(T) dt = \gamma C(T) dT$, where $\lambda$ is the volumetric ratio of superconductor in the metal/superconductor composite, $J_m$ the current density in the metal matrix, $\rho(T)$ the resistivity of the metal matrix, $\gamma C(T)$ the volumetric heat capacity averaged across the conductor, $T$ the temperature, and $t$ the time, predicts that hot spot temperature rises to 300 K within 0.82 seconds in commercial Ag/Bi-2212 multifilamentary round wires with $\lambda = 0.25$ when wire operating current density $J_o = 300$ A/mm$^2$ ($J_o = 300$ A/mm$^2$ is typical for solenoids), and within 0.21 seconds when $J_o = 600$ A/mm$^2$ ($J_o = 600$ A/mm$^2$ is typical for accelerator dipoles and quadruples). Experimental results that will be reported elsewhere show that a successful quench protection approach would need to limit the hot spot temperature in Bi-2212 magnets to < 300 K, beyond which conductor $J_c$ might degrade; this has to do with the fact that inhomogeneous temperature rise introduces strains that affect the
current carrying capability of brittle Bi-2212 phase (the \( J_c \) of melt processed Ag/Bi-2212 wires degrades irreversibility when the tensile strain exceeds a limit, ranging from 0.3-0.45% depending on conductor design and fabrication, and also when a compressive strain is applied [18]). Thus quick and reliable quench detection when the hot spot temperature is low (preferred to be <50 K) is important for leaving enough time for forcing magnet current to go to zero, which is challenging and is also comprised by the slow normal zone propagation.

Active quench detection of existing Nb-Ti and Nb\(_3\)Sn superconducting magnets currently relies on measuring resistive voltage that builds up when a normal zone is created. However, a concern is that developing a detectable normal zone voltage in Bi-2212 magnets might need a high hot spot temperature due to the slow normal zone propagation. For a Bi-2212 wire carrying \( J_o = 300 \text{ A/mm}^2 \) to yield a resistive voltage of 0.1 V, the hot spot temperature needs to reach 235 K and 52 K if the length of the normal zone is 2 cm and 20 cm, respectively (assuming that silver has a RRR (residual resistivity ratio) of 230 and that temperature is homogeneous within the normal zone). Assuming that the normal zone propagates only one-dimensionally along conductor, with a propagation speed of 10 cm/s (Figure 1), Bi-2212 would need 0.1 s and 1 s to develop a 2 cm long and a 20 cm normal zone, respectively, whereas with normal zone propagating at a speed of 10 m/s, Nb-Ti and Nb\(_3\)Sn would only need only 2 ms and 20 ms to develop a 2 cm long and a 20 cm normal zone, respectively. For HTS magnets including Bi-2212 coils, significant time needs to be allocated for detecting the normal zone whereas for Nb-Ti and Nb\(_3\)Sn magnets, primary consideration is on designing quench protection circuitry to ensure the time constant of current decay \( \tau \) to be small. This change in design philosophy may limit the use of Bi-2212 conductors to low \( J_o \) regions.

For designing an active quench protection system for Bi-2212 magnets, magnet designers need to know the hot spot temperature at which a detectable resistive voltage develops in a practical magnet. This knowledge is important for evaluating the effectiveness of voltage measurement for detecting a quench in Bi-2212 magnets and for determining the limits of Bi-2212 magnet technology. Measurements performed so far [15,16,19-21] focuses on determining minimum quench energy and normal zone propagation velocity, and some of these measurement [15] report hot spot temperature, measured by thermocouples that unlikely track temperature rises faster than 10 K/s accurately. This report will present a careful measurement of time evolution of hot spot temperature \( T_{\text{max}} \) vs. \( V_{\text{zn}} \), the normal zone resistive voltage for various \( J_o \) in magnetic fields, in a Bi-2212 solenoid. We also measured the minimum quench energy and propagation speeds in this coil and compared them to those obtained in short strands of Bi-2212 multifilamentary wires. These measurements were enabled by using a small epoxy heater (1 cm long) to initiate a point-like quench and using two complimentary temperature measurement methods to measure coil temperature.

2. Methods

2.1. Strand design and coil fabrication
Quench behaviors of Ag-sheathed Bi-2212 multifilamentary round wires were investigated using heater-induced experiments in both a solenoid and short length (reacted in 15 cm with ends open and tested in 13 cm) strands. The specifications of the solenoid are summarized in Table 1. The coil was wound on a pre-oxidized Inconel 600 coil former using wires insulated with a sleeve (~100 μm thick) braided from alumino-silicate (mullite) fibers (Figure 1c). The coil was reacted in 1 bar flowing oxygen by heating it from room temperature to 820 °C at 160 °C/h, holding at 820 °C for 2 hours, heating again from 820 °C to 891 °C at 48 °C/h, holding at 891 °C for 0.2 hour, cooling to 881 °C at 10 °C/h, further cooling to 835 °C at 2.5 °C/h, holding at 835 °C for 48 hour, and then quickly cooling to room temperature [22]. This is the standard partial melt processing schedule used by the National High Magnetic Field Laboratory [7,15,23] and Fermi National Accelerator Laboratory [24] (impacts of varying some of its important parameters on wire $I_c$ were previously investigated [2,22,25,26]), and similar to those used by Oxford Instruments for making their wind-and-react coils [8,27]. After the reaction, the reacted coil was vacuum impregnated using CTD-101k and cured by heating it at 110 °C for 5 hours with a post cure of 16 hours at 125 °C. Figure 1a shows a graph of the coil as mounted on the test probe.

The PIT multifilamentary Bi-2212 round wire used to fabricate the coil was manufactured by the Oxford Superconducting Technology (OST) at New Jersey by drawing a pure Ag tube with Bi-2212 precursor powder, then using a double restack to form 18 bundles. Its transverse cross-section is shown in Figure 2b. The final wire, 1.2 mm in diameter, contains filaments of ~20 μm in diameter embedded in a matrix of pure silver, which is again encased in an oxidation precipitation-hardened Ag - 0.2 wt% Mg sheath. The filaments in as-drawn wires have an oxide packing density of ~74%.

### 2.2. Heater-induced quench tests

The MQE and normal zone propagation velocity of short strands were measured using an experimental protocol similar to that used by Ye et al. [21]. For coils, heaters were mounted to Bi-2212 conductor sections (insulation was removed) in the test coil (layer 6, the outermost layer) to trigger a quench. The heater, together with thermocouples, was potted with the coil to minimize heat leak into helium and to better simulate a quench in an adiabatic condition. 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). The heater was made from graphite based electrically conductive epoxy ECOBOND 60L, previously used by Ghosh et al. [28]. This heater is 1 cm long and 4 mm in width (covering three turns), and weights ~50 mg. Heat was deposited on the strand by passing a current pulse through the heater, using the turn 30 as the current return path; heat was dominantly deposited into the turn 30, for which the mulite insulation was removed.

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, at each of six layers, across the halves of the layer 6, and at coil terminals, and voltage
signals were recorded using a National Instrument 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 and energized to an operating current $I_0$ of 100 A, 150 A, 200 A, 300 A, 350 A, and 400 A at 50 A/s and dwelled for 3 seconds before a heat pulse was applied. The heat pulse was applied with increasing amplitude until the conductor is quenched. The minimum quench energy (MQE) 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 0.2 second of a bucked signal ($V_{layer123}$-$V_{layer456}$, the voltage differential between the layer 1 to 3 and the layer 4 to 6) exceeding a detection criterion.

2.3. Methods of determining hot spot temperature and RRR measurement

The hot spot temperature was determined by two methods. Temperature of the quench zone was directly measured using an E-type thermocouple (Lake Shore Cryogenics, Inc., Chronmel – Constantan, 36 AWG) (as shown in Figure 3), following previous studies [15,16,19,21]. The response time of an E-type thermocouple, confirmed by our measurements, is ~100 ms so it tends to underestimate the temperature rise if the temperature rising rate is >10 K/s. Temperature was also estimated by cross-examining $V_{HZ}$, the voltage measured across the 2 cm conductor section where the heater was mounted (Figure 3), with the temperature dependence of the resistivity of silver measured. Most of our measurements were made in a background field of 7 T, at which the $T_c$ of Bi-2212 is around 21-28 K so the temperature converted from the voltage was inaccurate when the actual temperature is lower than 30 K due to the uncertainty with the amount of current flowing in silver matrix. But it provides a nearly instantaneous measurement of the hot spot temperature when the temperature is above 50 K. The accuracy of the second approach was calibrated using the E-type thermocouple data when the temperature rise rate was known to be less than 10 K/s.

Estimating temperature from the resistivity measurement requires knowing the temperature dependence of the resistivity of silver, which was measured using the standard four-point technique on a wire cut from the same conductor batch but melt processed with a maximum processing temperature 15 °C lower than optimum (filaments of this sample carry nearly zero $I_c$ so the resistivity measurement was made down to 4.2 K; current applied during the measurement is 2 A). The heat-treated wires were measured to take into consideration of potential RRR reduction due to Cu dissolving into the silver during the melt processing. The residual resistivity ratio (RRR) of silver, defined as $RRR = \rho(293 K) / \rho(4.2 K)$, was measured to be 230. In a background field of 7 T, RRR was reduced to 30, estimated using the magnetoresistance data of silver in Iwasa et al. [29].

3. Results
3.1. Strand and coil \( I_c(B, T) \)

The magnetic field dependences of the \( I_c \) of the strand (\( \phi 1.2 \) mm, 85x18 design) studied were presented in Figure 4. The coil quenched spontaneously during \( I_c \) measurements. Its quench current \( I_q \) was also presented in Figure 4. At 7 T, the \( I_q \) of the coil is 417 A, reaching 72% of its short-sample \( I_c \) [8]. The resulted wire engineering current density \( J_c \) is about 442 A/mm\(^2\) at 4.2 K and 7 T, 50% higher than the \(~280-300\) A/mm\(^2\) in solenoids [7,15,23] previously fabricated from OST wires using 1 bar melt processing. Coil survived more than 20 spontaneous quenches, which likely initiated from regions around one of the current leads, and 50 heater-induced quenches without degradation, during which the highest coil temperature measured reached 280 K.

3.2. Voltage and hot spot temperature during critical recovery

To get the first degree of appreciation of what quench detection voltage criterion should be used, figure 5 examined the coil terminal voltage in cases of critical recovery [30] upon firing the epoxy heater. Coil sustained a large terminal voltage without quenching. For example, the terminal voltage reached 45 mV when \( I_o = 100 \) A, and 4.3 mV when \( I_o = 400 \) A. Integrating \( v(t) \cdot i(t) \) from 0 to 8 s indicates that joule heating deposits heat of 24.9 J, when \( I_o = 100 \) A, and heat of 1.18 J, when \( I_o = 400 \) A, into the coil. The maximum voltages across the 2 cm normal zone recorded (not shown) during a recovery indicates that roughly 20% of the joule heating dissipated in the 1.5 cm heater section.

3.3. Voltage and hot spot temperature during quenches

Figure 6 and Figure 7 present the growth of the hot spot temperature and signals of voltage taps for the test coil when it experienced a quench at 4.2 K and 7 T while carrying \( I_o \) of 100 A and \( I_o \) of 400 A, respectively. Voltage and temperature curves for quenches at \( I_o = 150 \) A, 200 A, 250 A, 300 A, and 350 A were omitted for similarity. The temperature measured by the thermocouple tracked well with that converted from \( V_{NZ} \) for \( I_o = 100 \) A (\( I_o = 88.5 \) A/mm\(^2\), and \( J_m = 118 \) A/mm\(^2\)) when the temperature rise rate is low (\( dT/dt = 10 \) K/s at 60 K), verifying the effectiveness of the method of converting \( V_{NZ} \) to temperature (the error was estimated to be <10 K). The thermocouple failed to track the temperature rise for \( I_o = 400 \) A (\( J_o = 354 \) A/mm\(^2\), \( J_m = 472 \) A/mm\(^2\), \( dT/dt = 148 \) K/s at 60 K), significantly underestimating the hot spot temperature. When the coil terminal voltage reached 0.1 V, the normal zone propagated to the layer 3 for \( I_o = 100 \) A whereas the normal zone didn’t even propagate to the layer 5 for \( I_o = 400 \) A, indicating the normal zone exists only in a conductor turn (the turn 30\(^{\text{th}}\) of the layer 6).

3.4. Dependence of hot spot temperature on detection criterion
To quantify the difficulty of detecting normal zones of small sizes, Figure 8 plots the hot spot temperature when the terminal voltage of the test coil reached 0.1-1 V while experiencing a quench. Both the background field and the current of the test coil were kept roughly the same so the coil terminal voltage represents the resistive voltage of the normal zone well. At a given $V_d$, hot spot temperature rises with $I_o$, showing the increasing difficulty with quench detection with increasing $I_o$. For $V_d = 0.1$ V, $T_{max}$ was 79 K for $I_o = 400$ A and 39 K for $I_o = 100$ A, respectively, whereas for $V_d = 1.0$ V, $T_{max}$ was 140 K for $I_o = 400$ A and 64 K for $I_o = 100$ A, respectively.

4. Discussion

We have built small insert solenoids using a multifilamentary Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ round wire, and characterized them in background fields to explore the quench behaviors and limits of Bi$_2$Sr$_2$CaCu$_2$O$_x$ superconducting magnets, with an emphasis on assessing the impact of slow normal zone propagation on quench detection. Quench propagation is intrinsically a thermal transport event and likely depends on the coil construction method, e.g. insulation materials and the thickness of the insulation. Our measurements were made in a solenoid wound and reacted from Bi-2212 wires insulated with mullite insulation sleeve (100 μm in thickness) and epoxy impregnated; similar construction method was used by Oxford Instrument to fabricate a 2.5 T Bi-2212 solenoid insert to achieve a total field of 22.5 T [23].

The hot spot temperature upon quench detection in our coil showed a strong dependence on the quench detection voltage threshold. The hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from ~40 K to ~80 K with increasing the operating wire current density $J_o$ from 89 A/mm$^2$ to 354 A/mm$^2$ whereas for the voltage to reach 1 V, it increases from ~60 K to ~140 K, showing the increasing negative impact of slow normal zone propagation on quench detection with increasing $J_o$ and the need to limit the quench detection voltage to < 1 V. With increasing $J_o$, though normal zone propagation speed increases, the temperature rises more quickly and the normal zone increasingly becomes a local hot spot. At $J_o$ of 354 A/mm$^2$, the normal zone only exists in a conductor turn when the resistive voltage rose to 100 mV (we estimated the total length of the conductor in normal states to be less than 10 cm). Such a strong dependence of hot spot temperature on the quench detection voltage threshold has an important implication for quench detection and protection circuitry design, and therefore the design of the entire magnet.

The consequence of not detecting quench at low temperatures is that the time for ramping down the magnet current is reduced. The temperature rise during a quench in a metal/superconductor wire of length $r$, carrying a current $I_o$ normal to its cross-section $A$ can be calculated by considering the heat balance of unit volume of winding:

$$(1 - \lambda)\int_0^r (\rho(T) \tau(T) \rho(T)dt = \gamma C(T)\tau + w \quad (1)$$
In which the \((1 - \lambda)\int_0^t \gamma C(T)\rho(T)\,dt\) represents joule heating, \(\gamma C(T)\,dT\) represents the heat absorbed by the conductor volume \(Ar\), and the quantity \(w\) represents the power density leaving the volume \(Ar\) through transverse and longitudinal heat transfer. On fast quenches (adiabatic condition), the last term is negligible.

Assuming adiabatic conduction and reorganizing equation (1), one arrives at [9,10,31]:

\[
\int_0^t (1 - \lambda) J_m^2(t)\,dt = \frac{T_{\text{max}}}{\rho(T)} \int_0^t \gamma C(T)\,dT
\]

The quench integral on the right hand-side of the equation (2) only depends on the material properties. The temperature dependence of the quench integral of a commercial Bi-2212 wire is presented in Figure 8a and temperature rising rate estimated from equation (2) is presented in Figure 8b. The equation (2) can also be used to estimate temperature rising rate, which is presented in Figure 8c and agrees well with the experimentally determined values. From equation (2), one can also assume that quench detection was made at 50 K, 75 K, 100 K, 125 K, and 150 K, and derive a quantitative dependence of time remained for driving the magnet current to zero on temperature at which quench was detected. The results of such an analysis are presented in Figure 9 and show the importance of quench detection at low temperatures.

The normal zone resistive voltage can be expressed as \(U(t) = l(t) \cdot R(t) = \rho_{\text{ave}}(T) \cdot J_m(t) \cdot l_{NZ}(t)\), where \(l(t)\) is the magnet current, \(R(t)\) the internal resistance that develops, \(\rho_{\text{ave}}(T)\) the average resitivity of the normal zone, \(l_{NZ}(t)\) the total length of the normal zone. When a quench begins, the resistance is initially low, but rises steadily as the temperature increases. At the same time, the quench spreads from the point of origin with a certain velocity and new regions of conductor go normal and begin heating, developing greater resistance. This rising resistance comes from both the increase in temperature and the increase in the total length of normal zones, which is proportional to the longitudinal quench velocity along the conductor and the quench propagation velocity in the transverse direction.

The difficult quench detection shown above was clearly due to the very low quench propagation along Bi-2212 conductor and in our coil. One method to make easier the quench detection is to enhance 3-D quench propagation in Bi-2212 coil windings, through increasing normal zone propagation velocity along conductors or improving the transverse heat diffusion. The traverse quench propagation velocity \(U_t\) in a superconducting solenoid hexagonally wound from a round superconducting wire and impregnated with epoxy resin is related to the longitudinal propagation velocity \(U_l\) through this relationship [32]:

\[
\frac{U_t}{U_l} = A \left(\frac{K_t}{K_l}\right) = A \left(\frac{k_r R}{k_t e}\right)
\]
where $A$ is a universal correlation constant to be determined experimentally, $K$ the transverse thermal conductance, $K_t$ the longitudinal thermal conductance, $k_i$ the insulation thermal conductivity, $k_e$ the conductor thermal conductivity, $R$ the radius of bare superconducting wire, and $t$ the insulation thickness. For the Bi-2212 winding tested here, $R$ and $t$ are 0.6 mm and 0.1 mm, respectively, and thus $(R/t) = 6$. Thinner insulation is desired. A thin, 15-25 mm thick TiO$_2$-polymer insulation coating has been developed by nGimat LLC and it yields a $(R/t) = 24 - 40$, which, in combination with an improvement in thermoconductivity properties of TiO$_2$ coating as compared to mullite insulation [33], improves $U_l$ by a factor of 2 – 2.6 [34]. The nGimat TiO$_2$ insulation was applied in a NHMFL coil that generated a 2.6 T in a background field of 31 T and provides an electric breakdown voltage of 100 V [35], which is lower than that of the mullite insulation (~1679 V [6]) but should be sufficient for Bi-2212 coils. The layer-to-layer voltage and the turn-to-turn voltage, or even the maximum internal voltage in a Bi-2212 winding ($|V_{in}|_{max} < R_{nz}/l_{op}$), shall be less than 100 V because of small $R_{nz}$ in Bi-2212 coils.

A potential second method is to increase $U_l$ along Bi-2212 conductor. Heat transfer models of quench initiation and propagation [9,10,31] predict that normal zone propagation velocity along a conductor can be expressed as $V_{ad} = J/\gamma C \cdot ((\rho k/(T_c - T_{cs}))^{1/2}$, where $V_{ad}$ is the normal zone propagation velocity under adiabatic conditions, $J$, $\rho$, and $k$ the operating current density, the resistivity, the thermal conductivity averaged over the composite conductor, $T_c$ the superconducting transition temperature, and $T_{cs}$ the current sharing temperature. Therefore the low speed at self-field for Bi-2212 is readily explained by the large temperature margin (the $T_c$ of Bi-2212 at self-field is 82 K) and given the strong influence of magnetic field on the $T_c$ of Bi-2212, applying magnetic fields should increase the normal zone propagation velocity significantly. However, measurements by Ye et al. [16] in epoxy-impregnated showed that the highest speed obtained is 9 cm/s at self-field and it remains small in magnetic fields of up to 20 T (Figure 1). This propagation speed was analytically derived assuming that the voltage – current $V$-$I$ (or electric field–current density $E$-$J$ transition) of superconductor wire to the normal state is very sharp [9,10,31]. The $E$-$J$ characteristics of metal/superconductor composite conductors can be described using a power-law relationship, $E = E_c \cdot (J/J_c)^n$, characterized by the parameter $n$. The $n$-value of Cu/Nb-Ti wires is ~40-60 at 4.2 K and 5 T and the $n$-value of Cu/Nb$_2$Sn wires is ~30-40, and therefore the assumption applied to them well. The $n$-value of Ag/Bi-2212 short wires, melt processed in 1 bar oxygen with ends open, is ~15-20 at 4.2 K and self field, and ~12 at 4.2 K and 12 T measured by A. Ghosh [27] and us. Long Bi-2212 strands (>30-50 cm) processed in 1 bar oxygen was known to carry lower $J_c$ than short strands heat treated with open ends and they also have reduced $n$-values (5-10) due to the negative effects of internal gases [8]. A study that will be published elsewhere shows that the low $n$-value of Bi-2212 wires reduces $U_l$ by a factor of ten at high magnetic fields. Therefore, for the overpressure processed wires that carry a $J_c$ of 700 A/mm$^2$ and have a $n$-value of ~15 at 4.2 K and 20 T, the $U_l$ might be significantly increased. We are actively fabricating Bi-2212 coils using overpressure processing and testing their quench behaviors at high-fields and high current density regions.
The measurement and discussions so far paint a pessimistic view of using Bi-2212 conductors to their $J_c$ limits. However, we have to caution that for our measurements, the quench was triggered at the outmost layer and the low-field region of the coils with the normal zone being point-like. Figure 5 indicates that the Bi-2212 coil is very stable, which shows that the total heat needed to quench Bi-2212 conductor, defined as the sum of the heater energy and the joule heating energy, is high. In the case of $I_c$=400 A for which the quench was localized in the turn 30, the heater energy is 0.3 J and the joule heating introduces additional 1.18 J.

Figure 10 shows the measured minimum quench energy of the Ag/Bi-2212 round strands (both the $\phi$1.2 mm, 85x18 design wire and the $\phi$0.8 mm, 37x18 design wire were included) and that obtained in epoxy-impregnated coils at 4.2 K by others and us in a magnetic field up to 20 T. Even at 20 T with $J$=600 A/mm$^2$, the plot projects that the minimum quench energy of a Bi-2212 strand will unlikely be lower than 10 mJ. Thus Bi-2212 magnets might withstand large local disturbances without quenching (the energy released in a superconducting winding by a sudden slippage of conductor and epoxy cracking, two primary sources of quenches in Nb-Ti and Nb$_3$Sn magnets, is in range of $10^{-2}$ J cm$^{-3}$), except in unusual scenarios with accelerator magnets that the particle beam is lost into a small section of the superconductor. Therefore, perhaps the best way to use Bi-2212 conductors to their $J_c$ limits is to further stabilize it so the coil will not quench when operating standalone (it should be noted that Bi-2212 coils are often used as high-field insert coils, stacked inside Nb-Ti and Nb$_3$Sn coils. The electromagnetic interactions between LTS coils and HTS coils should be considered carefully when designing quench protection systems).

However, we have to note that the MQE data summarized in Figure 10 were heater input 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. This definition ignored the heat that went into helium and might severely overestimate the stability. Second, our test coil quenched spontaneously without degradation and another 800 kJ Superconducting Magnetic Energy Storage system made from a stack of double-pancake coils wound from Bi-2212 dip-coated tapes suffered from a spontaneous quench [36,37], which degrades the system. The source of the quench in Tixador’s system [36,37] was proposed to originate from a conductor section with less $J_c$ [36,37]. Therefore, a conservative approach needs to be used, assuming that a short-section of Bi-2212 coils might quench.

Taking this conservative view, we provide several suggestions for designing the active quench detection and protection circuitry for high-field Bi-2212 coils constructed similarly to our coils. We want to caution that quench propagation in a coil depends on insulation materials and the thickness of the insulation, and therefore one need to keep that in mind when applying these guidelines to other Bi-2212 coils constructed, for example, using thin TiO$_2$ insulation coating.

1) Normal zone resistive voltage measurement should be a part of the quench detection portfolio for Bi-2212 and other HTS magnets. In spite of slow normal zone propagation,
voltage measurement still allows detection of normal zones of small sizes, as shown by our data, in particularly by Figure 8. Other methods, such as fiber-optics sensors and acoustic emission sensors are promising and may become an auxiliary quench detection tool but so far they have not yet been fully proved in practical magnets and face issues such as making quick decision while analyzing large volume of data (gigabytes per second), taken along a long-length fiber optics sensor or by acoustic emission sensor working at >500 MHz. In contrast, data acquisition rate of >1 kHz would suffice for resistive zone voltage measurements.

2) Cautions should be taken to make sure the maximum normal zone resistive voltage to not exceed 1 V at high operating current density. Superconducting solenoids constructed from Nb-Ti and Nb$_3$Sn can afford to have quench trip voltage of several or ten volts [38]. Using such a large quench detection voltage will likely result in irreversible degradation to Bi-2212 coils because as can be seen from Figure 8, the hot spot temperature may well exceed 300 K before the magnet current can be ramped down. Therefore the suggestion is that the maximum quench detection voltage shall not exceed 1 volt. This voltage is smaller than the forward voltage of cold silicon diodes (~3-10 V at 4.2 K) often used in passive quench protection circuits and therefore passive protection using a pair of diodes and resistor electrically in parallel with the superconducting coil will unlikely be effective at protecting Bi-2212 coils against quenches occurring at the high operating current density.

3) The maximum normal zone resistive voltage may be increased to several volts at low and medium operating current density, because extrapolation of data in Figure 8 for $I_c=100$ A to several volts shows that the hot spot temperature would likely still be less than 100 K. Quench detection at low $J_c$ benefits from transverse quench propagation to adjacent turns and layers (which is possible due to the slow temperature rise), as can been seen from voltage data of coil layers presented in Figure 6 and 7.

4) The minimum quench detection voltage shall be larger than 50 mV to not to falsely trigger quench protection. This is necessary as it can be seen from Figure 5 that Bi-2212 coils are quite stable against disturbances and withstood a resistive voltage of tens of mV for seconds without quenching. This will help improve the signal-to-noise ratio when a quench occurs during activation of large magnets whose inductive voltage of coils can be as large as 10-20 V. If a decision has been made to use detection voltages close to 50 mV, the ramping rate of Bi-2212 coils should be kept low and the inductance of the coil should be reduced as much as possible.

5) Determining at what hot spot temperature a quench can be detected through measurements similar to those reported here should be one of the quench protection circuitry design steps for Bi-2212 high-field magnets as significant time would need to be allocated for quench detection.

The relatively small detection voltage suggested demands that the quench detection electronics can distinguish a real quench event from a variety of rapid voltage spikes that large epoxy impregnated superconducting coils often see during ramping tests and even occasionally in hold
at constant current [39,40]; the magnitude of these spikes can range from tens of mV to even several volts depending on the magnet construction, the inductance of the coil, and the capability of power supply and quench detection data acquisition systems. The nature of voltage spikes hasn’t been thoroughly understood due to a lack of comprehensive tests. It has been suggested that voltage spikes generated by conductor motion and epoxy cracking have a characteristic time of several ms and can be filtered whereas the voltage spikes caused by a stick-slip behavior as the coil expands and frictionally slides against its coil former can last tens of milliseconds and difficult to be filtered out.

5. Conclusion

We have reported fabrication of small-scale coils using commercial Ag/Bi-2212 strands and their quench behaviors at 4.2 K and in an externally applied field. Our experiments, for the first time, systematically measured the time evolution of the hot spot temperature and the normal zone resistive voltage using two complimentary methods in an epoxy-impregnated Bi-2212 coil. The coil was made using wires insulated with an alumino-silicate insulation sleeve with a thickness of ~100 µm. For this coil, the hot spot temperature for the resistive voltage of the normal zone to reach 100 mV increases from ~40 K to ~80 K with increasing the operating wire current density $J_o$ from 89 A/mm$^2$ to 354 A/mm$^2$ whereas for the voltage to reach 1 V, it increases from ~60 K to ~140 K. This result highlights the difficulty of quench detection in Bi-2212 coils and the need to allocate a more significant amount of detection time for Bi-2212 coils when designing quench detection and protection circuitry than for Nb-Ti and Nb$_3$Sn magnets.

The difficulty of quench detection is due to the slow normal zone propagation along the conductor and between conductor turns. We have compiled master plots of minimum quench energy and normal zone propagation velocity as a function of magnetic field and operating current density for Bi-2212 wires and coils. Such plots shall be useful for predicting, at the first degree, the magnitude of the minimum quench energy and the normal zone propagation speed and their variations with magnetic field and transport current. Transverse normal zone propagation speed in our test coil was measured to increase from 1.4 mm/s to 7.5 mm/s with increasing $J_o$ from 89 A/mm$^2$ to 354 A/mm$^2$. To use Bi-2212 towards its $J_o$ limits, it is suggested that it is important to enhance the 3-D normal zone propagation using thinner insulations and to increase the normal zone propagation speed along conductor, perhaps by an order of magnitude, through understanding the effects of n-values and improving n-values. We also presented a new method of measuring the RRR of Bi-2212 wires for numerical quench simulation. We fed the RRR value obtained into an analytical quench integral calculation to calculate temperature rises during a quench, and showed that they matched well with experimental results.

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This work was supported by the Office of High Energy Physics at the U.S. Department of Energy (DOE) through Fermi Research Alliance (DE-AC02-07CH11359) and an Early Career Award to T.S.
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References

Shen, submitted to *Superconductor Science and Technology* on January 19, 2015


Figure 1: Measured normal zone propagation velocity at 4.2 K as a function of $J_o$, the operating current density averaged over the conductor in magnetic fields up to 19 T. Samples include an epoxy-impregnated coil whose specifications are presented in the table, a 13 cm long piece of the same conductor used to fabricate this coil and a wire with a diameter of 0.8 mm and a design of 37 x 18 (reacted and tested as 13 cm long), epoxy impregnated coils tested by Ye et al. [16] and by Trociewitz et al. [15] All of these wires were manufactured by OST and have the similar Ag/AgMg/Bi-2212 ratio. For the data obtained in our test coil, the following approach was used: the transverse normal zone propagation velocity was obtained by comparing the layer voltage signals; the lower bound and the upper bound of the longitudinal normal zone propagation speed were derived by timing the transverse speed with a factor of 5 and 20, which was experimentally found by Ye et al. [16] and Trociewitz et al. [15] in epoxy impregnated Bi-2212 coils fabricated using similar strands and insulation, respectively.
Table 1: Specifications of the solenoid sample

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding technique</td>
<td>Wind-and-react</td>
</tr>
<tr>
<td>Conductor</td>
<td>Ag/Bi-2212 PIT wire</td>
</tr>
<tr>
<td>Wire diameter and design</td>
<td>1.2 mm; 85 x 18 filaments</td>
</tr>
<tr>
<td>Wire superconductor/Ag/AgMg ratios</td>
<td>0.25/0.5/0.25</td>
</tr>
<tr>
<td>Conductor insulation</td>
<td>Alumino-silicate braided sleeve</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>100 µm&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Inner diameter i.d. (mm)</td>
<td>33.40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Outer diameter o.d. (mm)</td>
<td>48.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Overall winding length (mm)</td>
<td>57.80&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total number of layers</td>
<td>6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total number of turns</td>
<td>244.5&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Central-field constant (mT A&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>4.5&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Inductance (mH)</td>
<td>1.1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> measured value  <sup>b</sup> computed values
Figure 2: (a) The epoxy-impregnated coil fabricated as mounted on the test probe, (b) the transverse cross-section of the Bi-2212 wire used to fabricate the coil, and (c) a side-view of the mullite braided insulation sleeve.
Figure 3: (a) Schematics of the epoxy spot heater ECOBOND 60L on the 30th conductor turn of the layer 6 (the bottom half), together with an E-type thermocouple and a voltage tap (tap length=1.5 cm) that reads $V_{NZ}$. (b) Hot spot temperature recorded by the thermocouple for two heater input energies. When the heater energy is 0.342 J, the wire returned to superconducting state after a temperature rise to ~18 K; when the heater energy was 0.349 J, the wire experienced a thermal runoff. For this case, the minimum quench energy was defined at 0.349 J whereas the recovery case was called a critical recovery because the conductor recovered after receiving an energy that is slightly lower than the minimum quench energy and a short temperature rise.
Figure 4: The $I_c$ of the $\phi$1.2 mm Bi-2212 strand at 4.2 K and in applied fields up to 14 T and the quench current $I_q$ of the test coil. The witness strand, 8 cm long, was melt processed with the coil but with its ends open during the heat treatment. The strand $I_c$ was determined using a standard four-probe method at an electric field criterion of $1 \mu$V/cm, whereas the coil $I_q$ was plotted against the background field only.
Figure 5: Voltage-time evolution when the test coil experienced critical recovery for $I_0=100$ A, 150 A, 200 A, 250 A, 300 A, and 400 A at 4.2 K and 7 T. Signals were synchronized by placing the rising edge of heat pulses at 0.1 s.
Figure 6: Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying a current $I_o$ of 100 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from $V_{\text{NZ}}$. The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had propagated to the layer 3.
Figure 7: Evolution of (a) the hot spot temperature and (b) the layer and terminal voltage for the test coil when it experienced a heater-induced quench at 4.2 K and 7 T while carrying an current $I_o$ of 400 A. Figure (a) presents both the temperature directly measured by the thermocouple and the temperature converted from $V_{NZ}$. The insert in (b), plotted using a log 10 scale, highlights that when the terminal voltage reached 0.1 V, normal zone had just propagated to the layer 5.
Figure 8: The hot spot temperature in the test coil when it experienced heater-induced quenches while carrying an $I_o$ of 100 A, 200 A, 300 A, and 400 A, and its terminal voltage reached 0.1-1 V. The tests, results of which were presented in Figure 7 and Figure 8 for $I_o=100$ A and $I_o=400$ A, respectively, were performed at 4.2 K and in a background field of 7 T. The hot spot temperature was estimated from $V_{NZ}$. 
Figure 9: (a) Quench integrals for commercial Ag/Bi-2212 wires (λ=0.25). (b) Temperature rise predicted using quench integrals for commercial Ag/Bi-2212 wires. (c) Hot spot temperature rising rate dT/dt when T_{max} = 60 K predicted by quench integral calculation as compared to experimental data. (d) Time available for forcing magnet current to go to zero and its dependence on operating current density and the quench detection temperature.
Figure 10: Measured minimum quench energy at 4.2 K as a function of $J_o$, the operating current density averaged over the conductor, for the epoxy-impregnated coil whose specifications were presented in the table 1, 13 cm long pieces of the same conductor used to fabricated table 1 coil and a wire with a diameter of 0.8 mm and a design of 37 x 18 (reacted and tested as 13 cm long), an epoxy impregnated coil tested by Ye et al. [16], and an epoxy impregnated coil tested by Yang et al. [20]. Note that samples in this paper were tested using the 1 cm epoxy heater, whereas the coil of Ye et al. [16] tested by a spiral heater wound from Nichrome wire (~1.5 cm in length), and the coil of Yang et al. [20] tested by a thin film Constantan heater (40 mm x 1 mm x 20 mm x 22 cm). All of these wires were manufactured by OST and have the similar Ag/AgMg/Bi-2212 ratio.