Critical Current Distributions of Recent Bi-2212 Round Wires

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Abstract—Bi$_2$Sr$_2$CaCu$_2$O$_8$$_x$ (Bi-2212) is the only high-field, high-temperature superconductor (HTS) capable of reaching a critical current density $J_c(16$ $T$, $4.2$ $K$) of 6500 $A$·$mm^{-2}$ in the highly desirable round wire (RW) form. However, state-of-the-art Bi-2212 conductors still have a critical current density ($I_c$) to depairing current density ($|J_{dd}|$) ratio around 20 to 30 times lower than that of state-of-the-art Nb – Ti or REBCO. Previously, we have shown that recent improvements in Bi-2212 RW $J_c$ are due to improved connectivity associated with optimization of the heat treatment process, and most recently due to a transition to a finer and more uniform powder manufactured by Engi-Mat. One quantitative measure of connectivity may be the critical current ($I_c$) distribution, since the local $I_c$ in a wire can vary along the length due to variable vortex-microstructure interactions and to factors such as filament shape variations, grain-to-grain connectivity variations and blocking secondary phase distributions. Modeling the experimental $V - I$ transition measured on a low resistance shunt as a complex sum of voltage contributions of individual filament and wire subsection allows a numerical extraction of the $I_c$ distribution from the $d^2 V/dI^2$ treatment of the $V - I$ curves. Here we compare ~ 0.1 mm length $I_c$ distributions of Bi-2212 RWs with recent state-of-the-art very high-$J_c$ Engi-Mat powder and lower $J_c$ and older Nexans granulate powder. We do find that the $I_c$ spread for Bi-2212 wires is about twice the relative standard of high-$J_c$ Nb – Ti well below $H_{irr}$. We do not yet see any obvious contribution of the Bi-2212 anisotropy to the $I_c$ distribution and are rather encouraged that these Bi-2212 round wires show relative $I_c$ distributions not too far from high-$J_c$ Nb – Ti wires.

Index Terms—Bi-2212, Critical current distribution, HTS.

I. INTRODUCTION

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T advances in the critical current density ($J_c$) of powder-in-tube Bi-2212 round wires have generated great interest for their use in high field magnet technology [1]. An irreversibility field ($H_{irr}$) of more than 100 $T$ at 4.2 $K$, along with its macroscopically isotropic, twisted, multifilamentary architecture make Bi-2212 a promising conductor for applications above 25 $T$, where the low temperature superconductors (LTS) Nb – Ti and Nb$_3$Sn are limited by their much lower irreversibility fields of ~ 11 $T$ and ~ 25 $T$ (at 4.2 $K$) [2], [3]. Although its $J_c(16$ $T$, $4.2$ $K$) = 6500 $A$·$mm^{-2}$ far exceeds the Future Circular Collider (FCC) specification of $J_c(16$ $T$, $4.2$ $K$) = 1500 $A$·$mm^{-2}$, $J_c$ for state-of-the-art Bi-2212 is still lower than 1% of the depairing current density $|J_{dd}| (|J_d| \sim H_{irr}/A \sim 3 \times 10^6$ $A$·$mm^{-2}$, where the thermodynamic critical field $H_{irr} \sim 1$ $T$ [5] and the penetration depth ($\lambda$) of Bi-2212 ~ 240 nm), as opposed to the 20 – 30% values achieved with Nb – Ti or REBCO. Our recent comprehensive survey of many Bi-2212 wires made between 2009 and 2019 has shown that while $J_c$ defined by $I_c/A$, where $A$ is the total Bi-2212 cross-section, varied by almost a factor of 6 they actually all had almost identical normalized $I_c(H)$, leading us to conclude that very similar vortex pinning properties were shared by all wires and that $|J_{dd}|$ was determined by the effective filament connectivity [6]. Filament connectivity is affected by multiple factors on many length scales, including filament cross-section variations before reaction and post-reaction defects such as, cracks, voids, blocking secondary phases, and grain-to-grain connectivity variation. Moreover, cuprate grain boundary $J_c$ drops exponentially with increasing grain-boundary misorientation angle. Indeed, grain misorientation has historically been the main impediment to the realization of high $J_c$ in cuprate HTSs [1]. Although the quasi-biaxial texture produced by the RW Bi-2212 heat treatment process is believed to mitigate this high angle grain boundary limitation [7], the $c$ - axis rotation of the highly anisotropic Bi-2212 grains results in an inherent $J_c$ variation along the length of each filament. Another commonly observed wire defect is variation of the filament cross section due to the highly non-uniform grain growth characteristics of Bi-2212 from the liquid state. More recently we have seen that the grain texture and filament structure in Bi-2212 RWs are strongly dependent on powder type [4], heat treatment parameters [8], and wire diameter [9].

The $I_c$ distribution is a potential quantitative measure of this complex connectivity variation. We are motivated by the possibility that this distribution can identify avenues for improving $I_c$ and perhaps for wire production quality control. Recently, a transition to finer powder made by Engi-Mat has more than doubled $J_c$ in state-of-the-art Bi-2212 wires [4] compared to earlier wires made with Nexans granulate powder.
To extract the $I_c$ distribution of our wires, we employed the method previously employed to characterize the $I_c$ distribution from $V-I$ characteristics of Nb–Ti and Nb$_3$Sn wires using a normal shunt to make $d^2V/dI^2$ analysis possible [10]–[13]. We should note that the shunt resistance of the normal metal matrices of Cu in Nb–Ti and Ag in Bi-2212 are rather similar, both having residual resistivity ratio (RRR) $>100$ [14], [15].

II. Experimental

Two Bi-2212 RWs with the same nominal powder composition of Bi$_2$Sr$_2$CaCu$_2$O$_y$CuO$_2$ but very different powders and time of fabrication were selected. The pmm100913 and pmm180410 wires were fabricated in 2010 and 2018 by Bruker-Oxford Superconducting Technology (B-OST) using Nexans granulate (lot 77) and Engi-Mat (LXB 116) powder. Both powders were state-of-the-art at the time. Double restack multifilamentary wires were made by the Powder-In-Tube (PIT) process using powder-filled pure Ag tubes and an outer sheath of Ag–0.2 wt.% Mg alloy. The heat treatment of 1.5 m spiral wires was done at 50 bar over-pressure with an oxygen partial pressure of 1 bar [4]. Wires were then soldered onto a brass ITER-like barrel [16] and the $V-I$ characteristics of multiple 10 cm sections of each sample were measured using standard four-probe transport measurement methods at 4.2 K in magnetic fields up to 15 T. The peak applied currents were well above the standard $1\mu V\cdot cm^{-1}$ criterion limit far into the flux flow regime, so as to obtain the full $I_c$ distribution. A standard Nb–47 wt.% Ti wire of high $J_c$ manufactured by Supercon Inc. was also measured. Detailed specifications of the samples are listed in Table I.

A. Measurements of the Critical Current Distribution

Traditional four-probe transport measurements reveal only the lower end of the $I_c$ distribution. In a well-optimized material like Nb–Ti where current is believed to flow uniformly, magnetization and transport measurements typically agree well when corrections for electric field ($E$) differences are made (and filament sausaging is avoided). Bi-2212 is more complex: the current path is percolative and uncertain with a fractional occupancy of as little as 1% [6]. Moreover, most transport measurements typically characterize only $\sim$ 1 cm of conductor due to use of straight wires in narrow-bore magnets. Because of the greater stability of Bi-2212 compared to Nb–Ti and Nb$_3$Sn it appears that a relatively high criterion of $1\mu V\cdot cm^{-1}$ reliably predicts the quench performance of even potted magnets [17], making it interesting to explore the $V-I$ transition at both lower and higher $E$ values.

An early method that was successfully used to characterize the $I_c$ distribution of Nb–Ti and Nb$_3$Sn wires used a substantial normal metal shunt to avoid conductor burn out [11], [18]. The method models the $I_c$ distribution as a series array of many short longitudinal sections of varying $I_c$ [13], [19]. As the applied current exceeds the local critical current ($i_c$) of a section, the section transitions from a pinned to a flux flow state. Since the flux flow resistivity is two to three orders of magnitude higher than the silver matrix and the high conductance barrel [11], almost all the excess current is carried by the normal matrix and shunt without excessive heating and depinning of vortices in the superconductor. As originally formulated by Baixeras and Fournet [10], the voltage across a sub-element with critical current $i_c$ as a function of applied current $I$ is given by a series distribution of variable $i_c$ elements:

$$V(I, i_c) = R(I - i_c)$$

The normal method of degradation of $I_c$ in Nb–Ti is by onset of filament sausaging which fits the series $i_c$ array model well but almost all other practical superconductors have more complex series-parallel current paths. Plummer and Evetts [18] extended this analysis to filamentary Nb$_3$Sn conductors, where the normal bronze matrix can have higher ohmic dissipation than flux flow in the Nb$_3$Sn filaments (bronze Cu is always poisoned by the residual Sn content, typically 0.15 – 1 at.% meaning that its RRR is < 5), using a dynamic flux flow relation to determine the Nb$_3$Sn distribution, arriving at the same equation as Baixeras and Fournet. In their model, the $I_c$ distribution was assumed to be Gaussian due to many variations of grain size, local Sn content and filament uniformity, none of which were well controlled or easy to measure. In this more general case of a wire with many filaments, varying vortex pinning and varying active cross-section, the distribution of $i_c$ values is both parallel and series and complex. Denoting the desired distribution $\phi(i_c)$ as the probability distribution density of $i_c$ in the wire suggests use of a Gaussian function since many independent factors are locally determining the local $i_c$ values. Taking $R_{eff}$ as the effective resistance of the normal currents in the stabilizer and shunt, integrating over all possible $i_c$ values gives the following expression for the total voltage measured across the wire at a given applied current $I$:

$$V(I) = R_{eff} \int_0^{i_c} (I - i_c) \phi(i_c) di_c$$

$$\phi(I) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(I - \mu)^2}{2\sigma^2}\right)$$

$$\frac{d^2V(I)}{dI^2} = R_{eff} \phi(I) = \frac{R_{eff}}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(I - \mu)^2}{2\sigma^2}\right)$$

### Table I

| Sample   | Material | Powder | Sheath Material | Manufacturer | Diameter [mm] | No. of Filaments | Filling Factor | $J_c$ (5 T, 4.2 K) [A · mm$^{-2}$] |
|----------|----------|--------|-----------------|--------------|---------------|-----------------|----------------|----------------------------------|
| pmm100913 | Bi-2212  | Engi-Mat | Ag–0.2 wt.% Mg | B-OST        | 1.0           | 85x18           | 0.201          | 7115                             |
| pmm180410 | Bi-2212  | Nexans  | Ag–0.2 wt.% Mg | B-OST        | 0.8           | 37x18           | 0.221          | 4085                             |
| Nb–Ti    | Nb–47 wt.% Ti | Cu    | Supercon Inc.   |              | 0.6           | 54              | 0.436          | 3280                             |

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Differentiating $V(I)$ twice with respect to $I$ yields $R_{\text{eff}} \cdot \phi(I)$, which allows extraction of the $I_c$ distribution and $R_{\text{eff}}$. To reduce noise, a Savitzky-Golay filter was used to smooth the data before calculating the second derivative \cite{11, 20} by regression fitting a second order polynomial to a typical comb size ($m$) of $7 - 15 \ V - I$ points, the analytical derivative being determined from the coefficient at the center of a group of $2m+1$ points. The $7 - 15$ point comb size was kept low to avoid smoothing out subtle features of the distribution curve shape. Since the factors that affect local critical current are thought to be randomly distributed and uncorrelated, the distribution of $I_c$ plausibly converges to a Gaussian as predicted by the central limit theorem \cite{13, 18, 21, 22} enabling extraction of distribution parameters, such as the mean $I_c$ ($\mu$ in (4)) and the standard deviation ($\sigma$).

B. The Fraction of Superconductor in Flux Flow

$f_{D}(I)$ represents the fraction of superconductor wire in the flux flow state at a given current and this was calculated from $\frac{d^2V}{dI^2}$ at $I_c$ determined by both $0.1 \ \mu V \cdot cm^{-1}$ and $1 \ \mu V \cdot cm^{-1}$ criteria according to:

$$f_{D}(I) = \int_{0}^{I_c} \phi(i_c) di_c$$ \quad (5)

C. Critical Current Measurements of Short (4.5 cm) Samples

To compare regular measurements on short samples to those determined on the shunted barrel samples, 10 cm long wires of Bi-2212 were heat treated along with each spiral sample. Transport critical currents $I_c$ were measured using the four-probe method at 4.2 K in perpendicular magnetic fields up to 15 T using both $0.1 \ \mu V \cdot cm^{-1}$ and $1 \ \mu V \cdot cm^{-1}$ criteria. The resistive transition index ($n$ value) was calculated by fitting the $V - I$ curve from 0.6 – 20 $\mu V \cdot cm^{-1}$.

III. RESULTS

Fig. 1(a) shows the $I_c$ distribution of a 10 cm section of the higher-$J_c$ Engi-Mat wire at 5 T and 14 T. The basic features are similar in all measured samples. Both 5 T and 14 T curves are slightly asymmetric due to an extended high current tail but it is also evident that the 14 T $I_c$ distribution is sharper than the 5 T distribution. Two separate lines mark the short sample $I_c$ position based on $0.1 \ \mu V \cdot cm^{-1}$ and $1 \ \mu V \cdot cm^{-1}$ criteria. The $I_c$ of the higher-$J_c$ Engi-Mat short sample at $1 \ \mu V \cdot cm^{-1}$ is 1078 A at 5 T and 782 A at 14 T compared to the distribution analysis mean $I_c \sim 1039.8 \pm 16.9 \ \text{A}$, $\sigma \sim 99.3 \pm 4.9 \ \text{A}$, and $\sigma/\mu \sim 0.095 \pm 0.0044$ at 5 T. By contrast, the older and lower-$J_c$ Nexans wire shows mean $I_c \sim 448.2 \pm 5.1 \ \text{A}$, $\sigma \sim 59.1 \pm 3.4 \ \text{A}$, and $\sigma/\mu \sim 0.132 \pm 0.0084$ at 5 T. For comparison to a more classical wire Fig. 1(b) shows the $I_c$ distribution of the Supercon Nb – Ti wire at various fields. At 5 T, it has $I_c \sim 394.9 \pm 3.6 \ \text{A}$, $\sigma \sim 18.6 \pm 1.5 \ \text{A}$, and $\sigma/\mu \sim 0.047 \pm 0.0034$. The Nb – Ti wire distribution width is significantly lower than both Bi-2212 samples at fields well below $H_{\text{irr}}$ but does cross the Engi-Mat Bi-2212 wire close to $H_{\text{irr}}$. Further details of the distribution parameters are listed in Table II.

Fig. 2(a) shows $J_c(H)$ for Engi-Mat, Nexans and Nb – Ti wires. The power law fit of $J_c(H)$ from 3 T to 15 T for both Bi-2212 wires is shown in the inset of Fig. 2(a).

Fig. 2(b) shows $\sigma/\mu$ of the $I_c$ distribution for Engi-Mat, Nexans, and Nb – Ti wires with error bars of one standard deviation calculated from multiple sections of the spiral on each barrel. For Nb – Ti, $\sigma/\mu$ increases monotonically with field from $0.034 \pm 0.0023$ at 3 T to $0.125 \pm 0.0272$ at 10 T, but it varies only slowly with increasing magnetic field in Bi-2212 wires, most likely because, unlike for Nb – Ti, $H/H_{\text{irr}}$ is always significantly lower than unity. At 10 T, Nexans and Engi-Mat wires show $\sigma/\mu \sim 0.14$, and 0.10, respectively, but is then 0.13 for Nb – Ti. The fractional energy dissipation ($f_{D}$) and the ratio of short sample critical current to mean critical current ($I_c/\mu$) are listed in Table II. The $f_{D}(I_c)$ of the Engi-Mat wire, where $I_c$ using the $1 \ \mu V \cdot cm^{-1}$ electric field criterion on the 4.5 cm long sample shows that 60 – 65% of the superconductor has transitioned from the flux pinning...
In this work, we have compared the $I_c$ distribution of two Bi-2212 RWs made by B-OST prepared with newer and better and older and worse quality powders from Engi-Mat and Nexans. We were motivated to better understand the conclusion of Brown et al. [6] that the magnitude of $J_c$ in Bi-2212 wires was almost completely determined by the effective connectivity of the current path which we interpreted to be very small since the ratio $J_c/J_d$ is of order 1% or less. Even if the vortex pinning in Bi-2212 is weak (it is also not yet clarified and may just be due to cation defect fluctuations within the Bi-2212 structure), such a low ratio of $J_c$ to $J_d$ implies that the long range current path may occupy a small fraction of the total cross-section. In the absence of detailed measurements of $J_c$ at the filament level (we have done this earlier for sections of Bi-2223 filament and found values of $J_c$ several times the average [23]), we started this work to see if the distribution of $J_c$ values extracted from $d^2V/dI^2$ measurements would offer a better understanding of the differences between representative wires made with the former champion Nexans and the more recent champion Engi-Mat powders with about a factor of 2 difference in the filament $J_c$ defined by the measurement of $I_c$ divided by the fully densified Bi-2212 cross-section.

In analyzing the data we take the common view [12], [21], [22], [24] that the local $I_c$ along the wire is controlled by multiple independent factors that justify a Gaussian approximation consistent with the central limit theorem [18]. Gaussian distributions have earlier been measured in Nb3Sn [13], [18], [19] with $\sigma/\mu$ values of 0.15 at 15 T, about 0.6 $H_{\text{irr}}$. Here we show that a high-$J_c$ Nb–Ti has a significantly smaller $\sigma/\mu$ of $\sim$ 0.05 at 5 T ($\sim$ 0.5 $H_{\text{irr}}$), although it does rise significantly above 0.1 at 8 T close to $H_{\text{irr}}$. Both Nb–Ti and Nb3Sn are isotropic with respect both to vortex pinning and to $H_{c2}$ [25]. [26]. Given the meandering $c$-axis along the filament, we expect that some grains will have very favorable orientations for $H_{c2}$ and some quite unfavorable. Not yet being clear what the strong pinning centers are in Bi-2212, we cannot yet a priori say whether the high $H_{c2}$ ab-plane orientation has stronger pinning than the $c$-axis orientation but we might expect that the $d^2V/dI^2$ would be broadened on the high $I_c$ side by this anisotropy.

Indeed, we found that our two Bi-2212 wires showed Gaussian behavior over about three quarters of their $I_c$ distribution but also possessed a notable non-Gaussian extended tail beyond about 150% of the mean $I_c$. Such a tail was also seen in studies of Bi-2223 tapes [27]. Since both Bi-2223 and Bi-2212 are strongly anisotropic cuprates and both have percolative current paths, broader transitions and some non-Gaussian behavior is not unexpected, particularly at higher $I_c$ values that may correspond to grains with higher $H_{c2}$ values. Qualitatively then the non-Gaussian high-side tail has a plausible physical basis, even if we are very far from being able to access the whole range of $I_c$ of grains with strongly varying orientations.

It is worth pointing out that the Bi-2212 distributions yield mean critical current values $\mu$ within a few percent of the measured short ($\sim$ 5 cm) sample $I_c$($1 \mu V \cdot cm^{-1}$) results, with a dissipation fraction $f_{\text{diss}}$ rather independent of field, whereas for Nb–Ti $f_{\text{diss}}$ increases from 15% to 68% between 3 T and 10 T with $\mu$ moving from above to below $I_c$. This corresponds to a decrease in dissipation from $\sim$ 200 mW $\cdot$ cm$^{-3}$ at 3 T to only 10 mW $\cdot$ cm$^{-3}$ at 10 T at a 1 $\mu V \cdot cm^{-1}$ criterion, in the context of the low enthalpy margin of Nb–Ti, on the order of 1 – 10 mJ $\cdot$ cm$^{-3}$. The higher dissipation occurring at lower fields causes LTS conductors to quench rapidly when even a fraction of the distribution is normal, as seen by the higher $n$ values of their transitions. By contrast, for Bi-2212, the dissipation

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**Fig. 2.** (a) Critical current density evaluated at 1 $\mu V \cdot cm^{-3}$, and (b) relative standard deviation of $I_c$ distribution as a function of applied field for pmn180410 (square), pmn100913 (circle), and Nb–Ti (diamond) wires at 4.2 K. The power law fit from 3 T to 15 T for both Bi-2212 wire is shown in the inset. Dashed lines are guides for the eye.

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**IV. DISCUSSION**

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changes are much less, ~160 – 100 mW cm⁻³ from 3 – 14 T for the Engi-Mat wire, and the enthalpy margin is two orders of magnitude larger, leading to more uniform \( f_0 \) and \( n \) values. At higher fields the margin decays only gradually for Bi-2212, which still has over 10 times more margin at 30 T than Nb – Ti has at 5 T.

The relative standard deviation (\( \sigma/\mu \)) is a significant parameter which considers both the breadth and the mean of the \( I_c \) distribution. Previous investigations of the \( I_c \) distribution of technological conductors yielded \( \sigma/\mu \sim 0.02 – 0.50 \) for Nb₃Sn, Nb – Ti, and Bi-2223 [11], [13]. However, Warnes et al. also reported an enhanced \( \sigma/\mu \sim 0.14 \) for a severely sausaged Nb – Ti wire at 4 T (reduced field, \( H/H_{irr} \sim 0.36 \)) which increased to \( \sim 0.33 \) at 10 T [11], thus correlates a high \( \sigma/\mu \) value with strong filament sausaging. Here we measured the \( I_c \) distributions of Bi-2212 wires up to 15 T but since this is only 10 – 15% of \( H_{irr} \), the complete \( H/H_{irr} \) dependence of \( \sigma/\mu \) in our wires is not known. Hence, we believe that it is more appropriate to compare the low field \( \sigma/\mu \) values of Nb – Ti to our Bi-2212 wires. The relative broadening width near the irreversibility field seen in the Nb – Ti probably results from large fluctuations in the effective vortex pinning near \( H_m \) as the elementary pinning forces generated by the dense \( \alpha\)-Ti vortex-pins become proximity coupled to the superconducting \( \beta \)-phase matrix [23].

In line with our original conjecture, we did find a marked difference in \( \sigma/\mu \) between the Engi-Mat (pmm180410) and Nexans (pmm100913) wires. It is evident (see Fig. 2(b)) that the older and lower-\( I_c \) Nexans wire has about 40% higher \( \sigma/\mu \) (0.14 vs. 0.14). As noted earlier by Brown et al. [6], many wires made with Nexans, Engi-Mat and other powder sets had the same normalized \( J_c(H) \) characteristics, even though the magnitude of \( J_c \) varied by almost 6. We conclude that the effective percolative connectivity of wires is what is really controlling the \( J_c \) magnitude. The modern fine particle Engi-Mat powder has more uniform characteristics than the earlier generation Nexans powder as demonstrated experimentally by Jiang et al. [4]. We conclude that much of the ~ 60% \( J_c \) improvement is due to improved filament connectivity of the Engi-Mat powder [4]. Thus, we conclude that the 30% lower \( \sigma/\mu \) in our Engi-Mat sample compared to the lower-\( I_c \) Nexans sample is due to improved connectivity associated with the much finer and more uniform Engi-Mat powder.

As noted above, the Nexans \( \sigma/\mu \) values are very similar to that of a severely sausaged Nb – Ti wire [11]. Knowing that Nexans powder has many hard particles of varying size which distort the filament structure, it is plausible to compare the degraded connectivity of Bi-2212 wire made with Nexans powder to sausaged Nb – Ti wire [11]. However, we do not conclude that filament sausaging is the sole reason for the degraded \( \sigma/\mu \) of our Nexans sample. It is interesting that a Bi-2223 wire (\( \mu \sim 134.6 \mathrm{A} \Omega \mathrm{cm}, \sigma \sim 16.8 \mathrm{~A} \Omega \mathrm{cm} \), \( \sigma/\mu \sim 0.12 \) at 4.2 K, 0.5 T) also had a large \( \sigma/\mu \) [27]. Many other factors are also still in play, one being degraded grain-to-grain connectivity that is certainly present in both Bi-2212 and Bi-2223.

Although better connected than the Nexans powder wire, the higher-\( I_c \) Engi-Mat powder wire has a ~3 fold higher \( \sigma/\mu \), and an almost 50% smaller \( n \) value compared to our high-\( I_c \) Nb – Ti wire. Based on the experimental evidence it can be expected that \( I_c \) of Bi-2212 RWs could be increased further if the \( \sigma/\mu \) can be minimized by identifying and addressing connectivity limitations. To this end, we believe that the \( \sigma/\mu \)

| Sample  | Magnetic Field | Mean, \( \mu \) | Standard Deviation, \( \sigma \) | Relative Std. Deviation, \( \sigma/\mu \) | \( R_{eff} \) (\( \mu \Omega \cdot \mathrm{cm}^{-1} \)) | Critical Current, \( I_c \) | \( n \) value | \( f_0(I_c f) \) | \( f_0(I_c f)^b \) | \( \frac{I_c}{\mu} \) |
|---------|----------------|----------------|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| pm180410 | [T] | [A] | [A] | [\( \mu \Omega \cdot \mathrm{cm}^{-1} \)] | [A] | [%] | [%] |
| Engi-Mat | 3 | 1210.6 | 96.6 | 0.080 | 0.025 | 1242.5 | 26.6 | 22.8 | 61.9 | 1.03 |
| | 4 | 1899.8 | 99.3 | 0.095 | 0.028 | 1708.8 | 26.7 | 30.5 | 64.2 | 1.04 |
| | 5 | 947.6 | 91.2 | 0.096 | 0.027 | 982.6 | 25.6 | 28.7 | 64.1 | 1.04 |
| | 6 | 881.3 | 84.4 | 0.096 | 0.027 | 916.5 | 26.2 | 29.6 | 63.7 | 1.04 |
| | 7 | 859.6 | 85.7 | 0.100 | 0.028 | 888.9 | 25.7 | 29.5 | 63.1 | 1.03 |
| | 8 | 834.0 | 85.7 | 0.103 | 0.028 | 863.3 | 25.2 | 29.1 | 62.6 | 1.04 |
| | 9 | 793.8 | 85.9 | 0.108 | 0.029 | 814.1 | 25.0 | 24.9 | 60.9 | 1.03 |
| | 10 | 774.8 | 84.3 | 0.105 | 0.026 | 799.7 | 22.2 | 30.6 | 62.1 | 1.03 |
| Nexans  | [T] | [A] | [A] | [\( \mu \Omega \cdot \mathrm{cm}^{-1} \)] | [A] | [%] | [%] |
| 3 | 448.2 | 59.1 | 0.132 | 0.030 | 445.2 | 17.4 | 16.5 | 49.6 | 0.99 |
| 4 | 376.6 | 53.5 | 0.142 | 0.032 | 377.2 | 18.8 | 18.6 | 47.8 | 1.00 |
| 5 | 336.2 | 50.1 | 0.149 | 0.032 | 328.0 | 15.2 | 13.3 | 43.8 | 0.98 |
| Nb – Ti | [T] | [A] | [A] | [\( \mu \Omega \cdot \mathrm{cm}^{-1} \)] | [A] | [%] | [%] |
| 3 | 589.7 | 20.3 | 0.034 | 0.047 | 556.1 | 50.2 | 1.7 | 14.3 | 0.94 |
| 4 | 394.9 | 18.6 | 0.047 | 0.048 | 382.8 | 62.6 | 8.1 | 30.5 | 0.97 |
| 5 | 233.0 | 13.8 | 0.059 | 0.048 | 230.1 | 58.6 | 18.6 | 43.9 | 0.99 |
| 6 | 154.9 | 12.0 | 0.077 | 0.048 | 155.2 | 55.2 | 23.6 | 53.5 | 1.00 |
| 7 | 82.1 | 11.2 | 0.136 | 0.048 | 84.4 | 44.5 | 36.1 | 59.9 | 1.03 |
| 8 | 25.1 | 3.1 | 0.125 | 0.049 | 26.9 | 15.8 | 21.3 | 68.5 | 1.07 |

\( ^1 \) Distribution is measured for multiple sections of the spiral sample at each field. Here average results of the fitting parameters are listed.
\( ^2 \) Each voltage tap in pmm180410, pmm100913, and Nb – Ti samples is 10 cm, 20 cm, and 30 cm apart, respectively.
\( ^3 \) Critical current is calculated from a 4.5 cm short sample based on 1 \( \mu \Omega \cdot \mathrm{cm}^{-1} \) criterion at 4.2 K.
\( ^a \) \( f_0(I_c f) \) is calculated based on short sample \( I_c \) at 0.1 \( \mu \Omega \cdot \mathrm{cm}^{-1} \) criterion.
\( ^b \) \( f_0(I_c f) \) is calculated based on short sample \( I_c \) at 1 \( \mu \Omega \cdot \mathrm{cm}^{-1} \) criterion.

The table above shows the parameters derived from the critical current distribution for different samples. The table includes the magnetic field, mean current, standard deviation, relative standard deviation, effective resistivity, critical current, and other values for comparison.
value can be used as a quantitative parameter for conductor quality control.

V. Conclusion

In fact, the $I_c$ distribution, though wider for Bi-2212 than for optimized Nb–47 wt.% Ti, is not a great deal larger, in spite of Bi-2212 being strongly anisotropic along each filament, possessing current-blocking regions, and having highly non-uniform filament shapes. The much lower-quality control. The much lower-quality control.

The relative standard deviation of Engi-Mat wire is ~30% lower than Nexans wire. The implication is that $e$-suggestion of poorer connectivity. The relative standard deviation of Engi-Mat wire is ~30% lower than Nexans wire. The implication is that $e$-suggestion of poorer connectivity. The relative standard deviation of Engi-Mat wire is ~30% lower than Nexans wire. The implication is that $e$-suggestion of poorer connectivity.

The much lower-quality control.

We believe that measurements like these can be a useful tool in further understanding of how best to raise $I_c$ in Bi-2212 conductors.

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