Critical current measurements of DI-BSCCO tapes as a function of angle in high magnetic fields

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Critical current measurements of DI-BSCCO tapes as a function of angle in high magnetic fields

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Abstract. Controlled Over-Pressure is used by Sumitomo Electric Industries Ltd. to process so-called DI-BSCCO Bi-2223 superconducting tape reaching high critical current (I_C) in high magnetic fields. This paper reports the critical current of DI-BSCCO tape at 77 K in low fields and at 4.2 K in our horizontal split-pair magnet in fields up to 13 T at various angles between the surface of the tape and the direction of the magnetic field. These critical current data are strongly influenced by the anisotropy of Bi-2223, the texturing of the tape and the magnetic history of the magnetic field. The magnetic field and angular dependence of I_C at 77 K can be parameterised with a simple anisotropic Kim model. For 4.2 K measurements where large currents and magnetic fields are required, it is demonstrated that a split-current-lead design can be used to reduce rotation of the probe during the I_C measurements.

1. Introduction

The performance of the silver-sheathed multifilamentary Bi-2223 superconducting tapes produced by the Powder-in-tube method has been improved drastically by applying the Controlled Over-Pressure (CT-OP) technique at the final heat treatment [1-9]. Sumitomo Electric Industries Ltd. manufactures high performance DI-BSCCO tape with enhanced critical current density and excellent mechanical strength. These tapes are valuable for many applications such as power cables, transformers, motors, generators, and high field magnets. Hence their performance in high magnetic fields under the conditions that the tapes will experience when they are used is of great interest to the research community.

Unlike low temperature superconductors, high temperature superconducting (HTS) tapes are strongly anisotropic which affects the current transport properties. The anisotropy of the critical current density has been studied experimentally in Bi-2223 superconducting tapes and theoretical models have been introduced to describe the local current path [10, 11] and the magnetic field and angular dependence of the critical current density [12-14]. Early data on Bi-2223 thin films demonstrated that high critical current density can be achieved [15, 16] and that the two-dimensional superconducting behaviour of these layered structures is a rather general property of HTS materials [17]. There has followed a long period of continuous improvement in the critical current density of Bi-2223 tapes achieved by improved texturing and densification [18]. It is now clear that measurements of the angular dependence of the critical current density (J_C) are not only necessary to assess the technological potential of new materials being developed but also can been used as a tool to investigate their texture and dimensionality. In this work we explore the challenges and limitations associated with angular J_C measurements in a 15 T horizontal split-pair superconducting magnet and propose a split-current-lead design for the critical current measurement. In high applied magnetic fields, this lead design helps minimise errors associated with the probe twisting under the large torques produced by the large currents flowing in high magnetic fields. The J_C data obtained are then parameterized following the work of Zhang *et al.* using anisotropic Ginzburg-Landau theory and a simple Kim model [19] for the field dependence of the critical current density [12].

2. Experimental method

The CT-OP processed Bi-2223/Ag tape was provided by Sumitomo Electric Industries Ltd. It has a width of 4.3 ± 0.3 mm and a thickness of 280 ± 30 microns. The critical current measurements on the DI-BSCCO tape were carried out using a standard four-terminal technique. The 18-cm long tape was mounted on the copper beryllium sample holder, with the voltage taps 50 mm apart and the current contacts soldered directly to the ends of the tape. The critical currents were determined using a 100 μVm^{-1} electric field criterion. The measurements were performed at different angles (θ) between the field and the tape surface at 77 K in a conventional iron-cored electromagnet in fields up to 0.5 T and at 4.2 K in our 15 T horizontal superconducting split-pair magnet. Angular measurements were made by rotating the critical current probe from $\theta = 0°$ to 90° and from $\theta = 0°$ to -90° in different fixed magnetic field strengths.

Figure 1 shows the schematic for the experimental setup in our measurement. The computer interface was used to control the 2000 A sample power supply and collect the electric field versus current data for the critical current measurements. The current from the power supply passed through a standard resistor for direct measurements of the applied sample current. As shown in figure 1, the split-current-lead design means that the positive current path is split into two equal parts separated about the superconducting tape. This design ensures that to first order: the magnetic field produced by the current in the leads is minimised at the tape and hence the tape should only experience the magnetic field from the magnet and its own self-field; the torque associated with currents flowing in the leads and the superconducting sample is minimised so the probe should not progressively twist (or rotate) while the current is increasing during the measurement.

To investigate whether the bottom of the probe is rotating during the critical current measurement (while the top of the probe is held fixed), an HGCT-3020 Hall sensor from Lake Shore Cryogenic, Inc. was attached directly on to the sample and the component of the magnetic field orthogonal to the sample was monitored. The sensor has the maximum linearity error ± 1.0 % for fields less than 3 T and ± 2.0 % for fields up to 15 T.

3. Results and discussion

3.1. Electric field versus current density characteristics

Figure 2 shows typical electric field versus current density characteristics of the DI-BSCCO tape at 77 K in applied magnetic fields up to 0.3 T which were perpendicular to the tape ($\theta = 90°$). A critical current of 160 A was obtained for the DI-BSCCO tape in self-field. The results in figure 2 show that as expected, at any electric field criterion the critical current density of the DI-BSCCO tape decreases as the applied magnetic field increases.

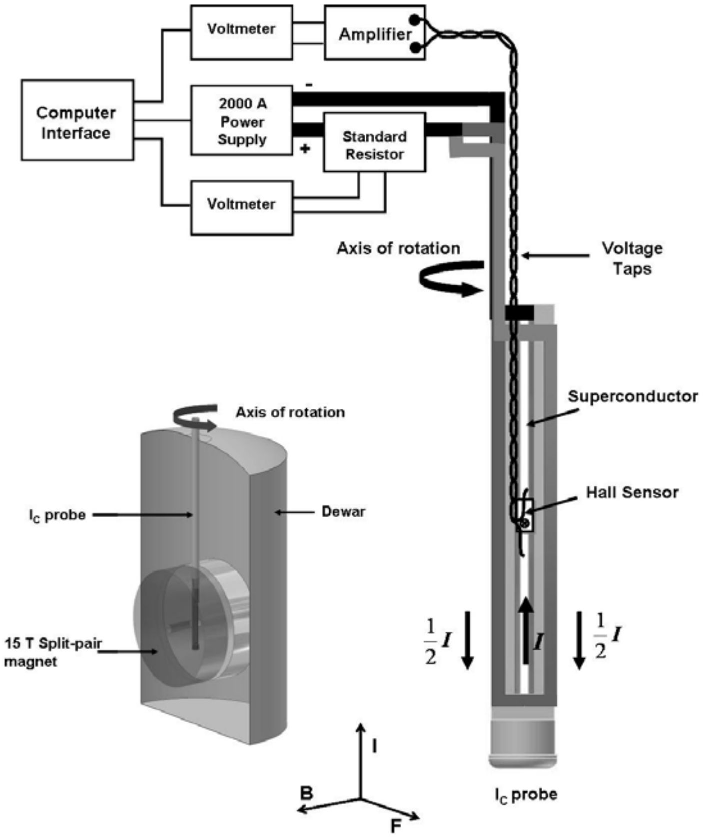

Figure 1. Experimental setup for the critical current measurements on a DI-BSCCO tape.

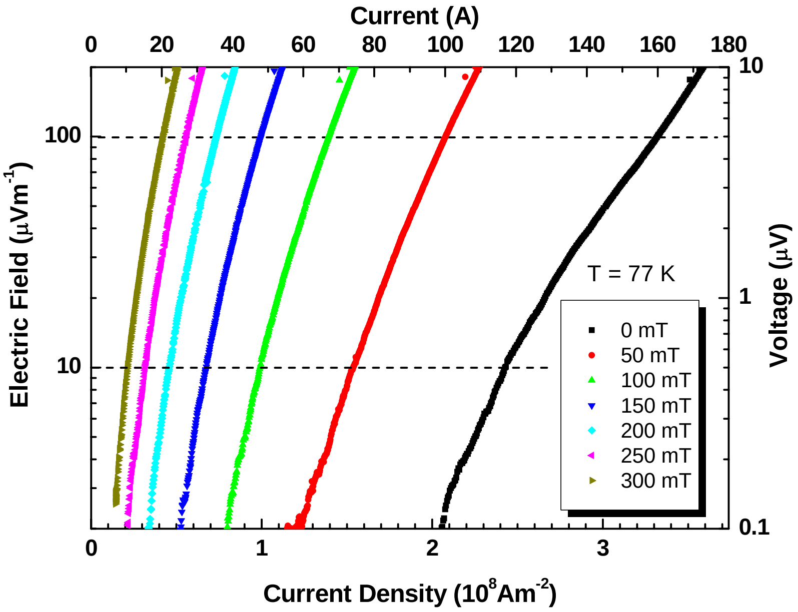

Figure 2. Electric field versus current density characteristics of the DI-BSCCO tape at 77 K in various applied magnetic fields perpendicular to the surface of the tape.

3.2. Angular dependence of the critical current density

The anisotropic properties of the DI-BSCCO tape at 77 K are shown in figure 3 and figure 4. Figure 3 shows the critical current density as a function of the angle between the applied magnetic field and the tape surface. The critical current density shows a peak value when the direction of the applied field is parallel to the tape surface (θ = 0°) which decreases with increasing angle. Figure 4 shows the critical current density of the DI-BSCCO tape in various applied magnetic fields up to 0.5 T with the fields parallel and perpendicular to the tape surface. The critical current density is higher in the parallel fields than in the perpendicular field due to the intrinsic pinning associated with the Cu-O planes and the high upper critical field [20, 21]. Current understanding is that the critical current density depends mainly on the perpendicular component of the field to the tape surface (i.e. the component of magnetic field along the *c*-axis direction). Our data at 77 K can be parameterized using this assumption and the work of Zhang *et al.* who considered tapes where grains were aligned in the tape. They proposed a model using anisotropic Ginzburg-Landau theory (the effective mass theory) to give the angular dependence of the upper critical field ($B_{c2}(\theta)$), and a simple Kim model to give the field dependence of the critical current density ($J_c(B,T)$). They obtained an expression for the angular dependence of the critical current density of the form [12]:

$$\frac{J_c(B,\theta)}{J_c(B,0)} = \left(\frac{1+\dfrac{B}{B_{0//}}}{1+\dfrac{B}{B_{0//}}\left(\gamma^2\sin^2\theta+\cos^2\theta\right)^{1/2}} \right)^n \tag{1}$$

where $J_c(B,0)$ is the critical current density for the magnetic field *B* applied parallel to the tape surface, $B_{0//}$ is a model dependent parameter which is weakly dependent on magnetic field and characteristic of the material [19] and γ is the standard Ginzburg-Landau anisotropy parameter [21, 22].

We have used equation (1) to describe the results at 77 K in figure 4. The differences between the theoretical curves and the experimental data are only significant at low fields and low angles. When the field is nominally parallel to the tape surface, the distribution of the grain misalignment in the tape becomes important [23]. This distribution means that locally in some parts of the tape there is always a small angle between the field and the ab-plane of the grains within the tape. This has not been considered explicitly by Zhang *et al.* but can be used to correct the low angle functional form given in equation (1) [24].

Initial measurements at 4.2 K, where currents and magnetic fields are much larger than used at 77 K, showed very large errors associated with the bottom of the probe twisting/rotating during the measurement. We reduced this rotation by introducing a split-current-lead design as shown in figure 1. When the current is balanced in both legs of the split-current-lead (i.e., ½ I), the design minimises both the additional field the tape is exposed to from the current leads and the net torque on the bottom of the probe. The electric field versus current data obtained at 4.2 K are shown in figure 5. By simultaneously monitoring the Hall probe during the critical current measurements, we determined the instantaneous angle when the electric field reached the 100 μV m^{-1} criterion used to specify the critical current density. The data obtained by this method are shown in figure 6 for the fields 3 - 13 T, where the angles shown in the figure were those obtained from the Hall probe and the lines in the figure are guides to the eye. Figure 7 shows more detailed data taken at 3 T in the range from θ = 0 to -90° and then θ = 0 to + 90°. It is clear that these data are not symmetric being systematically lower at positive angles and higher at negative angles. We interpret these results as a consequence of the history of the sample. It is well known that the critical current is not a thermodynamic property and that particularly in heterogeneous or granular samples, the critical current depends on the history of the magnetic field

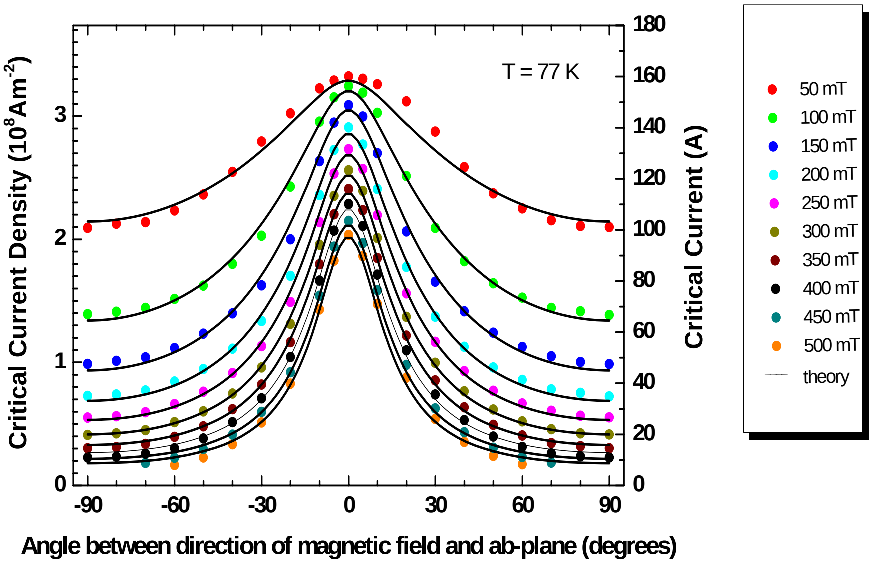

Figure 3. Critical current density as a function of the angle between the applied magnetic field and the surface of the DI-BSCCO tape at 77 K at various applied magnetic fields. The lines were generated using equation (1).

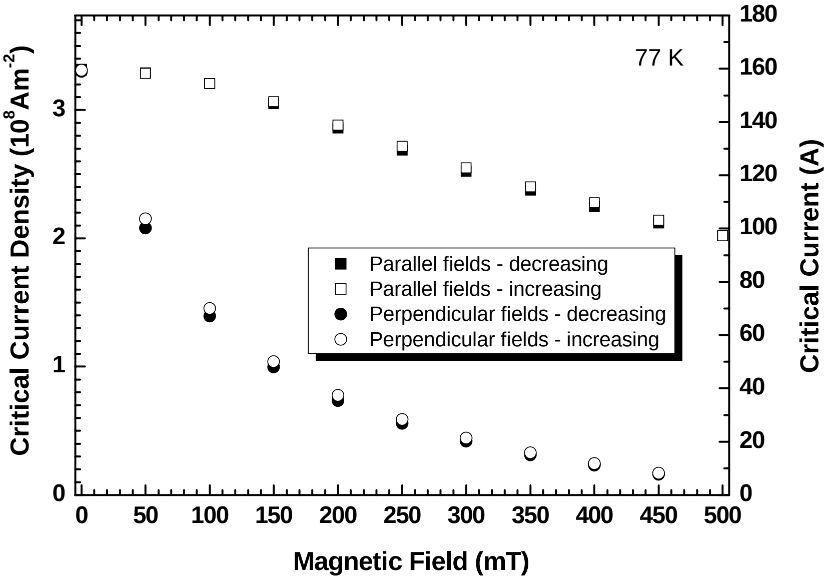

Figure 4. Critical current density as a function of the applied magnetic field of the DI-BSCCO tape at 77 K for fields applied perpendicular and parallel to the tape surface.

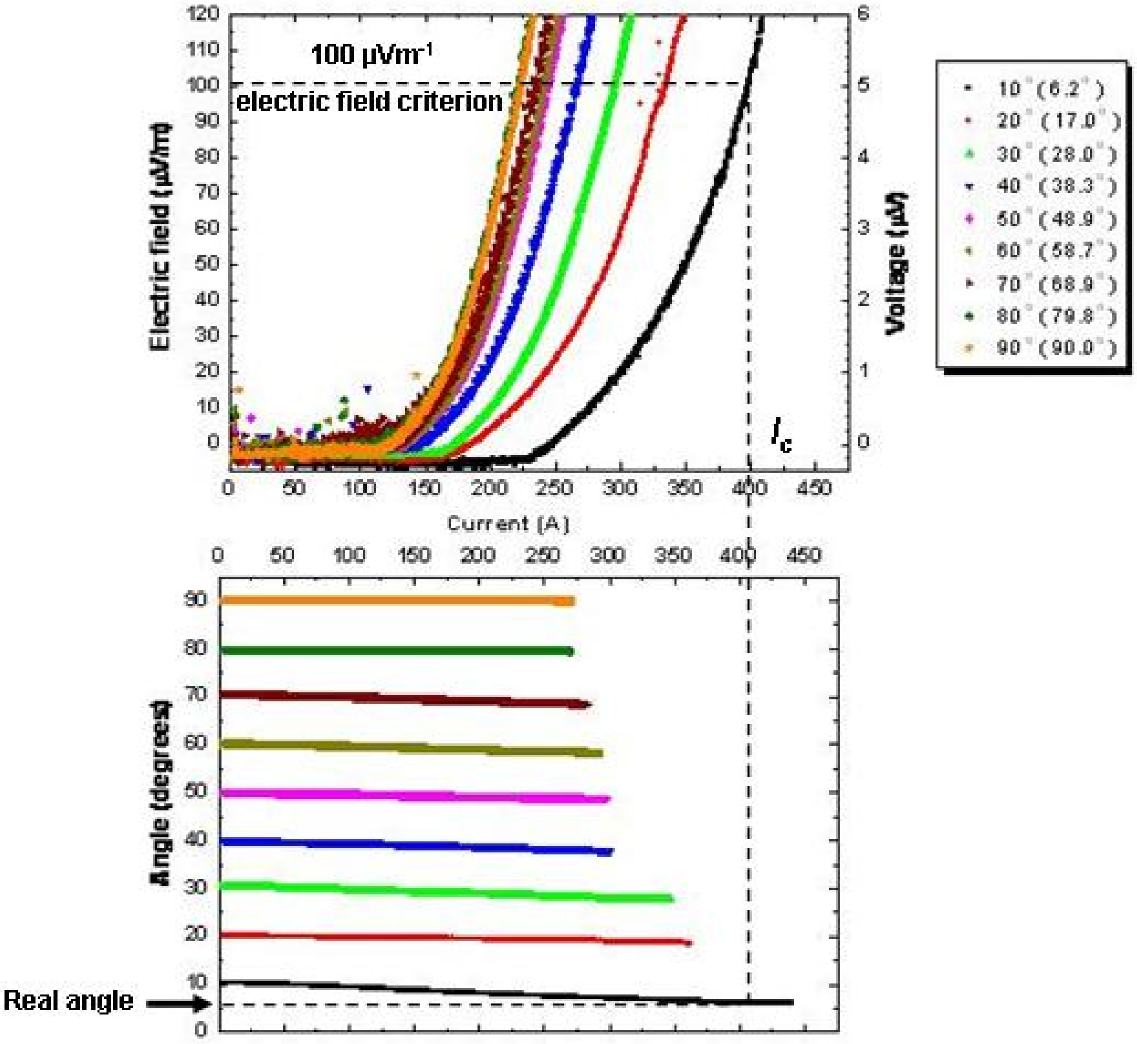

Figure 5. Data showing simultaneous monitoring of voltage across the superconductor, current through the superconductor and angle between the superconductor and the magnetic field for different starting angles. These data were used to identify the instantaneous angle (shown in brackets) between the applied magnetic field and the surface of the DI-BSCCO tape at 4.2 K and 3 T when the electric field produced by the superconductor was 100 μVm^{-1} (which is the criterion for specifying when the critical current was flowing).

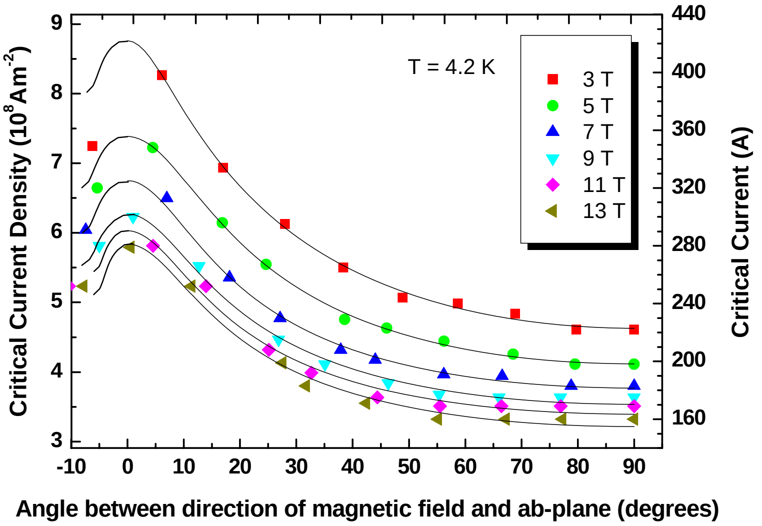

Figure 6. Critical current density as a function of the angle between the applied magnetic field and the surface of the DI-BSCCO tape at 4.2 K and various magnetic fields. The lines are a guide to the eye.

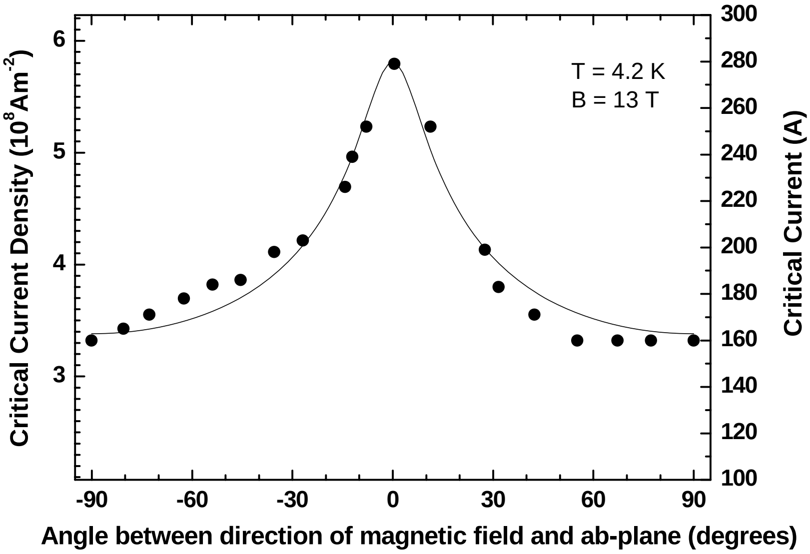

Figure 7. Critical current density as a function of the angle between the applied magnetic field and the surface of the DI-BSCCO tape at 4.2 K when the applied field was 13 T. The line is a guide to the eye.

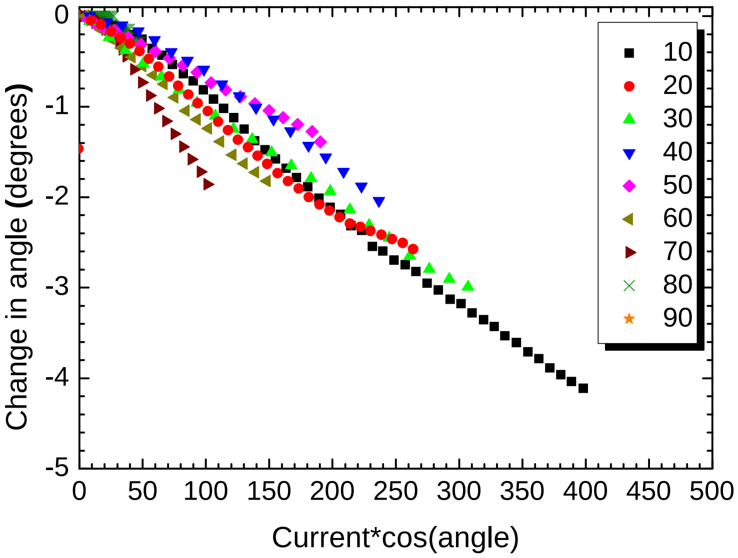

Figure 8. The change in angle as a function of the product of the current flowing through the sample and the cosine of the instantaneous angle between the applied magnetic field and the normal to the tape (Current* cos (angle)) for the critical current measurements taken at 4.2 K when the applied magnetic field was 3 T.

[25-27]. In our measurements, after the initial conditions are set, the direction of the applied field changes due to a twisting of the probe while the critical current measurement is being made. This interpretation is consistent with the opposite trends observed in the different quadrants in figure 7. The direction of the torque remains the same in both quadrants – so for negative angles the component of the field orthogonal to the tapes decreases whereas for positive angles it increases.

Figure 8 shows the magnitude of the change in the twisting angle while measurements were made at 3 T. The twisting is linear with current suggesting that the torque is produced either by the inhomogeneity in the field produced by the magnet or by an imbalance in the current in the two parts of the split-current-lead. The angular data in figure 8 are plotted versus the $current \cdot \cos(\theta)$ which is proportional to the torque acting on the probe in the event that the split-current-lead currents are not balanced. To first order the data superimpose. We conclude that by balancing the current passively to reduce the rotation, we can expect to limit the variation in the angle during the critical current measurement to about 1°. To obtain angular stability significantly better than this, active control of the current is needed. Other designs being considered are active control of a second current loop in feed-back to provide a compensating torque or mechanically rotating in feed-back the top of the probe.

4. Conclusions

The anisotropy of the critical current density of the DI-BSCCO tape was investigated at 77 K and 4.2 K. The critical current density is hysteretic and depends on the magnetic field, angle of the field and temperature. The data can be parameterised by a model which considers the component of the magnetic field orthogonal to the tape to primarily determine the field dependence of the critical current. In addition, a new split-current-lead design has been implemented and reduced the rotation of the probe in high fields. We conclude that in high current and fields, measurements can be made stable to about 1° with improved passive control but for stability better than 1°, active control is needed.

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References

[1] T Kato, S Kobayashi, K Yamazaki*, et al* 2004 *Physica C* 412-414 1066-72

[2] K Yamazaki, T Kato, K Ohkura, M Ueyama, N Ayai, H Takigawa, B Ueno, K Hayashi and K Sato 2004 *Trans Mater Res Soc Jpn* 29 1229-33

[3] S Kobayashi, K Yamazaki, T Kato*, et al* 2005 *Physica C* 426-431 1132-7

[4] Y Himeda, M Kiuchi, E S Otabe, T Matsushita, J Fujikami, K Hayashi and K Sato 2006 *Physica C* 445-448 722-5

[5] N Ayai 2006 *Journal of Physics: Conference Series* 43 47-50

[6] M Kikuchi, T Kato, K Ohkura*, et al* 2006 *Physica C* 445-448 717-21

[7] T Matsushita, M Kiuchi, K Kimura, S Takayama, Y Yamada, Y Shiohara, J Fujikami, K Hayashi and K Sato 2007 *Physica C* 463-465 686-91

[8] S Yamade 2007 *Physica C* 463-465 821-4

[9] N Ayai, T Kato, J Fujikami*, et al* 2008 *Journal of Physics: Conference Series* 97

[10] L N Bulaevskii, J R Clem, L I Glazman and A P Malozemoff 1992 *Phys. Rev. B* 45 2545-8

[11] B Hensel, J-C Grivel, A Jeremie, A Perin, A Pollini and R Flukiger 1993 *Physica C* 205 329-37

[12] G M Zhang, L Z Lin, L Y Xiao and Y J Yu 2003 *Physica C* 390 321-4

[13] O v d Meer, B t Haken and H H J t Kate 2001 *Physica C* 357-360 1174-7

[14] Y Wang, X Zhao, X Xu, L Xiao, L Lin, G Lu, D Hui and S Dai 2004 *Superconductor Science & Technology* 17 705-9

[15] K Endo, H Yamasaki, S Misawa, S Yoshida and K Kajimura 1992 *Nature* 355 327-8

[16] H Yamasaki, K Endo, S Kosaka, M Umeda, S Yoshida and K Kajimura 1993 *Phys. Rev. Lett.* 70 3331-4

[17] P Schmitt, P Kummeth, L Schulktz, B Road and G Saemann-Ischenko 1992 *Superconductor Science & Technology* 5 S101-4

[18] V Garnier, R Paqsserini, E Giannini and R Flukiger 2003 *Superconductor Science & Technology* 16 820-6

[19] Y B Kim, C F Hempstead and A R Strnad 1962 *Physcial Review Letters* 9 306-9

[20] J R Clem 1991 *Phys. Rev. B* 43 7837-46

[21] J R Clem 2004 *J. Supercond.* 17 613-29

[22] J Clem 1998 *Superconductor Science & Technology* 11 909-14

[23] B Xu, J H Su and J Schwartz 2005 *Superconductor Science & Technology* 18 503-7

[24] O van der Meer, B ten Haken and H H J ten Kate 2001 *Physica C* 357-360 1174-7

[25] K C Chung, E S Lee, B S Lee, S M Lim, B I Bhang and D Youm 2004 *Superconductor Science & Technology* 17 1113-20

[26] A B Sneary, C M Friend, J C Vallier and D P Hampshire 1999 *IEEE Trans. Appl. Supercond.* 9 2585-8

[27] M N Kunchur and T R Askew 1998 *J. Appl. Phys.* 84 6763-7