

Critical Current Distributions of Recent Bi-2212 Round Wires

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Abstract— $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8-x}$ (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 $6500 \text{ A}\cdot\text{mm}^{-2}$ in the highly desirable round wire (RW) form. However, state-of-the-art Bi-2212 conductors still have a critical current density (J_c) to depairing current density (J_d) 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 sub-sections allows a numerical extraction of the I_c distribution from the d^2V/dI^2 treatment of the V - I curves. Here we compare ~ 0.1 m 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

RECENT 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, multi-filamentary architecture make Bi-2212 a promising conductor for applications above 25 T, where the low temperature superconductors (LTS) Nb-Ti and Nb_3Sn 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) $\sim 6500 \text{ A}\cdot\text{mm}^{-2}$ far exceeds the Future Circular Collider (FCC) specification of $J_c(16 \text{ T}, 4.2 \text{ K}) = 1500 \text{ A}\cdot\text{mm}^{-2}$,

J_c for state-of-the-art Bi-2212 is still lower than 1% of the depairing current density [4] ($J_d \sim H_c/\lambda \sim 3 \times 10^6 \text{ A}\cdot\text{mm}^{-2}$, where the thermodynamic critical field $\mu_0 H_c \sim 1 \text{ T}$ [5] and the penetration depth (λ) of Bi-2212 $\sim 240 \text{ nm}$), 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 $J_c(H)$, leading us to conclude that very similar vortex pinning properties were shared by all wires and that $|J_c|$ 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

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TABLE I
SAMPLE SPECIFICATIONS

Sample	Material	Powder	Sheath Material	Manufacturer	Diameter [mm]	No. of Filaments	Filling Factor	$J_c(5\text{ T}, 4.2\text{ K})$ [$\text{A}\cdot\text{mm}^{-2}$]
pmm180410	Bi-2212	Engi-Mat	Ag-0.2 wt % Mg	B-OST	1.0	85×18	0.201	7115
pmm100913	Bi-2212	Nexans	Ag-0.2 wt % Mg	B-OST	0.8	37×18	0.221	4085
Nb-Ti	Nb-47 wt.% Ti		Cu	Supercon Inc.	0.6	54	0.436	3280

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 Nb₃Sn 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_{2.17}Sr_{1.94}Ca_{0.90}Cu_{1.98}O_x 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 $1\ \mu\text{V}\cdot\text{cm}^{-1}$ 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 ~ 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 Nb₃Sn it appears that a relatively high criterion of $1\ \mu\text{V}\cdot\text{cm}^{-1}$ 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 Nb₃Sn 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:

$$V(I, i_c) = R(I - i_c) \quad (1)$$

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 Nb₃Sn conductors, where the normal bronze matrix can have higher ohmic dissipation than flux flow in the Nb₃Sn 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 I_c 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 $\varphi(i_c)$ 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 :

$$V(I) = R_{\text{eff}} \int_0^I (I - i_c) \varphi(i_c) di_c \quad (2)$$

$$\varphi(I) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(I-\mu)^2}{2\sigma^2}} \quad (3)$$

$$\frac{d^2V(I)}{dI^2} = R_{\text{eff}} \varphi(I) = \frac{R_{\text{eff}}}{\sqrt{2\pi}\sigma^2} e^{-\frac{(I-\mu)^2}{2\sigma^2}} \quad (4)$$

Differentiating $V(I)$ twice with respect to I yields $R_{\text{eff}} \cdot \varphi(I)$, which allows extraction of the I_c distribution and R_{eff} . To reduce noise, a Savitzky-Golay filter was used to smooth the data before calculating the second derivative [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 [13], [18], [21], [22], enabling extraction of distribution parameters, such as the mean I_c (μ in (4)) and the standard deviation (σ).

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 d^2V/dI^2 at I_c determined by both $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ and $1 \mu\text{V}\cdot\text{cm}^{-1}$ criteria according to:

$$f_D(I) = \int_0^I \varphi(i_c) di_c \quad (5)$$

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 $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ and $1 \mu\text{V}\cdot\text{cm}^{-1}$ criteria. The resistive transition index (n value) was calculated by fitting the V - I curve from $0.6 - 20 \mu\text{V}\cdot\text{cm}^{-1}$.

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 $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ and $1 \mu\text{V}\cdot\text{cm}^{-1}$ criteria. The I_c of the higher- J_c Engi-Mat short sample at $1 \mu\text{V}\cdot\text{cm}^{-1}$ is 1030 A at 5 T and 782 A at 14 T compared to the distribution analysis mean $I_c \sim 1039.8 \pm 16.9$ A, $\sigma \sim 99.3 \pm 4.9$ 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 $I_c \sim 448.2 \pm 5.1$ A, $\sigma \sim 59.1 \pm 3.4$ 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 $I_c \sim 394.9 \pm 3.6$ A, $\sigma \sim 18.6 \pm 1.5$ 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_{irr} but does cross the Engi-Mat Bi-2212 wire close

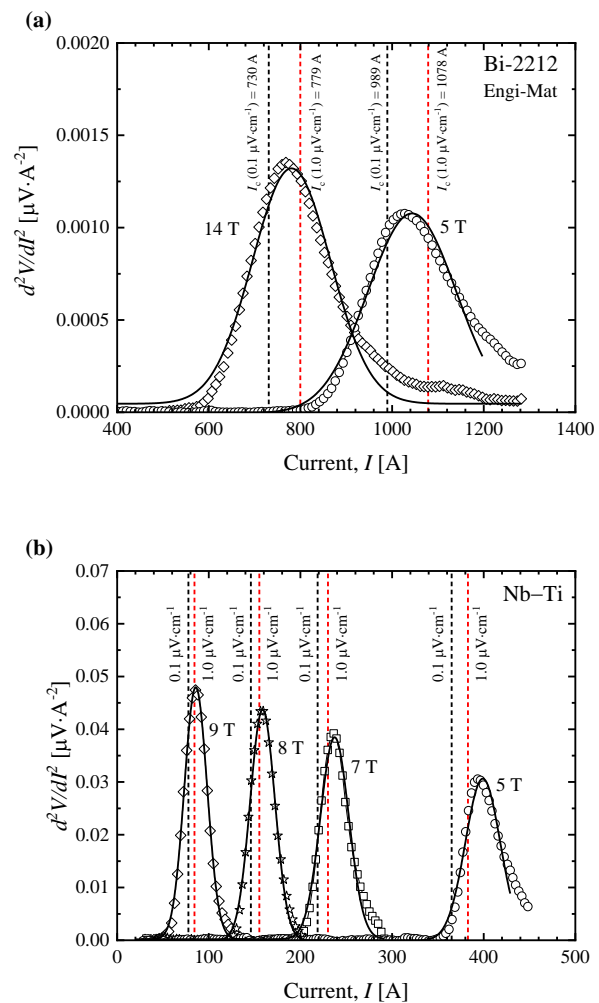


Fig. 1. Critical current distribution of (a) pmm180410 (Engi-Mat) wire at 5 T (circle) and 14 T (diamond) at 4.2 K, (b) Nb-Ti wire at 5 T (circle), 7 T (square), 8 T (star), and 9 T (diamond) at 4.2 K. Two separate lines are drawn in the distribution plot for each field to delineate the short sample I_c based on $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ (black dotted line) and $1 \mu\text{V}\cdot\text{cm}^{-1}$ (red dotted line) criterion. Solid black lines represents the Gaussian distribution.

to H_{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 σ/μ 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, σ/μ increases monotonically with field from 0.034 ± 0.0023 at 3 T to 0.125 ± 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_{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/μ) are listed in Table II. The $f_D(I_c)$ of the Engi-Mat wire, where I_c us-

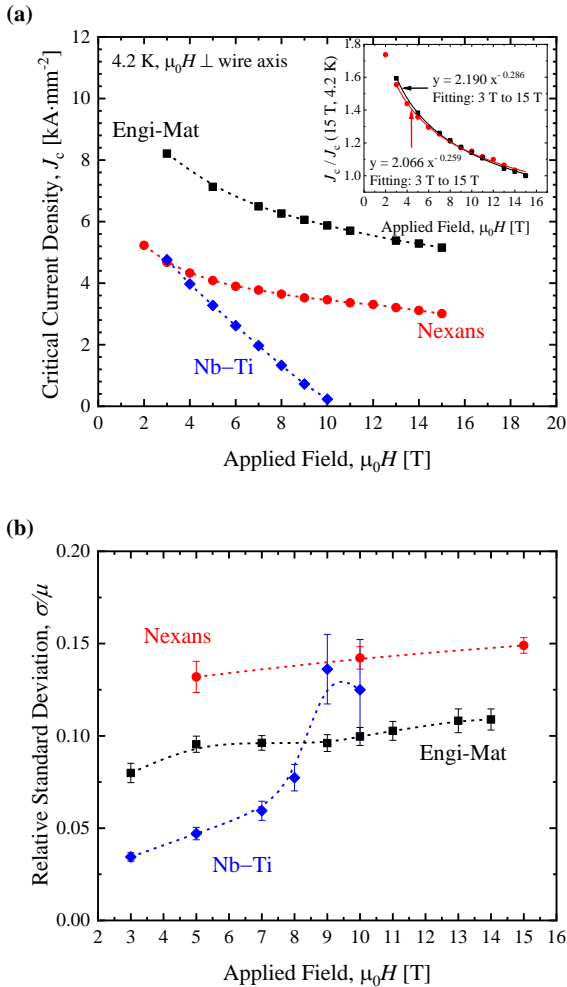


Fig. 2. (a) Critical current density evaluated at $1 \mu\text{V}\cdot\text{cm}^{-1}$, and (b) relative standard deviation of I_c distribution as a function of applied field for pmm180410 (square), pmm100913 (circle), and Nb-Ti (diamond) wires at 4.2 K. The power law fit from 3 T to 15 T for both Bi-2212 wire is shown in the inset. Dashed lines are guides for the eye.

ing the $1 \mu\text{V}\cdot\text{cm}^{-1}$ electric field criterion on the 4.5 cm long sample shows that 60 – 65% of the superconductor has transitioned from the flux pinning to the flux flow state. In contrast, the more conservative $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ criterion corresponds to 22 – 27% in flux flow. In the lower- J_c Nexans wire f_D ranges from 43 – 50% at I_c ($1 \mu\text{V}\cdot\text{cm}^{-1}$), while the conservative (I_c $0.1 \mu\text{V}\cdot\text{cm}^{-1}$) criterion yields $\sim 15 - 19\%$. For the Nb-Ti wire, f_D increased from 14% to 69% with an increasing magnetic field. The I_c/μ ratio of Engi-Mat, Nexans, and Nb-Ti wires are ~ 1.04 , $\sim 0.98 - 1.0$, and $0.94 - 1.07$, respectively.

IV. DISCUSSION

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 Nb_3Sn [13], [18], [19] with σ/μ 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 σ/μ of ~ 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_{irr} . Both Nb-Ti and Nb_3Sn 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 μ within a few percent of the measured short (~ 5 cm) sample I_c ($1 \mu\text{V}\cdot\text{cm}^{-1}$) results, with a dissipation fraction f_D rather independent of field, whereas for Nb-Ti f_D increases from 15% to 68% between 3 T and 10 T with μ moving from above to below I_c . This corresponds to a decrease in dissipation from $\sim 200 \text{ mW}\cdot\text{cm}^{-3}$ at 3 T to only $10 \text{ mW}\cdot\text{cm}^{-3}$ at 10 T at a $1 \mu\text{V}\cdot\text{cm}^{-1}$ criterion, in the context of the low enthalpy margin of Nb-Ti, on the order of $1 - 10 \text{ mJ}\cdot\text{cm}^{-3}$. 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 changes are much less, $\sim 160 - 100 \text{ mW}\cdot\text{cm}^{-3}$ from 3 – 14 T for

TABLE II
PARAMETERS DERIVED FROM THE CRITICAL CURRENT DISTRIBUTION[†]

Sample	Magnetic Field	Mean, μ	Standard Deviation, σ	Relative Std. Deviation, $\frac{\sigma}{\mu}$	R_{eff}^+	Critical Current, I_c^{++}	n value	$f_D(I_c)^a$	$f_D(I_c)^b$	$\frac{I_c^{++}}{\mu}$
	[T]	[A]	[A]		$[\mu\Omega\cdot\text{cm}^{-1}]$	[A]		[%]	[%]	
pmm180410 (Engi-Mat)	3	1210.6	96.6	0.080	0.023	1242.5	26.6	22.8	61.9	1.03
	5	1039.8	99.3	0.095	0.028	1078.8	26.7	30.5	64.2	1.04
	7	947.6	91.2	0.096	0.027	982.6	25.6	28.7	64.1	1.04
	9	881.3	84.4	0.096	0.027	916.5	26.2	29.6	63.7	1.04
	10	859.6	85.7	0.100	0.028	888.9	25.7	29.5	63.1	1.03
	11	834.0	85.7	0.103	0.028	863.3	25.2	29.1	62.6	1.04
	13	793.8	85.9	0.108	0.029	814.1	25.0	24.9	60.9	1.03
	14	774.2	84.3	0.109	0.029	799.7	22.2	30.6	62.1	1.03
pmm100913 (Nexans)	5	448.2	59.1	0.132	0.030	445.2	17.4	16.5	49.6	0.99
	10	376.6	53.5	0.142	0.032	377.2	18.8	18.6	47.8	1.00
	15	336.2	50.1	0.149	0.032	328.0	15.2	13.3	43.8	0.98
Nb-Ti	3	589.7	20.3	0.034	0.047	556.1	45.3	1.7	14.3	0.94
	5	394.9	18.6	0.047	0.048	382.8	48.4	8.1	30.5	0.97
	7	233.0	13.8	0.059	0.048	230.1	45.7	18.6	43.9	0.99
	8	154.9	12.0	0.077	0.048	155.2	37.4	23.6	53.5	1.00
	9	82.1	11.2	0.136	0.048	84.4	27.7	36.1	59.9	1.03
	10	25.1	3.1	0.125	0.049	26.9	12.5	21.3	68.5	1.07

[†]Distribution is measured for multiple sections of the spiral sample at each field. Here average results of the fitting parameters are listed.

[‡]Each voltage tap in pmm180410, pmm100913, and Nb-Ti samples is 10 cm, 20 cm, and 30 cm apart, respectively.

^{***}Critical current is calculated from a 4.5 cm short sample based on $1 \mu\text{V}\cdot\text{cm}^{-1}$ criterion at 4.2 K.

^a $f_D(I_c)$ is calculated based on short sample I_c at $0.1 \mu\text{V}\cdot\text{cm}^{-1}$ criterion.

^b $f_D(I_c)$ is calculated based on short sample I_c at $1 \mu\text{V}\cdot\text{cm}^{-1}$ criterion.

the Engi-Mat wire, and the enthalpy margin is two orders of magnitude larger, leading to more uniform f_D 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 (σ/μ) 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 Nb_3Sn , Nb-Ti, and Bi-2223 [11], [13]. However, Warnes *et al.* also reported an enhanced $\sigma/\mu \sim 0.14$ for a severely saused Nb-Ti wire at 4 T (reduced field, $H/H_{\text{irr}} \sim 0.36$) which increased to ~ 0.33 at 10 T [11], thus correlates a high σ/μ value with strong filament sausing. 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 σ/μ in our wires is not known. Hence, we believe that it is more appropriate to compare the low field σ/μ 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_{irr} as the elementary pinning forces generated by the dense α -Ti vortex-pins become proximity coupled to the superconducting β -phase matrix [28].

In line with our original conjecture, we did find a marked difference in σ/μ between the Engi-Mat (pmm180410) and Nexans (pmm100913) wires. It is evident (see Fig. 2(b)) that the older and lower- J_c Nexans wire has about 40% higher σ/μ (~ 0.1 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 $\sim 60\%$ J_c improvement is due to improved filament connectivity of the Engi-Mat powder [4]. Thus, we conclude that the 30% lower σ/μ in our Engi-mat sample compared to the lower- J_c Nexans sample is due to improved connectivity associated with the much finer and more uniform Engi-Mat powder.

As noted above, the Nexans σ/μ values are very similar to that of a severely saused 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 saused Nb-Ti wire [11]. However, we do not conclude that filament sausing is the sole reason for the degraded σ/μ of our Nexans sample. It is interesting that a Bi-2223 wire ($\mu \sim 143.6$ A, $\sigma \sim 16.8$ A, $\sigma/\mu \sim 0.12$ at 4.2 K, 0.5 T) also had a large σ/μ [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- J_c Engi-Mat powder wire has a ~ 3 fold higher σ/μ , and an almost 50% smaller n value compared to our high- J_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 σ/μ can be minimized by identifying and addressing connectivity limitations. To this end, we believe that the σ/μ 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- J_c Nexans wire has the same normalized vortex pinning (same normalized $J_c(H)$ curve) and a broader σ/μ , suggestive of poorer connectivity. The relative standard deviation of Engi-Mat wire is $\sim 30\%$ lower than Nexans wire. The implication is that effective filament connectivity can be quantified from the d^2V/dI^2 measurement. We believe that measurements like these can be a useful tool in further understanding of how best to raise J_c in Bi-2212 conductors.

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