

# Temperature and magnetic field dependence of the critical current of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ tape conductors

D.C. van der Laan, H.J.N. van Eck, B. ten Haken, J. Schwartz and H.H.J. ten Kate

**Abstract**—In order to improve the understanding of the dominant mechanisms that limit the critical current in high temperature superconductors, the dependence of the critical current on magnetic field and temperature of a  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$  tape has been investigated in detail. The critical current is measured in magnetic fields up to 8 T, at temperatures ranging from 4.2 K to 70 K. The results are compared with existing models that describe the current path as two parallel systems, one depending on weak links and the other on flux pinning. The critical current at low magnetic fields is reduced drastically by the self-field of the superconductor. At intermediate magnetic fields, the field dependence of the critical current is mainly dominated by weak links, while at higher fields it is dominated by the strong-links current path, and depends on flux pinning. To clarify the models used to describe the measurements, the temperature dependence of the parameters used in the models is studied. The temperature dependence of the parameters used to describe the weak-links current path points out that the weak links are formed by remnant  $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_x$  phase at the grain boundaries.

**Index Terms**—BSCCO, critical current, strong links, superconductors, weak links.

## I. INTRODUCTION

SINCE the discovery of superconductivity above liquid nitrogen temperature, long lengths of high quality conductors have been developed for power applications. Among these are  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$  (BSCCO 2223) tapes, produced with the powder-in-tube method. The critical current density of BSCCO 2212 single crystals is several orders higher than tapes made from BSCCO 2212. This can be explained by the granular nature of the material; the grains within the filaments are connected by weak links with a much lower critical current density than inside the grains themselves. The same is true for tapes made of BSCCO 2223.

Manuscript received September 17, 2000.

This work was supported in part by National Science Foundation under contract DMR-9527035, and by FOM (Fundamental Research on Matter), which is subsidised by NWO.

D.C. van der Laan: Corresponding author: University of Twente, Enschede, The Netherlands, and National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA. email: danko@magnet.fsu.edu

H.J.N. van Eck, B. ten Haken and H.H.J. ten Kate: University of Twente, Enschede, The Netherlands.

J. Schwartz: National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA, and Department of Mechanical Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310, USA.

The weak links between the grains are mainly formed by twist boundaries, large angle tilt boundaries, non-superconducting phases, and remnants of the BSCCO 2212 phase. Low-angle  $ab$ -axis grain boundaries are considered as strong links [1].

In applications of BSCCO 2223/Ag tapes in magnets, the superconductor is exposed to a relative high magnetic field. It has been shown that the critical current decreases drastically with magnetic field, especially when the magnetic field is applied perpendicular to the  $ab$ -plane of the grains. A double step behavior in critical current density as a function of magnetic field has been observed first by Ekin [2]. At very low magnetic fields the critical current remains constant. At low magnetic fields, the critical current of the weak links decreases with increasing magnetic field, and the first step in the plot of critical current versus magnetic field of the tape is observed. After the weak links lose their ability to carry supercurrent, the critical current remains constant as function of magnetic field. The supercurrent is subsequently carried only by strong links, and depends primarily on flux pinning. Near the upper critical magnetic field of the grains, the second drop in critical current occurs when the strong links lose their ability to carry supercurrent.

In this paper, the dependence of  $I_c$  of a BSCCO 2223 tape on magnetic field is reported. A model similar to the one used by Huang [3] is used to explain the results. This model describes the total current of the tape as a parallel network of a weak-links current and a strong-links current. The temperature dependence of the critical current in both current paths is considered to improve the understanding of the physics of both current paths.

## II. EXPERIMENTAL

A multifilament BSCCO 2223 tape with silver matrix, fabricated by the oxide powder-in-tube method, is used in the experiment. The tape consists of 85 filaments, and has a critical current density at 4.2 K of  $160 \text{ A/mm}^2$ . The critical current of a short sample is determined using a four-point configuration. The voltage criterion is  $1 \mu\text{V/cm}$ .

The critical current is measured as a function of the perpendicular magnetic field, up to 8 T, at temperatures ranging from 4.2 K to 70 K. The temperature is controlled by mounting the sample on a copper block, equipped with two heaters, in helium gas, as described by Ten Haken [4]. Superconducting current leads with a lower heat leak than copper current leads are used to increase the temperature range of the setup.

### III. RESULTS AND DISCUSSION

The magnetic field dependence of the critical current is described using the model of two parallel current paths in the tape. One current path consists of grains connected by weak links, thereby forming a weak-links network. Because the critical current of the weak links has a much stronger field dependence than the intragrain  $I_c$ , the field dependence of the critical current  $I_{cw}(B, T)$  of this current path is entirely determined by the weak links and not by the intragrain behavior.

The second current path is formed by strongly linked grains. The field dependence of the critical current  $I_{cs}(B, T)$  of the strong-links current path is determined by flux pinning, and will be discussed later. The total critical current  $I_c(B, T)$  is given by [3]:

$$I_c(B, T) = I_{cw}(B, T) + I_{cs}(B, T). \quad (1)$$

The weakly linked grain boundary system can be regarded as a network of Josephson junctions. The magnetic field dependence of the individual junctions is given by a Fraunhofer pattern. A distribution function of junction dimensions was first used by Peterson [5] to describe the network of weak links.

A different approach, not requiring a distribution function of junction parameters was taken by Müller [6]. The magnetic field dependence of the weak links is based on intergrain pinning. A Power-Law dependence similar to the phenomenological model introduced by Kim [7], as given in (2) is used:

$$I_{cw}(B, T) = \frac{I_{cw}(0, T)}{1 + \left( \frac{|B|}{B_0(T)} \right)^\beta}. \quad (2)$$

The temperature dependent parameter  $B_0(T)$  is related to the inverse of the average grain size and the inverse of the London penetration depth [8]. Parameter  $\beta$  depends on the junction geometry;  $\beta=1$  for rectangular junctions.

The pinning strength at the strong-links boundaries is larger than the intragrain pinning strength [9]. Consequently the magnetic field dependence of the strong-links network is determined by intragrain pinning. The following expression for the strong-links critical current can be used, based on the collective pinning theory [10]:

$$I_{cs}(B, T) = I_{cs}(0, T) \exp\left(-\frac{B}{B_{sc}(T)}\right)^{\alpha(T)}. \quad (3)$$

The scaling field  $B_{sc}(T)$  is closely related to the irreversibility field, where the fluxline lattice transfers from the vortex glass state into the vortex liquid state. The parameter  $\alpha(T)$  is introduced [11] to take into account thermally activated flux creep and is determined empirically

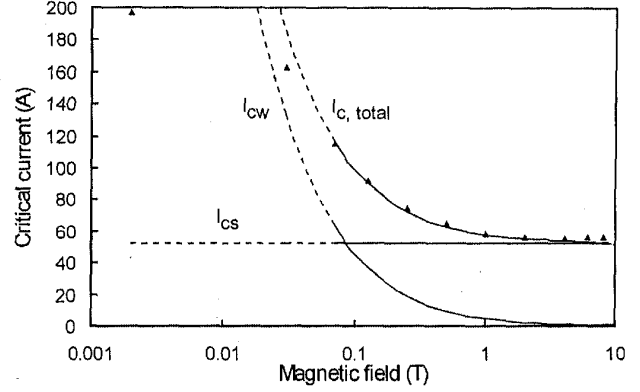


Fig. 1. Magnetic field dependence of the critical current at 4.2K for perpendicular applied magnetic field. The solid lines represent the models (1), (2) and (3), i.e. total-, weak-links-, and strong-links critical current respectively.

from the slope of the plot of the critical current at high magnetic field.

The temperature dependence of the scaling field  $B_{sc}(T)$  and  $I_{cs}(0, T)$  are given in (4) and (5), in agreement with [12]:

$$B_{sc}(T) = B_{sc}(0) \exp\left(-\frac{T}{T_{sc}}\right), \quad (4)$$

$$I_{cs}(0, T) = I_{cs}(0, 0) \left(1 - \frac{T}{T_c}\right)^{\alpha 2}. \quad (5)$$

The magnetic field dependence of the tape at 4.2 K, together with the graphical representation of models (1), (2) and (3) are shown in fig. 1. The values of the temperature independent parameters used in the model are summarized in table I. The first decrease in critical current can be seen at 30 mT where the weak-links critical current is decreasing rapidly. The model for the weak-links critical current shows that the weak-links contribution to the total critical current is still non-zero at 1 T. The double step behavior is not observed in fig. 1. The second step occurs at magnetic fields above 8 T. The strong-links critical current remains constant in the field range of fig. 1.

Although the field dependence is measured from 2 mT and up, only the data points starting at 70 mT are used in the calculation. The self-field of the tape has a large contribution

TABLE I  
PARAMETER VALUES, USED IN THE MODEL

$I_{cs}(0, 0)$	53.4	A
$\alpha 2$	0.3	
$T_c$	107.3	K
$B_{sc}(0)$	107.5	T
$T_{sc}$	10.7	K
$\beta$	1	
$I_{cw}(0, 0)$	733.5	A
$T_{cw}$	87.9	K
$B_0(0)$	7.8	mT

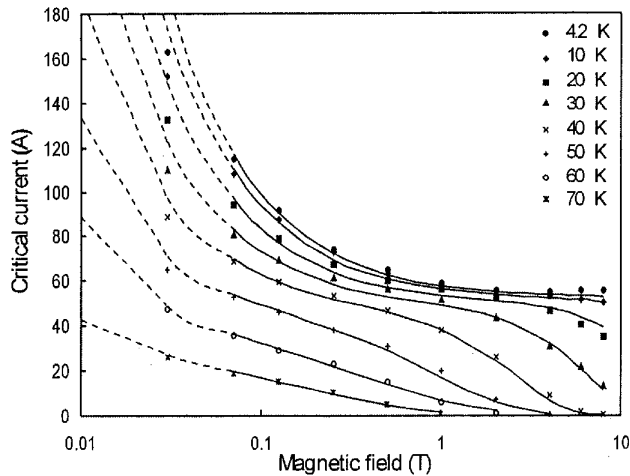


Fig. 2. Total critical current as function of magnetic field for temperatures ranging from 4.2 K to 70 K. Solid lines represent the model described by (1), dotted lines are an indication for the critical current when self-field is ignored.

in the decrease of the critical current at lower magnetic fields. The self-field contribution is small above 70 mT at all temperatures. The self-field at individual filaments in the tape is not known and should be calculated numerically, before applying the model for the entire magnetic field range. The dashed parts of the solid lines in fig. 1 give an indication on how the critical current behaves at low magnetic fields, when the tape does not generate a self-field perpendicular to the wide side of its surface. This would be the case in a slab geometry.

Fig. 2 shows the critical current measurements with the magnetic field applied perpendicular to the wide side of the tape, for temperatures ranging from 4.2 K to 70 K. The solid lines again represent the total critical current described by (1). The dotted parts of the solid lines indicate the range where the data points were used in the model, because of the self-field influence.

The self-field of the tape depends on the aspect ratio and the current through the tape. At higher temperatures, the critical current at low magnetic field is so low that the self-field of the tape does not play an important role. This can be concluded from the fact that the measured values of the

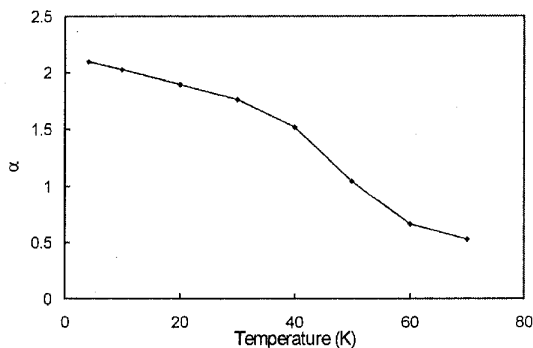


Fig. 3. Temperature dependence of the strong-links parameter  $\alpha$ . The line through the data points is a guide to the eye.

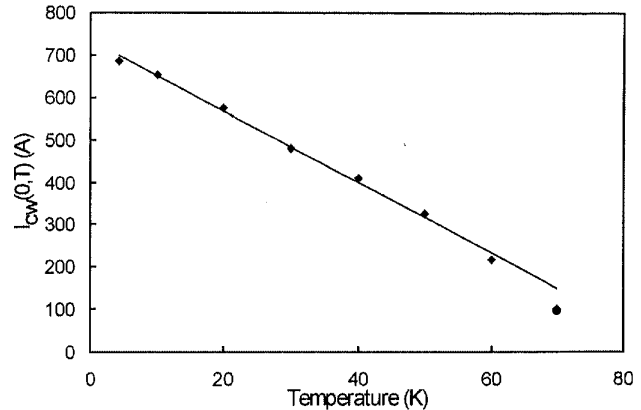


Fig. 4. Temperature dependence of the weak-links critical current at zero magnetic field. The solid line represents a linear fit as function of temperature according to (6a).

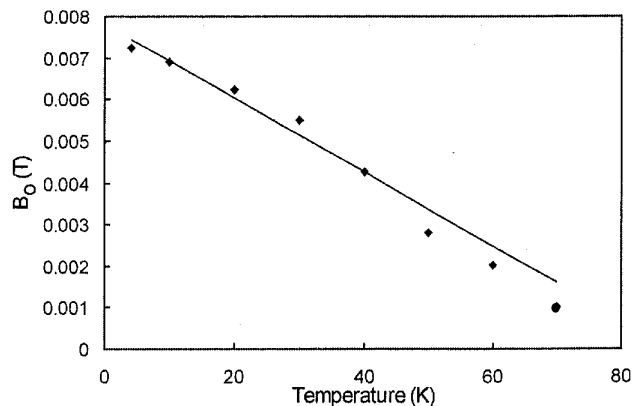


Fig. 5. Temperature dependence of  $B_0$ . The solid line represents a linear fit as a function of temperature according to (6b).

critical current at 30 mT are very close to the dashed line.

The double step behavior can clearly be seen for temperatures from 10 K to 60 K, where not only the critical current decreases as function of magnetic field in the low field range, but also for higher magnetic fields. The double step behavior is hard to observe at 70 K.

The weak-links critical current decreases rapidly with increasing temperature. This is also the case for the strong-links critical current. At temperatures above 40 K, flux creep in the grains is so severe that the total critical current vanishes before 8 T is reached.

The temperature dependence of parameter  $\alpha$ , used in the model for the strong-links critical current (3), is plotted in fig. 3 as a function of temperature. According to [11], flux creep determines the critical current dependence at high field, as opposed to flux flow, which occurs only above the irreversibility field. The value of  $\alpha$  changes as a function of temperature and is related to thermally activated flux creep. It should go to zero for low temperatures. From fig. 3 it can be seen that the value of  $\alpha$  increases from 0.5 at 70 K to a little over 2 at 4.2 K. Thermally activated flux creep cannot explain this behavior. The voltage criterion chosen to determine the

critical current can have an influence at high field, where the  $n$ -value of the tape decreases rapidly with increasing magnetic field. The field dependence of the critical current for different voltage criteria should be investigated to get a better insight of the meaning of  $\alpha$ .

The temperature dependence of the weak-links parameters of (2), *i.e.*  $I_{cw}(0, T)$  and  $B_0(T)$ , are plotted in fig. 4 and fig. 5 respectively. Both parameters decrease as a linear function of temperature. Functionally they can be approximated by:

$$I_{cw}(0, T) = I_{cw}(0, 0) \left( 1 - \frac{T}{T_{cw}} \right) \quad \text{and} \quad (6a)$$

$$B_0(T) = B_0(0) \left( 1 - \frac{T}{T_{cw}} \right). \quad (6b)$$

A linear temperature dependence of  $I_{cw}(0, T)$  is observed in SIS-type junctions, according to [13]. The values used for the parameters of (6a) and (6b) are given in table I. The temperature where both weak-links parameters go to zero is the critical temperature  $T_{cw}$  of the weak links. A best comparison with the data of  $I_{cw}(0, T)$  and  $B_0(T)$  is found, when a value of 87.9 K is used for  $T_{cw}$  in both (6a) and (6b). This is close to the critical temperature of BSCCO 2212. During the sintering of the material, the 2223 phase evolves from the 2212 phase. This could imply that the major part of the weak links in BSCCO 2223 tapes is formed by remnants of the 2212 phase at the grain boundaries.

According to [8],  $I_{cw}(0, T)$  depends on the London penetration depth as  $\lambda_L^{-1}$ , and will result in a non-linear temperature dependence, as long as the external magnetic field remains smaller than the lower critical field  $B_{c1}$  of the grains. The difference between this temperature dependence of  $I_{cw}(0, T)$ , and the one found can be explained by the value of magnetic field used. In our case, the external magnetic field is much higher than the  $B_{c1}$  of the grains. The Josephson critical current of a junction depends on the full phase difference of the order parameter across the junction. In our case, the phase difference is not only influenced by the magnetic field in the junction, generating Meissner shielding currents within the London penetration depth. When the lower critical field of the grains is reached, Abrikosov vortices start to penetrate the grains. The first row of Abrikosov vortices in the grains influence the phase difference of the order parameter [14]. The degree in which the Abrikosov vortices change the order parameter depends on the distance between them and the grain boundary.

#### IV. CONCLUSIONS

The reduction in critical current of a BSCCO 2223 tape as a function of magnetic field is determined at different temperatures. A double step behavior in the critical current is observed, explained by the influence of self-field at low magnetic fields, magnetic field dependence of weak links at intermediate fields, and flux pinning in the grains at high fields. It was found that a model based on two parallel current paths can explain the results rather well. The temperature

dependence of the parameters is considered to give better insight in the current limiting mechanisms of the conductor.

The critical temperature of  $\sim 87$  K of the weak links and the linear temperature dependence of  $I_{cw}(0, T)$ , suggest that the weak links are formed from remnant BSCCO 2212 phase on the grain boundaries.

To learn more about the nature of the strong-links parameter  $\alpha$ , the field dependence of the critical current should be investigated at higher fields at low temperatures. A tape with a high enough critical current to observe the double step behavior in the plot of the magnetic field behavior of the critical current above 70 K should be used. The influence of the voltage criterion on the behavior at high magnetic fields should be investigated.

To apply the model at very low magnetic fields, the self-field of the tape as function of position in the tape should be determined numerically. The self-field drastically reduces the critical current at low external magnetic field, as is shown in the model.

#### REFERENCES

- [1] A. A. Polyanskii, A. Gurevich, A. E. Pashitski, N. F. Heining, R. D. Redwing and D. C. Larbalestier, "Magneto-optical study of flux penetration and critical current densities in [001] tilt  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  thin-film bicrystals," *Physical Review B*, vol. 53 no. 13, pp. 8687-8697, April 1996.
- [2] J. W. Ekin, T. M. Larson, A. M. Hermann, Z. Z. Sheng, K. Togano and H. Kumakura, "Double-step behavior of critical current vs. magnetic field in Y-, Bi-, and Tl-based bulk high- $T_c$  superconductors," *Physica C*, vol. 160, pp. 489-496, 1989.
- [3] Y. K. Huang, B. ten Haken and H. H. J. ten Kate, "Critical current of high  $T_c$  superconducting Bi2223/Ag tapes," *Physica C*, vol. 309, pp. 197-202, 1998.
- [4] B. ten Haken, "Strain effects on the critical properties of high-field superconductors," Ph.D. thesis, University of Twente, Enschede, The Netherlands, ISBN 90-9007519-4, 1994.
- [5] R. L. Peterson and J. W. Ekin, "Josephson-junction model of critical current in granular  $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_{7-d}$  superconductors," *Physical Review B*, vol. 37 no. 16, pp. 9848-9851, 1988.
- [6] K. -H. Müller, J. C. MacFarlane and R. Driver, "Josephson vortices and flux penetration in high temperature superconductors," *Physica C*, vol. 158, pp. 69-75, 1989.
- [7] Y. B. Kim, C. F. Hempstead and A. R. Strnad, "Critical persistent currents in hard superconductors," *Physical Review Letters*, vol. 9, pp. 306, 1962.
- [8] K. -H. Müller, D. N. Matthews and R. Driver, "Critical current density of ceramic high-temperature superconductors in low magnetic field," *Physica C*, vol. 191, pp. 339-346, 1992.
- [9] K. Shibutani, Q. Li, R. L. Sibutani and M. Suenaga, "Limiting factors for critical current densities in  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ -Ag composite conducting tapes at elevated temperatures," *Applied Phys. Letters*, vol. 63 no. 25, pp. 3515-3517, 1993.
- [10] M. V. Feigel'man and V. M. Vinokur, "Thermal fluctuations of vortex line, pinning, and creep in high- $T_c$  superconductors," *Physical Review B*, vol. 41 no. 13, pp. 8986-8990, 1990.
- [11] J. Horvat, S. X. Dou, H. K. Liu and R. Bhasale, "Critical currents through strong links in Ag/Bi-Sr-Ca-Cu-O superconducting tapes," *Physica C*, vol. 271, pp. 51-58, 1996.
- [12] R. Wesche, "Temperature dependence of critical currents in superconducting Bi-2212/Ag wires," *Physica C*, vol. 246, pp. 186-194, 1995.
- [13] V. Ambegaokar and A. Baratoff, *Physical Review Letters*, vol. 10, pp. 486, 1963.
- [14] A. I. D'yachenko, "Hysteresis of transport critical current of high  $T_c$  superconductors in strong magnetic fields. Theory," *Physica C*, vol. 213, pp. 167-178, 1993.