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A new experimental method to determine the local critical current density in high-temperature superconducting tapes

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Abstract

The lateral critical current density (J_c) distribution in high-temperature superconducting tapes is determined with a new experimental method. With this method it is possible to determine a J_c-profile in a non-destructive manner. The experiment utilizes the strong suppression that occurs in the critical current (I_c) when a perpendicular magnetic field is applied to a Bi-2223 tape. A perpendicular magnetic field with a strong gradient that passes through zero is applied to a tape, to select a zone where the perpendicular field is small. This magnetically selected zone then determines the I_c of the entire tape. By moving this field gradient along the tape it is possible to observe the spatial variations in J_c. For a quantitative analysis of the critical current density a deconvolution of the measured I_c-profile with the system response is required. The local superconducting area is obtained from an optical micrograph of the tape cross-section. Finally a position dependent J_c is determined for two different types of superconducting tape. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: BSCCO/Ag tape; Current distribution; Non-destructive measurement; Critical current

1. Introduction

One of the questions which is still open about the transport properties of silver sheathed $Bi_2Sr_2Ca_2Cu_3O_x$ tapes is where the current exactly flows inside the superconductor. It is suggested that the transport critical current (I_c) is not homogeneously distributed inside the superconductor. Different experimental techniques have been developed to determine the current distribution. The experimental results published so far are somewhat contradictory and in most cases, the measuring method is indirect.

In 1993, Yamada et al. suggested a correlation between the Bi-2223 phase density and the local critical current density (J_c) [1]. By measuring the Vickers micro-hardness a maximum in J_c was claimed to occur at the center of the filament.

In 1995, Pashitski et al. [2] used magneto-optical imaging of the flux penetration to extract the current flow paths inside the BSCCO core. They found that the high-J_c regions correlate with colonies of well-aligned long grains, which are preferentially located near the silver interface. The less aligned and smaller grains in the central part of the tape showed a much lower current-carrying capability.

Another indirect method is the scanning Hall probe microscopy. This method maps out the normal component of the magnetic field generated above the broad face of the conductor. The field is deconvo-

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luted to obtain the J_c distribution. Volkozub et al. [3] measured the J_c distribution of multi-filamentary tapes and found a higher J_c in the central group of filaments.

In 1994 Grasso et al. [4] presented a strip-cutting technique. With this technique they directly measured the lateral J_c distribution of mono-filamentary Bi-2223/Ag tapes. A symmetrical behavior of J_c at both sides of the central axis was observed with the highest density at the sides. An explanation for this distribution could be the more complete conversion to the 2223 phase close to the Ag sheath, and the larger and better-aligned grains at the sides due to higher local compression [5].

Here we present a new non-destructive method to determine J_c distribution in the lateral direction. The experiment utilizes the strong suppression that occurs in I_c when a perpendicular magnetic field is applied to a Bi-2223 tape. A perpendicular magnetic field with a strong gradient that passes through zero is applied to a tape, to select a zone where the perpendicular field is small. This magnetically selected zone then determines the I_c of the entire tape. By moving this field gradient along the tape it is possible to determine the J_c-profile in a tape in a non-destructive manner. This profile is compared with the superconducting area that can be determined with a micrograph of the cross-section. The method is demonstrated on two multi-filamentary Bi-2223 tapes.

2. Experimental technique

In order to obtain a sharp gradient in the applied field, two iron cores are placed facing each other leaving a small air gap between them. This setup is presented in Fig. 1. The magnetic field in the air gap is induced by two copper coils, which generate fields opposite to each other. With the iron core a field profile is generated with a magnitude of a few hundred millitesla, resulting in a gradient of more than 100 T/m. The sample is moved through this field gradient with a stepper motor, while the I_c is determined using a four-probe technique at regular intervals for the position of 50 μm.

The measurements are performed at 77 K in liquid nitrogen, at this temperature the I_c of Bi-2223 is reduced significantly with the field that is generated in the core. The thermal contraction of the sample from 300 to 77 K is matched with the thermal contraction of the sample holder ($\approx 0.2\%$). The sample holder is made from epoxy reinforced glass fiber with the direction of the fibers along the length of the tape. Total length of the sample is 70 mm and the distance between the voltage taps is 10 mm. The effective length of the magnet (20 mm) is long compared to the distance between the voltage taps. The critical current is defined at a voltage criterion of 10^{-4} V/m.

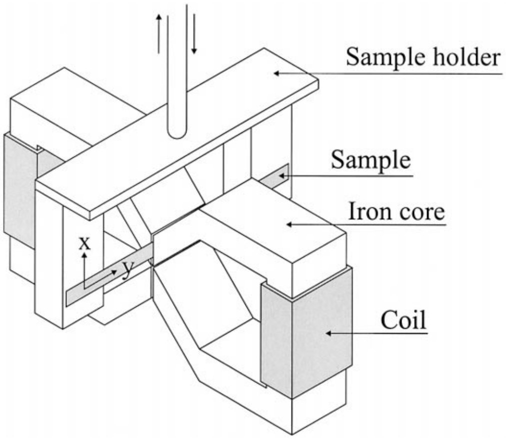

Fig. 1. Schematic presentation of the measurement setup. The iron joke with the two coils generates a perpendicular magnetic field in a small gap where the superconducting tape sample is placed in.

The I_c measurements are reproducible with-in 0.02 A and this variation is mainly determined by the reproducibility in the voltage measurement (10 nV). The shape of the profile is almost independent of the criterion used to determine the I_c, from 10^{-5} to 10^{-3} V/m. Depending on the direction of the applied sample current, the self field of the sample can either enlarge or decrease the current limiting effect of the applied magnetic field gradient. However, reversing the current direction does not induce any significant changes in the measured profile, which proves that the role of the self field is negligible. The most important source of possible errors appears to be the magnetic behavior of the iron core, in particular the hysteresis in the magnetization curve. This problem is effectively cancelled by applying a demagnetization sequence before the requested coil current is applied. The sample is moved stepwise in the field gradient at 77 K with a constant current in the coil. At each position the V–I curve is measured to determine the I_c. In order to keep the field constant in the magnetized iron core, it is important that temporary variations (spikes or ripples) in the coil current are avoided.

3. Analysis

For the analysis of the experiment the critical current density is assumed to be a function of the position (x) and the local magnetic field (B) in the tape. The tape geometry and all other properties are considered to be constant along the length of the tape. Additionally it is assumed that the field dependence of the critical current density can be separated from the position dependence: $J_c(x,B) = J_{c0}(x)J_c(B)$, with $J_c(0)=1$ by definition. In that case the critical current of the tape is calculated as a single integral over the width (w) of the tape:

$$I_c = \int_{-w/2}^{w/2} d(x)\, J_c(x,B)\, \mathrm{d}x$$

$$= \int_{-w/2}^{w/2} d(x)\, J_{c0}(x)\, j_c(B)\, \mathrm{d}x,$$

where d is the thickness of the superconducting structure, i.e. the thickness of a single filament or a summation over multiple filaments at a certain x-position.

A magnetic field (B_a) is applied with a gradient through $B_a = 0$ at position $x = x_0$. The critical current of the tape placed in this field profile can be calculated with a convolution integral:

$$I_c(x_0) = \int_{-w/2}^{w/2} d(x)\, J_{c0}(x)\, j_c(B_a(x-x_0))\, \mathrm{d}x$$

$$= \int_{-w/2}^{w/2} d(x)\, J_{c0}(x)\, g(x-x_0)\, \mathrm{d}x,$$

which implicitly defines the convolution function g. In this formulation the self field of the tape is neglected $(B = B_a)$, so it is only valid in a current free tape. With this relation it is possible to reconstruct a position dependent $J_{c0}d$ based on a I_c determination, if the convolution function is well defined. In an ideal experiment the convolution function g is equal to the Dirac delta function, which simplifies this equation to $d(x_0)J_{c0}(x_0) = I_c(x_0)$.

The convolution function can be reasonably localized compared to the width of the tape. In the experiment described here a field gradient from $+150$ to -150 mT is generated in a region of typically 1 mm wide shown in Fig. 2. In combination with the pronounced field dependence of Bi-2223 tapes for perpendicular magnetic fields this results in a convolution function with a FWHM of only 100 μm. Two other aspects are important about this convolution function. The base line occurs at $g = g_0 \approx 0.2$ and there is a relatively broad zone of approximately 1 mm, where g is significantly higher than g_0. The magnitude of the field (± 150 mT) is chosen to get an optimum in spatial resolution and amplitude in the $I_c(x)$ measurement. This field is far above the value of the trapped flux in the sample.

The baseline in g results in a non-zero I_c value, even if the entire tape is entirely placed in the zone where the magnetic field is high. Therefore the critical current can only be determined when an operating current with a similar magnitude (in the order of 10 A) is passed through the sample. The magnetic field generated by this ''baseline'' current disturbs the profile of the applied field. For the ratio of current and field used here the self-field is estimated to be negligible small (< 10 mT) compared to the applied field. Moreover, the magnitude of this

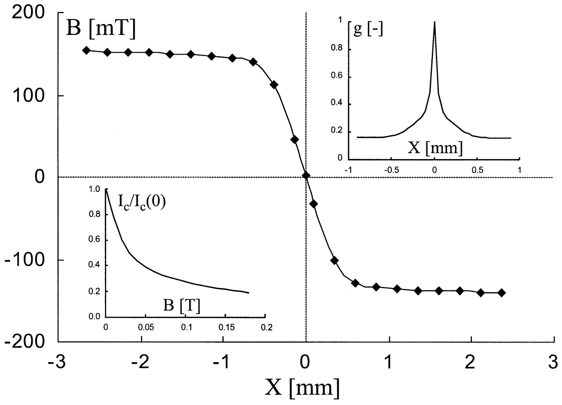

Fig. 2. A typical example of a field gradient that can be produced with the setup. This field gradient is measured using a Hall-probe at 77 K without a sample placed in the gap. The measured $j_c(B)$ dependence and the corresponding convolution function $g(x)$ are shown in the two small graphs inserted in this picture.

self-field disturbance can be verified experimentally by reversing the operating current of the sample.

The broad zone of g near the baseline occurs because of the specific shape of the field profile that can be generated with such an iron structure. Because of this specific shape of the convolution function the experimentally obtained $I_c(x_0)$ relation is only a qualitative measure for the critical current density distribution in the tape. For a quantitative analysis a deconvolution of $I_c(x_0)$ with g is required in order to obtain $J_{c0}\,d$.

4. Results

For each tape the $I_c(B)$ dependence is measured. Together with the measured $B(x)$ profile a tape specific g is calculated. The measured I_c-profiles are numerically deconvoluted with this g to determine the $J_{c0}\,d$ distributions that are presented in Figs. 3 and 4. This results in a variation in the $J_{c0}\,d$-profile that is more pronounced than the measured I_c variations, but the positions of the local minima and maxima are not changed. The measured $J_{c0}\,d$-profile is compared with the $d(x)$-dependence that is determined from a series of optical micrographs of the cross-section, taken at the position on the sample where the voltage is measured. The large variations in $d(x)$ occur because the filaments in these tapes are arranged in bundles. The position of the d-profile on the x-axis is translated to obtain the best possible correlation between the local minima for both profiles.

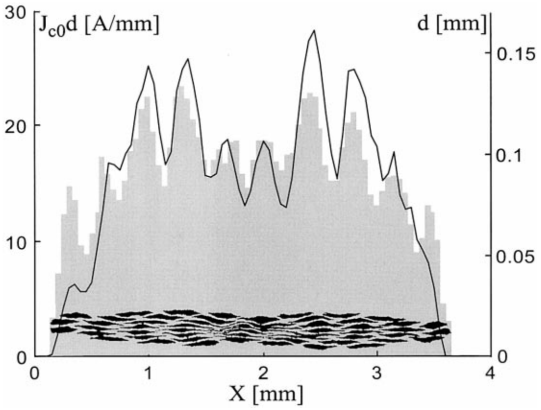

Fig. 3. $J_{c0}\,d$ — (black line) and d — (gray histogram) profile for tape A. The total area covered by both profiles in this graph is adjusted to an equal value by changing $J_{c0}\,d$- and d-scale on the left and right axis. The micrograph of the cross-section of the tape is stretched in the vertical direction.

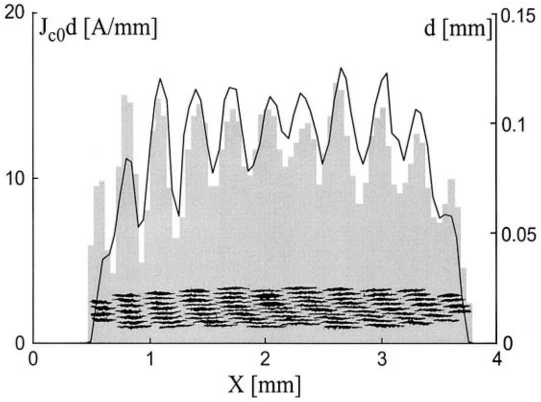

Fig. 4. $J_{c0}\,d$ — (black line) and d — (gray histogram) profile for tape B. The total area covered by both profiles in this graph is adjusted to an equal value by changing $J_{c0}\,d$- and d-scale on the left and right axis. The micrograph of the cross-section of the tape is stretched in the vertical direction.

By comparing both profiles one can immediately select the high and low J_c regions. For tape A (see Table 1) the average current profile in the center of the tape is lowered by 25%. The reduction in $d(x)$ is less pronounced than in $J_{c0}\,d$ indicating that the J_c is about 15% lower averaged over the center of the tape. Another striking result is the low J_c at the edges of the tape, which is also shown by tape B.

A more detailed picture for J_c is obtained if the $J_{c0}\,d$-profile is divided by the optically determined thickness of the superconductor. In order to eliminate local oscillations, due to small orientation errors between the two profiles, the data sets are filtered with a Bartlett (triangle) smoothing window with a width of 250 μm. The resulting J_c-profiles for the two tapes are presented in Fig. 5. The J_c profiles

Table 1
The measured properties of the investigated materials

Tape	Tape width [mm]	Tape thickness [mm]	Number of filaments	Filling factor [%]	I_c in self field [A]
A	3.8	0.26	55	31	56
B	4.1	0.30	85	21	34

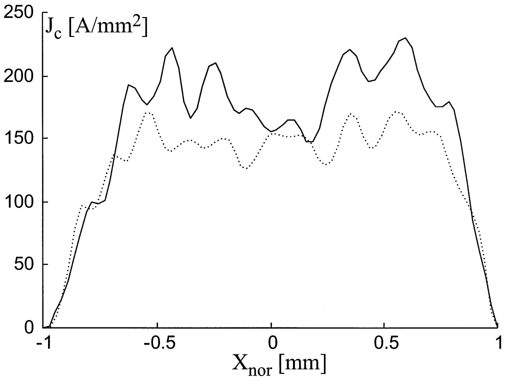

Fig. 5. The J_c-profile on a normalized x-position determined for both tapes.

show relatively large irregularities on a 0.1 mm scale, but the variations in J_c on a larger scale are much smaller. Averaged over 0.5 mm the variations are typically smaller than 10%, for the largest part of the cross-section. The lower J_c in the center of sample A and at the outer edges of the filamentary zone of both tapes can be attributed to the non-uniform distribution of stresses through the tape induced by the rolling process [6].

5. Conclusions

(1) A new experimental method is developed to determine the local critical current density in a BSCCO superconducting tape with a lateral resolution better than 100 μm. This non-destructive method utilises the strong dependence of the critical current on a perpendicular magnetic field to select a small section of tape in a transport current measurement.

(2) In combination with a determination of the superconducting area, a position dependent critical current density is determined along the conductor cross-section. A very good correlation is observed between the spatial variations in the critical current density and the position where the superconducting material is placed inside the cross-section of the tape.

(3) The two tape conductors investigated in this study show a relatively small variation in critical current density across the conductor cross-section. The largest part of the current is regularly distributed among the superconducting cross-section.

(4) Significant deviations in the critical current density distribution are only observed in the outer filaments of both conductors, where J_c is up to 50% lower. In one of the two investigated conductors a relatively small reduction of 15% in J_c is also observed in the center of the tape.

References

[1] Y. Yamada, M. Satou, S. Murase, T. Kitamura, Y. Kamisada, in: Proceedings of the 5th International Symposium on Superconductivity (ISS '92) Kobe, 1992, Springer, Tokyo, 1993, p. 717.

[2] A.E. Pashitski, A. Polyanskii, A. Gurevich, J.A. Parell, D.C. Larbalestier, Physica C 246 (1995) 133.

[3] A.V. Volkozub, A.D. Caplin, H. Eckelmann, M. Quilitz, R. Flükiger, W. Goldacker, G. Grasso, M.D. Johnston, in: Applied Superconductivity, Int. Phys. Conf. Ser. No. 158, vol. 2 1997, pp. 1263–1266.

[4] G. Grasso, B. Hensel, A. Jeremie, R. Flükiger, Physica C 241 (1995) 45.

[5] D.C. Larbalestier, X.Y. Cai, Y. Feng, H. Edelman, A. Umezawa, G.N. Riley Jr., W.L. Carter, Physica C 221 (1994) 299.

[6] W.R. Blumenthal, Y.T. Zhus, T.C. Lowe, R.J. Asaro, Physica C 260 (1996) 33.