Field Dependence of the Critical Current and Its Relation to the Anisotropy of BSCCO Conductors and Coils

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Abstract—The design of HTS magnets is often based on the properties of a number of short samples that are presumed to be representative of the conductor to be used. Variability in conductor properties and inhomogeneity in the magnetic field distribution within the magnets, coupled with conductor anisotropy, provide a significant challenge to accurately predict the field dependence of the magnet critical current. This work is based on measured superconducting properties of Bi-2212 and Bi-2223 conductors at 4.2 K in parallel and perpendicular magnetic fields up to 33 T. Properties of double pancake units and stacks, from the same or similar conductor batches, are presented, based on measurements at self-field and in applied co-axial background magnetic fields up to 19 T. Modeling of this data is based on short sample properties in perpendicular field; the average grain misalignment is used as the parameter to quantify the anisotropy. Correlations and discrepancies between the measured data and models based on short sample data are discussed for Bi-2212 and Bi-2223 conductors.

Index Terms—Anisotropy, coils, critical current, field dependence.

I. INTRODUCTION

THE ABILITY to predict the critical current of coils based on the properties of its constituent conductor is essential in magnet design. The relation between conductor and coil I_c is more complicated for HTS conductors than metallic superconductors due to the strong anisotropy typically observed in practical HTS conductors. Despite significant advances in the development of BiSrCaCuO superconductors without anisotropy at the conductor level [1], [2], anisotropic tape conductors remain widely used in HTS magnet technology [3], [4]. A desire to understand and predict the properties of HTS sections of 25 T superconducting magnets provided the motivation for this work. Specifically, the self-field critical current $I_{c}(\text{self})$ of double pancakes is hard to predict, but is essential for magnets consisting of double pancakes. Relations between I_c of short samples, double pancakes and larger coils must be developed so qualification standards and design procedures can be developed.

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TABLE I
CONDUCTOR AND MODEL PARAMETERS

	Conductor A	Conductor B
Material	Bi-2212	Bi-2223
Conductor width [mm]	4.95	2.92
Conductor thickness [mm]	0.195	0.243
$I_{c,ss}(\text{self})$ [A]	512	578
n -value	8	19
I_{cs} [A]	200	222
B_{sc} [T]	54	97
I_{cw} [T]	445	608
B_o [T]	0.22	0.09

The anisotropy in $I_c(\mathbf{B})$ for both a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ (Bi-2212) and a $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ (Bi-2223) conductor is quantified with a single conductor-specific parameter: the average grain misalignment α^* [5]–[7]. Use of this parameter reduces the vector relation $I_c(\mathbf{B})$ to a scalar relation $I_c(B_{\text{eff}})$, where B_{eff} is the effective field perpendicular to the conductor resulting in the same I_c as the vector $\mathbf{B}$ at angle ϕ . Following the references, B_{eff} is calculated from the total field value B_{total} and a scaling function $f(\phi)$ that is unique for each value of α^* :

$$B_{\text{eff}} = B_{\text{total}} \cdot f(\phi) \quad (1)$$

This work relates measured field dependence of coils to short sample properties using (1) to model anisotropy.

II. CONDUCTORS

The conductors considered here are reacted PIT multifilamentary tapes. The I_c measurements in perpendicular and parallel magnetic fields at 4.2 K are described elsewhere [8]. The model used for $I_c(B)$ for perpendicular field assumes parallel networks of strongly and weakly linked paths, contributing I_{cs} and I_{cw} to I_c in self-field conditions, respectively, and whose field dependence is in turn characterized with parameters B_{sc} and B_o . Several different models exist to describe $I_c(B)$ based on various physical phenomena and models. Here however, it suffices to note that for applied fields over 0.1 T the measurements are described, using (2) and the parameters of Table II, with an average error below 1%. For low values of B , (2) results in calculated values larger than the measured short sample self-field value $I_{c,ss}(\text{self})$. In those cases I_c is taken to be $I_{c,ss}(\text{self})$. It is assumed that the normalized $I_c(B)$

TABLE II
GEOMETRIC DOUBLE-PANCAKE PARAMETERS

Symbol	Unit	Coil A	Coil B
Inner diameter	mm	41	97.6
Outer diameter	mm	98	127
Height	mm	11	6
Turns [-]	-	2×115	2×49

Fig. 1. Modeled normalized $I_c(B)$ of conductors A and B.

Fig. 2. Calculated α^* values for conductors A and B.

behavior, shown in Fig. 1, is identical for conductors with different $I_c(\text{self})$.

$$I_c(B) = \frac{I_{cw}}{1 + \frac{B}{B_0}} + I_{cs} \exp\left(\frac{-B}{B_{sc}}\right) \quad (2)$$

The average grain misalignment α^* is determined from the ratio of parallel and perpendicular field resulting in the same I_c , and is shown in Fig. 2 using [8]. Tapes A-1, A-2 and A-3 represent samples of conductor A; tape B is a Bi-2223 sample. For conductor B ($B_{\text{eff}} > 0.5$ T) the calculated value of α^* is fairly constant. The calculated value of α^* for conductor A appears to show a dependence on B , in contradiction with the anisotropy model, although the variation is within the margin of error.

Fig. 3. Typical calculated values for B_{eff} in Coil A in the self-field condition (left) and in a 19 T background (right).

III. DOUBLE PANCAKES

A. Measured Properties

Two double pancake coils are discussed here. Both are epoxy-impregnated and produced from reacted conductor nominally identical to conductors A and B. Geometric parameters are listed in Table II. These coils were selected because their $I_c(B)$ measurement is reversible within 1 A, verifying the absence of stress induced I_c degradation. The measured properties are shown in the next section together with the model calculations.

B. Model

Quarter cross-sections of the windings are divided in 15 radial and 12 axial segments. The following parameters are calculated in the center of each segment: radial field, axial field, B_{total} , ϕ , B_{eff} , normalized I_c ($\%I_c$), conductor length l within the segment, electric field and voltage across the conductor length. The field components are calculated using the actual dimensions and current densities in the double pancakes and background magnet. The latter is described in [6]. The electric field E along the conductor is calculated using

$$E = E_{cx} \times \left(\frac{I}{I_{c_SS}(\text{self}) \times \%I_c} \right)^n \quad (3)$$

where E_c is the 10^{-4} V/m criterion, I the operating current, I_{c_SS} the assumed short-sample conductor self-field I_c and n the index of transition.

The most complicated condition to model for double pancakes is at self-field. The variations in magnetic field strength and direction are large at self-field and for low applied fields and the slope of $I_c(B)$ is relatively steep. In contrast, for $B_{\text{applied}} > 5$ T the field variations become relatively small and I_c is less sensitive to incremental changes in B . Figs. 1, 3 and 6 illustrate this. Therefore, one may expect that a proper model accurately describes the field dependence of I_c for $B > 5$ T, where B_{eff} is fairly homogeneous.

In the regime of $B_{\text{applied}} < 5$ T, B_{eff} varies with radius and more so with z , i.e. across the width of a single turn. Fig. 3 illustrates that for Coil A. The axial variation of B_{eff} will promote an axial redistribution of current toward the midplane, where B_{eff} is lowest. This effect is approximated by introducing an axial variation of the current density $J = J(z)$, independent of radius. The axial variation of J is determined iteratively such that the integral of electric field along the entire conductor length is

Fig. 4. Typical axial variation of current density within a turn versus applied field. Lines are a guide to the eye only.

TABLE III
COIL A FIT PARAMETERS

Current density	$I_{c,ss}(\text{self})$ [A]	α^*	n - value	Average error
Constant	302	6	8	3.8%
Axially variable	296	4	6	3.8%
Axially variable	302	6	6	2.9%
Axially variable	319	8	6	3.8%
Axially variable	296	$4.06 + 0.071 \cdot B_{\text{total}}$	6	1.0%
Axially variable	296	$4.06 + 0.071 \cdot B_{\text{total}}$	8	0.9%
Axially variable	296	$4.06 + 0.071 \cdot B_{\text{total}}$	10	1.1%

independent of z . This variation, and its effect on I_c , is significant below 10 T. Typical behavior is shown in Fig. 4. The effect of this current redistribution on the local magnetic field strength and angle is taken into account.

Imperfect scaling for Bi-2212 samples [8] leaves doubts whether they can be modeled with a single, field independent value of α^* . Therefore, α^* is alternatively set as a constant or described by

$$\alpha^* = 4.06 + 0.071 \cdot B_{\text{total}}, \quad (4)$$

Equation (4) is a linear fit to the α^* data of Fig. 2 when plotted versus applied parallel field. Thus α^* is calculated in every segment, and the scaling function $f(\alpha)$ follows from the average α^* .

C. Procedure

For any given choice of α^* and n -value, a value for $I_c(\text{self})$ is chosen such that the calculated voltage across the coil corresponds to the 10^{-4} V/m criterion when the operating current equals the measured critical current at $B_{\text{applied}} = 19$ T. All free parameters are now determined. The operating current corresponding to I_c is then calculated for lower values of the background field while optimizing the axial current distribution to minimize the coil voltage.

IV. RESULTS

A. Bi-2212 Double Pancake

Table III lists seven parameter sets used to model the measured I_c of Coil A and Fig. 5 shows the results. A comparison of the curves with and without axial grading (square and - markers)

Fig. 5. Measurement and calculations of I_c for Coil A. The curves for variable α^* are on top of each other.

Fig. 6. Measurement and calculations of I_c for Coil B. The range between minimum and maximum B_{eff} in the windings is on the right axis.

for $\alpha^* = 6$ illustrates that axial grading only affects the results significantly for $B_{\text{applied}} \leq 5$ T. Axial grading improves the fit in that range.

Choosing various field independent values for α^* change the shape of the $I_c(B)$ curve over the entire range, and most significantly for $B_{\text{applied}} \leq 5$ T. However, no value of α^* matches the slope of the $I_c(B)$ curve for $B_{\text{applied}} > 10$ T, nor for most of the lower field range.

Assuming the short sample data suggest a field dependence of α^* as in (4) results in a much closer fit to the measured data and is also practically independent of the n -value for $6 < n < 10$. The average fit error in coil $I_c(B)$ is now comparable to the conductor $I_c(B)$ fit error.

The calculated values for $I_{c,ss}(\text{self})$ are significantly below the measured values for short samples cut from the same conductor batch as the coil; six samples show an average I_c of 403 A with a standard deviation of 7 A. This is not satisfactory for predicting double pancake I_c from short sample data, so establishing that relation requires dedicated measurements.

B. Bi-2223 Double Pancake

Application of a field independent α^* value as suggested by the short sample measurements on conductor B immediately leads to a reasonable fit. As for Coil A, the calculation is slightly

Fig. 7. Measured quench current and calculated I_c of an insert coil from conductor A.

TABLE IV
COIL B FIT PARAMETERS

Current density	$I_{c_{SS}}(\text{self})$	α^*	n -value
Axially variable	312	2.7	20

TABLE V
GEOMETRIC PARAMETERS FOR DOUBLE-PANCAKE STACKS

	unit	Section A	Section B	Section C
Inner diameter	mm	41	106	156
Outer diameter	mm	96	146	165
Height	mm	184	184	209
Turns [-]	-	3723	2611	532

below the measured values in the range of 5 to 15 T. The calculated value for $I_{c_{SS}}(\text{self})$, 312 A, is significantly below measured values of around 408 A.

C. Double Pancake Stack

A larger insert coil consisting of two stacks of 17 double pancakes each and surrounded by a layer wound section is constructed using conductor similar to conductor A. Key parameters are summarized in Table V, while a detailed description is provided elsewhere [3], [7].

The model is adapted by changing the segment dimensions to 3 mm radially and 11 mm axially. The latter corresponds to the total thickness of a double pancake unit in the stacks. Axial grading of J is replaced by a varying conductor $I_{c_{SS}}(\text{self})$ and n -value per unit, to reflect the variation of properties between conductor batches. These values are derived from properties of double pancakes as measured in individual tests at 4.2 K.

This insert coil quenched before reaching the 10^{-4} V/m criterion, so a direct comparison with the model is not possible, although the I - V data does extrapolate to within a few amperes of the predicted I_c . When both the quench current (157.2 A) and calculated critical current (207 A) at self-field are normalized, the model is found to describe accurately the relative change of insert I_c with background field.

V. CONCLUSION

The field dependence of the critical current in a Bi-2212 and a Bi-2223 double pancake can be modeled based on the measured field dependence of I_c of corresponding short samples. An axial variation of the current density in double pancakes is introduced to allow better modeling of the effects of field-angle differences between the midplane and top/bottom surfaces on the local critical current density. Anisotropy is modeled through the average grain misalignment α^* . For the studied Bi-2223 conductor a constant value α^* is successfully used, as opposed to the Bi-2212 case where the best results are obtained using a field-dependent value of α^* . The latter is unexpected and warrants further investigation. The model is also accurate in describing the relative change of I_c with background field for a much larger insert. Predicting the self-field I_c for double pancakes based solely on short sample data, however, remains unsatisfactory.

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