Quench degradation limit of multifilamentary Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ round wires

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Abstract

Understanding safe operating limits of composite superconducting wires is important for the design of superconducting magnets. Here we report measurements of quench-induced critical current density $J_c$ degradation in commercial Ag/Bi$_2$Sr$_2$CaCu$_2$O$_x$ (Bi-2212) round wires using heater-induced quenches at 4.2 K in self magnetic field that reveal a general degradation behavior. $J_c$ degradation strongly depends on the local hot spot temperature $T_{\text{max}}$, and is nearly independent of operating current, the temperature gradient along the conductor $dT_{\text{max}}/dx$, and the temperature rising rate $dT_{\text{max}}/dt$. Both $J_c$ and $n$ value (where $n$ is an index of the sharpness of the superconductor-to-normal transition) exhibit small but irreversible degradation when $T_{\text{max}}$ exceeds 400-450 K, and large degradation occurs when $T_{\text{max}}$ exceeds 550 K. This behavior was consistently found for a series of Bi-2212 wires with widely variable wire architectures and porosity levels in the Bi-2212 filaments, including a wire processed using a standard partial melt processing and in which Bi-2212 filaments are porous, an overpressure processed wire in which Bi-2212 filaments are nearly porosity-free and that has a $J_c(4.2 \text{ K, self field})$ exceeding 8000 A/mm$^2$, and a wire that has nearly no filament to filament bridges after reaction. Microstructural observations of degraded wires reveal cracks in the Bi-2212 filaments perpendicular to the wire axis, indicating that the quench-induced $I_c$ degradation is primarily driven by strain. These results further suggest that the quench degradation temperature limit depends on the strain state of Bi-2212 filaments and this dependence shall be carefully considered when engineering a high-field Bi-2212 magnet.
1. Introduction

Quenching poses significant risks to the operation of superconducting magnets such as those in nuclear magnetic resonance (NMR) systems and particle accelerators. Without effective quench protection, magnets are at risk of permanent degradation, and the risk generally increases as the magnet operating current density and stored energy increase. It is therefore important to understand the quench degradation behavior and limit of superconducting composite wires, and equally importantly, to understand degradation mechanisms in order to operate magnets within safe limits. Moreover, it is also interesting to examine whether degradation limits change with conductor design, heat treatment, and operations.

During a quench, the local temperature inside a superconducting magnet winding rises at a rate $dT_{\text{max}}/dt$ roughly proportional to $J^2$, where $T_{\text{max}}$ is the local hot spot temperature and $J$ the operating current density of superconducting wire. To protect Nb-Ti and Nb$_3$Sn magnets against quench-induced damages, the $T_{\text{max}}$ is typically kept below 150 K, or more aggressively, 350 K. This design criterion may not apply to high temperature superconducting conductors such as Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_{x}$ (Bi-2212) multifilamentary round wires because of key differences between Bi-2212 and Nb-Ti and Nb$_3$Sn. For example, measurements in short samples of Bi-2212 conductors show that at 4.2 K normal zones propagate with velocities at the order of cm/s, compared to m/s for Nb-Ti and Nb$_3$Sn, even in strong magnetic fields up to 20 T [1, 2]. Such slow normal zone propagation means that the local temperature gradients, $dT_{\text{max}}/dx$, in Bi-2212 would likely be one or two orders higher. In addition, the superconducting filaments in even the best-performing Bi-2212 wires contain a significant amount of secondary phases and porosity. The impacts of these differences on quench degradation limits have yet been carefully studied in the Bi-2212 round wires, especially the overpressure processed wires that exhibit high critical current density $J_c$ at 4.2 K and 20 T exceeding 2500 A/mm$^2$ and engineering critical current density $J_e$ at 4.2 K and 20 T exceeding 720 A/mm$^2$.

Bi-2212 wires are brittle after reaction and its $J_c$ is sensitive to strains. The non-uniform temperature rise during a quench induces significant strain in Bi-2212 filaments and it is widely suspected that this strain drives degradation. While the axial strain dependence of the $J_c$ of Bi-2212 wires has been well studied [3-6], it has been hitherto unknown what portions
of superconducting filaments are more prone to degradation and whether wire design and processing can be modified to mitigate quench induced $J_c$ degradation. For example, high $J_c$ in overpressure processed wires was achieved by removing porosity in powder-in-tube (PIT) Ag/Bi-2212 wires, increasing the filament density to over 90%, as compared to 65-80% in the wires processed using the standard partial melt processing (PMP) in 1 bar flowing $O_2$ [7]. Yet it is unknown if quench degradation limits increase with filament density, as porosity has been shown to serve as stress concentration sites [8]. Similar questions can be asked for other microstructural features found in Ag/Bi-2212 wires, such as Bi-2201 grains and filament-to-filament bridges [9-11].

Here we study the quench-induced $J_c$ degradation behavior of a large inventory of commercial PIT Ag/Bi-2212 wires. Wires studied include both 1 bar processed wires and overpressure processed wires; their $J_c$ (4.2 K, self-field) values range from 1300 A/mm$^2$ to over 8000 A/mm$^2$, and corresponding $J_e$ range from 200 A/mm$^2$ to 1500 A/mm$^2$. We examine the importance of $T_{\text{max}}$, $dT_{\text{max}}/dt$, and $dT_{\text{max}}/dx$, using heater-induced quench experiments [12, 13], on inducing $J_c$ degradation. To investigate quench degradation mechanism, we further examine the microstructure of degraded samples wires.

2. Experimental Approach

2.1 Samples and heat treatments

The cross-sectional images of the investigated Ag-0.2wt%Mg/Ag/Bi-2212 multifilamentary round wires are presented in Figure 1. All wires were fabricated by Oxford Superconducting Technology (OST), New Jersey, using the PIT route. Conductor A, with a diameter of 0.8 mm and a wire architecture of 37 x 18 filaments (18 bundles; each of these bundles consist of 37 filaments), is a typical commercial wire used for making Rutherford cables for constructing accelerator dipole and quadruple magnets for high-energy particle accelerators [14, 15]. Conductor C, with a diameter of 1.2 mm and a architecture of 85 x 18 filaments, is typical of commercial wires used for high-field NMR solenoids. Both conductor A and conductor C contain extensive interfilamentary bridges after heat treatment. Conductor B, an R&D conductor, has a diameter of 1.0 mm and a architecture of 27 x 7 filaments. The larger interfilamentary spacing in the conductor B was intended to minimize interfilamentary
bridging [16], so it is included here to determine if such bridging influences quench-induced degradation.

Straight wires of each conductor, 8 - 16 cm in length, were heat-treated using a PMP in flowing pure O\textsubscript{2}. The PMP included heating them from room temperature to 820 °C at 160 °C/h, holding at 820 °C for 2 hours, heating 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. To evaluate the importance of porosity on quench degradation, conductor A was also processed using overpressure partial-melt processing (OPMP) in a mixed gas of Ar and O\textsubscript{2} at a gas pressure up to 100 bar. During both heat treatments, the oxygen partial pressure was maintained at 1 bar. The density of the filaments in overpressure-processed wires increased to >95% when the gas pressure applied was greater than 25 bar, as compared to 65-80% for wires processed at 1 bar.

2.2 Test protocols and instrumentations

The reacted straight wires were mounted on a G-10 sample holder and instrumented with heaters, Lakeshore Type-E thermocouple wires, and voltage taps using the layout shown in Figure 2 or a similar pattern. The heater was wound around a 1.0 cm long section of Bi-2212 wire using Formvar insulated Manganin wires, and had a total resistance of ~ 5.0 Ω at 4.2 K. Some samples were covered by a thin layer of Stycast 2850 blue epoxy after instrumentation wiring. The Stycast layer has a total weight of ~ 400 mg, and it thermally insulates the sample from helium during a rapid quench. All voltage taps and thermocouples were monitored using a 24-channel high-precision data acquisition system and recorded with a data acquisition rate of 1 kHz for each channel with 0.1 μV resolution. Samples were then cooled down to 4.2 K in liquid helium and their critical current $I_c$ was measured using the four-probe method with an electrical field criterion of 1 μV/cm. $J_e$ was determined by dividing $I_c$ by the entire cross-sectional area, and $J_c$ was determined by dividing $J_e$ by the cross-sectional area of Bi-2212 filaments, measured from optical images of transverse cross-sections of unreacted Bi-2212 wires using IMAGE J software. To study the influence of $dT_{\text{max}}/dx$, the heater shown in Figure 2 was replaced with a longer heater covering a ~6.5 cm long section of Bi-2212 wire.
Quench degradation experiments followed the protocols established in earlier studies [1, 2, 12, 13, 15, 17-20]. While carrying a steady-state transport current, the sample received a heat pulse of variable duration and amplitude, creating a local hotspot resulting in a maximum temperature $T_{\text{max}}$ and either thermal runaway or recovery. After cooling to 4.2 K and re-measuring $I_c$, $T_{\text{max}}$ was raised gradually with a 20-50 K step via increased heater pulse duration or amplitude until $I_c$ degradation was found. Table 1 summarizes samples studied with their heat treatment, heater set-up, and transport current $I_t$.

Table 1 List of samples investigated

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Conductor</th>
<th>Pressure during processing</th>
<th>Length of wire covered by the heater</th>
<th>Epoxy</th>
<th>$J_c$ (A/mm$^2$)</th>
<th>$J_c$ (A/mm$^2$)</th>
<th>$I_t$ (A)</th>
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<td></td>
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</tr>
<tr>
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<td></td>
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<td></td>
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</table>

Figure 3a shows typical the $V(t)$ and the $T(x,t)$ during a thermal runaway in the sample #1. The sample was heat-treated using the 1 bar standard PMP and its initial self-field $I_c$ at 4.2 K is $\sim$ 450 A. With the joule heating energy from both heater pulse and transport current, the highest peak temperature was reached on the central section (V4) at 5.26 s, when the thermocouple T4 reads 526 K.

One concern is that the thermocouples tends to underestimate the temperature rise when the temperature rising rate is greater than 10 K/s, because the response time of an E-type thermocouple is $\sim$100 ms. Furthermore, thermocouples were soldered to the wire and they may detach from the wire when local temperature exceed the melting temperature of the high melting point solder used for attaching thermocouples (597 K). Hence, the temperature was also estimated by cross-referencing the local voltage measured across each section with the temperature dependence of the resistivity of silver; this method has been proven to be more
reliable for estimating the hotspot temperature during a quench in a previous study [2]. Figure 3b illustrates the growth of the hot spot temperature on the central section using the thermocouple data and the voltage-based approach. The temperatures measured by the thermocouple track well with that converted from voltage for $T < 300$ K, but when the hotspot temperature exceeds 350 K, the results diverge. For the final peak temperature, the value obtained from voltage shows 561 K, about 10% higher than the value obtained with the thermocouple. Thus, in this study the peak hotspot temperature was based on the voltage method.

After quench experiments, the longitudinal cross-sections of selected samples were studied using optical and electron microscopes. Samples were mounted in an electrically conductive resin and ground using SiC papers with ethanol, with final polishing in a suspension of 0.05 μm alumina in ethanol using a vibratory polisher (Buehler Vibromet). The polished samples were etched using a solution made by mixing ammonium (NH4OH), hydrogen peroxide (H2O2), and methanol with a volume ratio of 5:2:7, and their microstructures were further examined using a JEOL-5900 scanning electron microscope (SEM).

3. Results

3.1 Quench degradation behavior of 1 bar processed wires

Figure 4a plots the $I_c$ degradation, defined by the ratio of the $I_c$ measured after a quench to the initial $I_c$, as a function of the peak temperature during a series of quench events for a commercial Ag/Bi-2212 round wire (sample #1). Note that the temperature increased in each sequential quench. The sample showed no $I_c$ degradation when $T_{\text{max}}$ reached 439 K, whereas its $I_c$ reduced by 2.5% when $T_{\text{max}}$ reached 466 K, by 7.5% when $T_{\text{max}}$ reached 547 K, and by 11% when $T_{\text{max}}$ reached 561 K. For each of these quenches, the peak temperature was located in the central 1 cm section of the wire where the heater was mounted. Figure 4b shows $I_c$ along the wire after the seventh (and final) quench as well as the peak temperature recorded during this quench event. The degradation is highly localized. The central 1 cm section shows $I_c$ degradation by 11% whereas the adjacent sections, where peak temperatures were between 350 K and 400 K, showed no degradation.

3.2 Roles of $dT_{\text{max}}/dx$ and $dT_{\text{max}}/dt$
Figure 5a plots the reduction in $I_c$ and the corresponding $T_{\text{max}}$ versus location along the sample for samples #1-3 after their final quenches. Note that sample #2 and sample #3 had the longer heater. Figure 5b plots the corresponding sequence of quenches in terms of the reduction in $I_c$ versus peak temperature in the central section. Despite having much smaller $dT/dx$ (<20 K/cm for sample #2 and #3 vs. >250 K/cm for sample #1 in the central sections), samples #2 and #3, like sample #1, show degradation when the local hotspot temperature exceeds 400-450 K.

A previous study shows that the rate at which the peak temperature increased did not influence conductor degradation [13], and the results found here are in agreement with that conclusion. In this work, the temperature increases most rapidly at lower temperature, e.g. at 400 K/s in the range of 100-200 K, whereas $dT/dt$ is only ~50 K/s when the >500 K. While an experiment designed to vary $dT/dt$ at higher temperature is required to determine if $dT/dt$ is a secondary factor in degradation, within the range of parameters studied here, it does not play a measurable role.

3.3 Roles of wire architectures and filament bridges

Figure 6 illustrates the quench degradation behavior for a series of wires, as shown in Figure 1, with different architecture. Only results from samples heat-treated at 1 bar atmospheric pressure and quenched using the shorter heater length are plotted, so the only variables are the wire architecture, the transport current during quenching and the presence of epoxy. Despite these differences, these samples follow a consistent trend. In short, while the amount that $I_c$ decreases varies from wire to wire, they all show no degradation until $T_{\text{max}}$ reaches ~400 K, gradual degradation for 400 K $< T_{\text{max}} < 550$ K, and a rapid decrease for $T_{\text{max}} > 550$ K.

3.4 Quench degradation behavior of overpressure processed, densified wires

Figure 7 compares results from two samples processed at 100 bar using OP-PMP (samples #9 and #10) and the corresponding 1 bar PMP processed sample (#4). In Figure 7a the results are plotted as the ratio of $I_c$ after quenching to the initial $I_c$ as a function of peak temperature, whereas in Figures 7b and 7c the absolute values of $I_c$ and $n$-value are plotted as a function of peak temperature. The onset of $I_c$ degradation in OP processed samples is also around 450 K. The $n$-value behaves similarly to the corresponding $I_c$. 
3.5 Microstructure of quench degraded samples

Figures 8 and 9 show SEM images of the longitudinal cross-sections from the sample #9, a 100 bar OP processed conductor-A wire. Figure 8 is a location ~1.25 cm from the sample center within section V2, where the peak temperature reached 350 K and $I_c$ was not degraded. The Bi-2212 filaments are dense with some porosity observed. No cracking or other evidence of quenching is seen. Figure 9a is from the sample center, within section V4, where the peak temperature reached 565 K and $I_c$ was reduced by 40%. Cracks are clearly seen, and their propagation was primarily perpendicular to the wire axis. Figures 9b and 9c are higher magnification images of the two large cracks circled in Figure 9a.

Figure 10 shows an example of a more dramatic failure. Sample #10 reached a peak temperature of 635 K and had an 80% reduction in $I_c$. It had a significant rupture. The image shown was taken in the central 0.2-0.3 mm of the wire, within the section V4.

4. Discussion

4.1 Evidences for a strain-driven quench degradation mechanism

The microstructures of degraded samples clearly support that the quench-induced $I_c$ degradation is driven by fracture of Bi-2212 filaments due to excessive strains. The cracks and their propagation paths as seen in Figure 9 are very similar to those reported by van der Laan et al. [21] and by Lu and Cheggour [4, 5] in their mechanically tested and damaged samples. Figure 11 illustrates a schematic of our experimental set-up and what occurs when the wire experiences a quench. During a quench, temperature on Bi-2212/Ag wire rises, whereas the G-10 sample holder and Cu leads are still at 4.2 K. Consequently, the wire buckles and forms an arc to accommodate wire elongation and minimize the total thermal stress. Therefore, Bi-2212 filaments are only subjected to a net tensile axial strain produced by differences in the thermal expansion between silver and Bi-2212. Assuming that the expansion is dominated by silver, this tensile strain for the Bi-2212 filaments can be appropriated by

$$
\varepsilon\big|_{Bi2212} = \frac{\Delta L}{L_{T_{\text{max}}-4.2K}}|_{Ag} - \frac{\Delta L}{L_{T_{\text{max}}-4.2K}}|_{Bi2212}
$$

where $T_{\text{max}}$ is the local hot spot temperature and $\Delta L/L_{T_{\text{max}}-4.2K}|_{Ag}$ and $\Delta L/L_{T_{\text{max}}-4.2K}|_{Bi2212}$ the total linear expansion from 4.2 K to $T_{\text{max}}$ for silver and Bi-2212, respectively.
thermal expansion is approximately linear above room temperature, the total expansion from 4.2 K to a $T_{\text{max}}$ above room temperature can be determined approximately from:

$$\varepsilon |_{\text{Bi-2212}} = (\Delta L/L_{293K-4.2K}|_{\text{Ag}} - \Delta L/L_{293K-4.2K}|_{\text{Bi-2212}}) + (\alpha_{\text{Ag},293K} - \alpha_{\text{Bi-2212},293K})(T_{\text{max}} - 293 \text{ K})$$

Since $\Delta L/L_{293K-4.2K}|_{\text{Ag}}$ is 0.413%, $\Delta L/L_{293K-4.2K}|_{\text{Bi-2212}}$ 0.152%, $\alpha_{\text{Ag},293K}$ 18.5 x $10^{-6}$ K$^{-1}$, and $\alpha_{\text{Bi-2212},293K}$ 8.3 x $10^{-6}$ K$^{-1}$ along the $a,b$-axes of Bi-2212 grains [22]. With a $T_{\text{max}}$ of 463 K, the strain on the Bi-2212 filaments is therefore predicted as 0.434%, consistent with measurements that indicate that the irreversible tensile strain is in the range of 0.4-0.6% [4-6, 23]. Note that the actual strain state for the Ag and Bi-2212 filaments within the composite wire is complex, because the presence of the filaments results in plastic deformation in the Ag matrix during the cooling from the processing peak temperature (~830 °C) to 4.2 K and the Bi-2212 filaments also reduce the ability of silver to expand during warming [24], which results in a tensile strain on the Bi-2212 filaments smaller than that predicted by the above ballpark analysis. Furthermore, a more accurate analysis may consider the temperature dependence of the silver and Bi-2212 mechanical properties. The ballpark analysis presented here, however, does affirm that the $I_c$ degradation during a quench is driven by the local strain in the Bi-2212 filaments. With the temperature continuing to rise and the hot zone spreading, the sample ruptures as seen in Figure 10. Note that the wire rupture is likely caused by macroscopic bending caused by thermal buckling specific to the straight sample set-up. Such sharp bending is not likely to occur in an epoxy impregnated coil winding pack.

Additional experimental evidence supports a strain-driven degradation mechanism. Figure 12a shows the dependence of $J_c$ degradation on $T_{\text{max}}$ obtained from the sample #5. Up to 400 K, the $J_c$ of this sample shows no degradation. With temperature rising beyond 400 K, the $J_c$ of the sample degrades irreversibly but interestingly, when the same sample sequentially subjected to quenches with a lower peak temperature, its $J_c$ shows no further degradation. This behavior is strikingly similar to the dependence of the $J_c$ of Bi-2212 wires on axial strain measured by Lu and Cheggour [4, 5] using a beryllium Walters spring, which is also shown in Figure 12b. The axial strain dependence of the $J_c$ of Bi-2212 wires has a reversible and irreversible behavior in that $J_c$ is reversible within a strain window and once a conductor is degraded, its irreversible strain limit increases.
4.2 Role of conductor architecture and processing on quench limits

Despite that the $I_c$ of Bi-2212 wires depends strongly on the internal connectivity between grains within Bi-2212 filaments and therefore also depends on processing and filament architecture [9-11, 16], our experimental results suggest that the quench degradation limit is fairly independent of the filament architecture, processing, and filament density. Therefore, our findings and arguments can be extended to other commercial PIT Ag/Bi-2212 wires with a architecture different from those invested here, such as the single-restack wires produced by Supercon Inc., and the 121 x 18, $\phi$1.5 mm wires produced by OST. It can also be deduced from our results that the strain dependence of Bi-2212 wires is weakly influenced by overpressure processing and filament density; this deduction is consistent with recent results that have shown that increasing $J_c$ significantly via filament densification does not improve strain-tolerance [6].

4.3 Implications for magnet design and further investigations

Our results show that the quench degradation is weakly influenced by $dT_{\text{max}}/dx$ up to 250 K/cm and $dT_{\text{max}}/dt$ up to 500 K/s. $T_{\text{max}}$ can therefore be used as the key parameter for designing a magnet against quench-induced damages. The maximum hot spot temperature $T_{\text{max}}$ during a quench can be estimated using this relationship [2, 25]:

$$\int_{4.2K}^{T_{\text{max}}} \gamma C(T) dT = \frac{A_m}{A_{cd}} \int_0^\infty j_m^2 dt$$

where $\gamma$ is density and $C(T)$ specific heat averaged over the winding-cross-section, $\rho_m(T)$ the resistivity of silver matrix, $j_m$ the current density in silver matrix, and $A_m$ the cross-sectional area of silver, and $A_{cd}$ the total cross-sectional area of the wire.

Our results indicate that the maximum allowable temperature during a quench can be as high as 400 K for free standing Ag/Bi-2212 wires without being subjected to additional electromagnetic stresses. However, as we have discussed, the maximum allowable temperature would decrease with increasing tensile axial strain. As high field solenoids such as those needed for >1 GHz NMR magnets are expected to work in the high stress regions and therefore, the dependence on maximum allowable temperature on the axial stress and strain needs to be carefully measured in magnetic fields. In a recent quench experiment on a
Bi-2212 coil operating in a 7 T background magnetic field, the conductor experienced a peak temperature up to 280 K without any $I_c$ degradation [2], with the hoop stress estimated at 60 MPa. Such dependence of quench degradation temperature limit on strain state needs to be considered when one designs a Bi-2212 magnet, or any high-field magnet using brittle superconductors. This is especially important for Bi-2212 high-field magnets because Ag-Bi-2212 wires are mechanically weak [26]. To increase the maximum allowable temperature during a quench, one can use an alloy sheath with increased modulus [17, 27], but note that alloying may degrade the low temperature electrical and thermal properties of silver [28, 29]. Furthermore, these results, showing highly localized degradation, highlight the need for distributed sensing within Bi-2212 magnets [30] or diagnostic tools that can accurately locate a quench [31].

5. Summary

We have studied experimentally the quench behavior of a variety of commercial Bi-2212/Ag round wires, including the effects of varying the pressure during PMP. The results show that reductions in $I_c$ due to quenching correlate primarily with $T_{\text{max}}$ rather than $dT_{\text{max}}/dx$ or $dT_{\text{max}}/dt$ or conductor architecture or $J_c$. We show that all of the wires tested here are resistant to degradation for $T_{\text{max}} < 400$ K and exhibit small irreversible $I_c$ and $n$-value degradation for $400$ K $< T_{\text{max}} < 550$ K. Above 550 K, the degradation is more severe. Strong evidence that $I_c$ degradation is caused by the local strain in the Bi-2212 filaments is also shown, including microstructural evidence of crack propagation and $I_c(T_{\text{max}})$ results that emulate $I_c$ strain results on similar wires. This implies that Bi-2212 magnet design, and in particular the design of high field Bi-2212 magnets, must consider the strain state of the wire when assessing quench protection and safe protection limits during a quench.

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at the Oxford Superconducting Technology and National High Magnetic Field Laboratory for providing us the 27x7 wire.

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Figure 8. SEM image of longitudinal cross-sections of a region of a 100 bar OP processed sample that was quenched but had no $I_c$ degradation.

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Figure 12. (a) Normalized $I_c$ versus $T_{\text{max}}$ for sample #5 as in Figure 6 and (b) electromechanical behavior of similar wire as reported in reported in [4, 5]

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Figure 1
Figure 2

Total length: 7.0 cm
Vete: 5.0 cm
V4: ~1.0 cm
Else: ~0.5 cm
Figure 3a
Figure 3b

\[ T_{\text{max,TC}} = 526 \text{ K} \]

\[ T_{\text{max,V}} = 561 \text{ K} \]
Figure 4a

The graph shows the relationship between $I_c$ after quench and $I_c/\text{initial } I_c$ as a function of $T_{max}$ (K). The data points are labeled Q1 to Q7.
Figure 4b
Figure 5a

- **Sample #1, Short Heater, $I_t = 100$ A**
- **Sample #2, Long Heater, $I_t = 100$ A**
- **Sample #3, Long Heater, $I_t = 10$ A**

Spatial Temperature Gradient: $dT/dx$

$T_{max}$ (K) vs. Position (cm)
Figure 5b

The graph shows the relationship between $I_c$ after quench and $I_c$ initial as a function of $T_{\text{max}}$ (K) for three different samples.

- **Sample #1** represented by black squares.
- **Sample #2** represented by red circles.
- **Sample #3** represented by blue triangles.

The data points indicate a decrease in $I_c$ after quench as $T_{\text{max}}$ increases, with each sample showing a distinct trend.

The $I_c$ after quench is normalized to the initial $I_c$ values as follows: 1.00, 0.95, 0.90, 0.85, 0.80.
Figure 6

The graph shows the relationship between $I_c$ after quench/initial $I_c$ and $T_{\text{max}}$ (K) for different samples:

- Sample #1, Conductor A
- Sample #4, Conductor A
- Sample #5, Conductor A
- Sample #6, Conductor B
- Sample #7, Conductor B
- Sample #8, Conductor C

The graph is labeled with "4.2 K, Self-field".
Figure 7a

The diagram shows the relationship between $I_c$ after quench/initial $I_c$ and $T_{max}$ (K). Three samples are plotted:
- Sample #9: 100 Bar OP
- Sample #4: 1 Bar PMP
- Sample #10: 100 Bar OP

The graph plots $I_c$ after quench/initial $I_c$ on the Y-axis against $T_{max}$ (K) on the X-axis.
Figure 7b

A graph showing the relationship between $I_c$ after quench (A) and $T_{max}$ (K) for different samples. The graph includes data points for Sample #4 (1 Bar PMP) and Sample #9 (100 Bar OP). The data points for Sample #10 (100 Bar OP) are also shown, with a notable drop in $I_c$ at higher $T_{max}$ values.
Figure 7c

The graph shows the relationship between the maximum temperature ($T_{max}$) and the $n$-value after quench. Different samples are represented by various symbols:

- Sample #9: 100 Bar OP (blue triangles)
- Sample #4: 1 Bar PMP (black squares)
- Sample #10: 100 Bar OP (red circles)

The $n$-value after quench is plotted on the y-axis, and $T_{max}$ (K) is plotted on the x-axis. The data points for each sample cluster around different temperature values, illustrating the variation in $n$-value with increasing $T_{max}$.
Figure 8

Bi-2212

Bi-2212

Ag

Bi-2212

Ag

AgMg

X500 50μm
Figure 9b
Figure 9c
Figure 10
Figure 11a

Ag/Bi-2212 hotspot under compressive stress
Figure 11b

Ag/Bi-2212 hotspot
compressive stress released with wire in arc

Cu
G-10
Cu
Figure 12a

Graph showing the relationship between $I_c$ after quench and initial $I_c$ with respect to $T_{\text{max}}$ (K). The graph indicates a reversible degradation process followed by irreversible degradation at higher temperatures.
Figure 12b

-0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6

Normalized critical current

Axial Strain [%]

T=4.04 K, B=5 T

Reversible

Irreversible