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Effect of external magnetic field on the critical current in single and bifilar Bi-2223 tapes

N. Shaked [a], A. Friedman [a,*], M. Sinvani [a], I.A. Al-Omari [b], Y. Wolfus [a], A. Shaulov [a], Y. Yeshurun [a]

[a] *Institute for Superconductivity, Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel*
[b] *Department of Applied Physical Sciences, Jordan University of Science and Technology, P.O. Box 3030, Irbid, Jordan*

Abstract

We report on measurements of the critical current in a single and bifilar multifilamentary Bi-2223/Ag tapes, at 77 K, under various DC magnetic fields applied perpendicular to the tape plane. At low applied fields the bifilar tape exhibits higher critical current, as expected. However, above ~50 G the situation is *reversed*, i.e., the critical current of the single tape is *higher*. These results are attributed to the different spatial distribution of the self-field in these two configurations. Our data and analysis imply that, in terms of critical current, the bifilar configuration has over advantage over the single tape configuration only in a limited range of external magnetic fields. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Bi-2223 tape; Critical current; Magnetic field; Bifilar sample

1. Introduction

Recent progress in manufacturing multifilamentary silver-sheathed $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ superconducting tapes has resulted in relatively long wires with improved electrical and mechanical characteristics [1–3]. Such wires have been used in the fabrication of prototype devices, including transformers, motors, generators, and superconducting magnetic energy storage (SMES) systems [4,5]. One of the main limitations of these tapes is the sensitivity of their critical current density to magnetic fields. The total field comprises the sum of the external field and the self-field resulting from transport current flowing in the tape. A significant reduction in the perpendicular component of the self-field, and consequently a substantial increase of the critical current at low fields, has been achieved by applying different wire configurations [6,7]. For example, in the bifilar configuration two tapes carrying opposite and equal currents are placed on top of each other, separated by a thin isolating tape. As a result, the perpendicular self magnetic field is, on the average, much reduced, resulting in higher critical current I_c [7]. Obviously, for external fields much larger than the self-field, similar critical currents are expected for both the single tape and bifilar configurations. In this work we identify a field range for which the bifilar configuration exhibits *lower* critical current than a single tape, indicating an advantage for the bifilar configuration *only* below a certain crossover field, B_c. We explain this result by considering the

* Corresponding author. Tel.: +972-3-531-8607; fax: +972-3-535-3298.
E-mail address: friedman@mail.biu.ac.il (A. Friedman).

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different self-field distributions within the superconducting material in the bifilar and single tape configurations.

2. Experimental

The multifilamentary Bi-2223/Ag (BSCCO) tape, purchased from American Superconductor Corporation, has a rectangular cross section of width $w = 3$ mm and thickness $= 0.2$ mm. It is specified for a critical current of 50 A at 77 K in the absence of external field. The same sample was used in both single tape and bifilar configurations, by placing two 20 cm long tapes on top of each other (Fig. 1). The tapes were isolated by 0.06 mm thick polyimide layer, and electrically connected at the common end (e in Fig. 1) by silver paint. The other two ends were connected to copper current leads (a and b in Fig. 1). In the bifilar configuration the current flows in opposite directions in the two tapes. In the single tape configuration the current passes through one of these tapes. The shielding currents of the adjacent tape may be contribute to the magnetic field. However, this contribution may be neglected due the small magnetic moment resulting from the small diameter of the superconducting filaments [8]. The voltage drop V, in both configurations, is measured between the voltage tapes c and d, see Fig. 1. The average electric field along the tape is calculated as $E = V/l$, where l is the sample length between the measurement tapes. The sample is placed between two long racetrack magnet coils, which produce a uniform magnetic field perpendicular to the tape plane, as shown in Fig. 1. The I–V curves of the sample were measured in both configurations in the presence of perpendicular magnetic fields up to 210 G.

3. Results and discussion

Fig. 2 shows typical E–I curves measured in bifilar and single tapes in the presence of the indicated external field directed perpendicular to the tape plane. All the curves are well fitted by a power law $E = E_0(I/I_c)^n$, where I_c is the critical current related to an average field criterion $E_0 = 1$ µV/cm.

Fig. 3 shows the critical current I_c and the exponent n as a function of the external applied field $B_{ext.}$ The data are extracted from Fig. 2. Errors in determining the critical current values from I–V curves are n ($n = 12$–22) times smaller than the error in the voltage measurements, i.e. less than 0.5% (0.2 A). One can see that, in the low field range (below ~50 G), the bifilar configuration exhibits higher critical current, as expected. However, ~50 G this situation is reversed. It is interesting to note that a similar behavior is exhibited

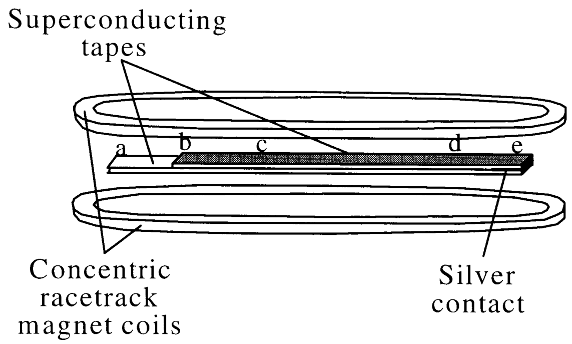

Fig. 1. The experimental configuration: Sample is placed between two racetrack magnet coils. Current leads are connected to the points a and b in the bifilar configuration or to the points b and e in the single tape configuration; c and d are the positions of the voltage tapes.

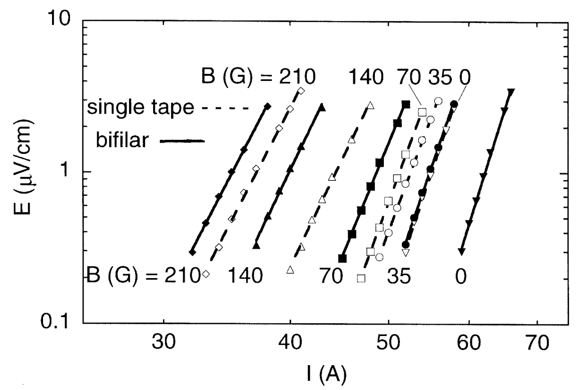

Fig. 2. I–V curves at 77 K in magnetic field perpendicular to the tape plane for bifilar (solid lines) and single tape (dashed) configurations.

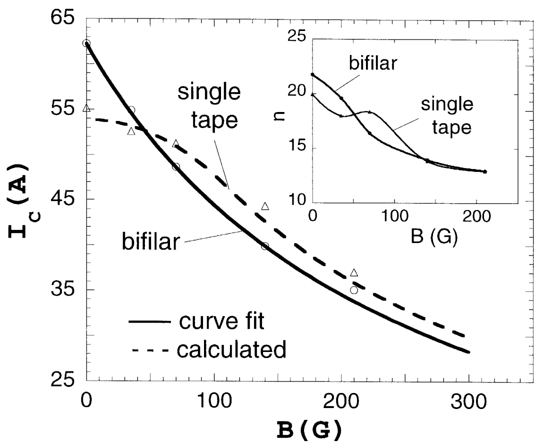

Fig. 3. Dependence of the critical current on an external magnetic field perpendicular to the tape plane. The solid and dashed lines are fits of the measured $I_{c,bifilar}$ (B) and $I_{c,tape}(B)$ to the integrals of Eqs. (1) and (2) along the sample width, respectively. The dependence $n(B)$ is shown in the inset (the lines are guides to the eye).

by the power exponent n (inset to Fig. 3), resulting in an almost field independent ratio $I_c/n \cong 3$ A [9,10].

The crossing of the $I_{c,tape}(B)$ and $I_{c,bifilar}(B)$ curves can be explained by considering the combined effect of the external field and the self-induced field. Since the critical current is much more sensitive to the perpendicular component of the field [11,12], the effect of the parallel component of the self-field will initially be ignored. The perpendicular component of the self-field is much smaller in the bifilar configuration compared to the single tape; thus in calculating the current density in the bifilar configuration we consider only the effect of the external field. We use the Kim–Anderson model [13,14], which is commonly applied in the analysis of data for high-temperature superconductors, see e.g. Ref. [15]:

$$J_{c,bifilar} = \frac{J_{c,0}}{1 + |B_{ext}|/B_0}, \tag{1}$$

where $J_{c,0}$ is the critical current density at zero field and B_0 is a constant.

In calculating the critical current density for the single tape configuration we consider the effect of both the external field and the normal component of the self-field. A linear distribution of the self-field $B_s = \alpha x$ (α is a constant and x is the position relative to the tape center $x = 0$) can be used as a good approximation [16]. For the dimensions of the tape used in our experiments, the Biot–Savart law yields $\alpha = 66.7$ G/mm at a critical current of 55 A in zero external field. The distribution of $J_c(B)$ along the cross section of the tape is:

$$J_{c,tape} = \frac{J_{c,0}}{1 + |B_{ext} + \alpha x|/B_0}. \tag{2}$$

The second approximation of the self-field distribution was obtained by applying the Biot–Savart law to this equation with $B_{ext} = 0$. This distribution is very close to linear. Therefore we did not go beyond the first approximation.

The spatial distribution of $J_{c,bifilar}$ and $J_{c,tape}$ (according to Eqs. (1) and (2) respectively) are sketched in Fig. 4 for different B_{ext}. It can be seen that at low fields the average $J_{c,tape}$ is smaller than $J_{c,bifilar}$. However, above $B_{ext} \sim 50$ G, the average $J_{c,tape}$ becomes larger than $J_{c,bifilar}$. When $B_{ext} \gg 50$ G the averaged $J_{c,tape}$ approaches $J_{c,bifilar}$ from above. The origin of this crossover is the dependence of the critical current on the *absolute value* of the total (external plus self) field. Since the self-field in the single tape configuration is positive on one side of the tape, and negative on the other side, the self-field adds to B_{ext} on one side and subtracted from B_{ext} on the other side. This results in a slow increase in the average field as compared to bifilar sample. Since the critical current is inversely proportional to the total field, the averaged value of J_c becomes larger in the single tape configuration beyond a certain field B_c. A lower average of the local field $|B_{ext} + \alpha x|$ as compared to bifilar sample is obtained for $|B_{ext}| < \alpha w/2 = 100$ G. However, because of the nonlinearity of $J_c(B)$, the crossover in the critical currents of the two configurations is expected to be roughly half of this figure, i.e. $B_c \sim \alpha w/4 = 50$ G.

A quantitative analysis of our data is obtained in the following way: The critical current I_c is obtained by integrating Eqs. (1) and (2) along the sample width. By fitting the measured $I_{c,bifilar}(B)$ of Fig. 3 to Eq. (1) – see solid line in Fig. 3 – we

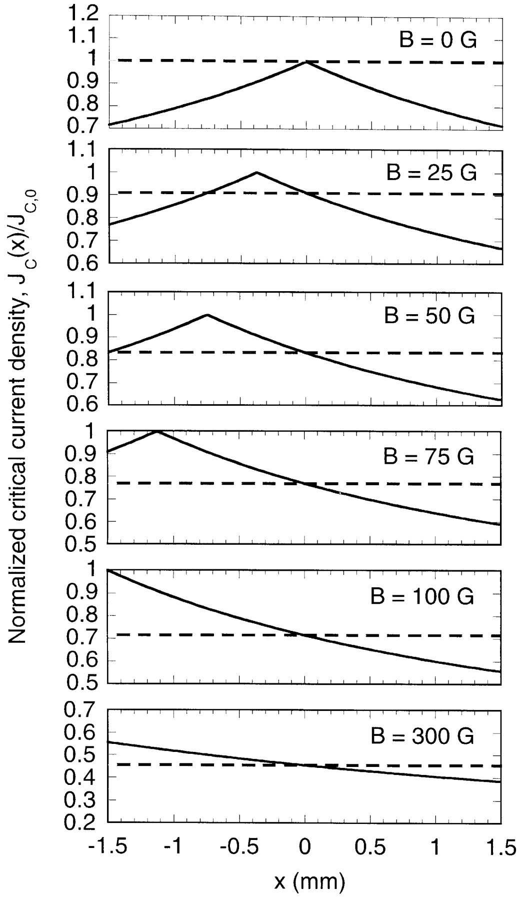

Fig. 4. Critical current density distribution in the single tape (solid line) and bifilar (dashed) configurations for various applied fields B in the range 0–300 G. Curves are normalized with respect to the maximum value obtained at zero local field.

obtain $B_0 = 250$ G and $J_{c,0} = 10.4$ kA/cm^2. The dashed curve in Fig. 3 is calculated on the basis of Eq. (2) (integrated across the sample width) by using the same value of B_0 and α and slightly larger value of $J_{c,0} = 10.8$ kA/cm^2. This slight difference ($\cong$4%) between $J_{c,0}$ in the bifilar and single tape configurations is ascribed to the influence of the parallel component of the self-field; the value of this component on the tape surface is about twice in the bifilar as compared to the single tape configuration. Apparently, the calculated curves are in good agreement with the experimental data. Specifically, the calculated curves, $I_{c,tape}(B)$ and $I_{c,bifilar}(B)$, cross each other around the predicted crossing field of 50 G.

4. Summary

In summary, our data and analysis imply that the bifilar configuration has a higher critical current as compared to the single tape configuration only in a limited range of external magnetic fields. This range is bounded between zero and a crossing field B_c which depends on J_c and the geometry of the sample. This result can be important for example in building a resistive fault current limiter based on bifilar coil.

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