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Estimation of the critical current of BSCCO coils based on the field dependent I–V curves of BSCCO tapes

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Abstract

Presented here are measurements at 77 K of *I–V* curves of reinforced BSCCO tapes in a perpendicular field regime of 0–700 G, and *I–V* curves of Ricor-made pancakes in self-field. The difference between the *I–V* characteristics of tapes and pancakes is discussed and explained by traveling across field different *I–V* curves of the tapes. We estimate the critical current of coils, based on the magnetic field dependence of the critical current in BSCCO tapes. The current distribution in the tape is assumed to be homogeneous, or non-homogeneous distribution opposing the local critical current density resulting from the magnetic field distribution in the tape. Applying our computational methods to the measured pancakes, results in a 90% (homogeneous current distribution) and 98% match (field-dependent current distribution) with the measured pancake's critical current.

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1. Introduction

In recent years HTS wires characteristics have been improved continuously [1], however, the high costs of the wire still prevent it from being widely used for building DC magnets. Nevertheless, for special requirements, where volume is limited, HTS magnets might be a proper solution allowing for compact cryogen free cooled cryostats.

The design of SC electromagnets require the knowledge of the critical current in the coils. For HTS wires, while the magnetic field dependent critical currents are known, the actual critical current of a specific winding geometry is difficult to predict because of the large field variations across the wire cross-section resulting in non-homogeneous current flow in the wire. Recently, a mathematical model of the *I–V* characteristics of BSCCO-2223 magnets was suggested [2]. This model is suitable for coil designs where the field variation across the tape is low.

In this work we examine two approximation methods for calculating the expected critical current

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of a single pancake (SP) used as a building block for a HTS electromagnet. In the first approximation we assume a homogeneous current flow distribution inside the wire, corresponding to the average magnetic field across the wire cross section. In the second approximation we divide the wire cross section into parallel regions carrying different currents depending on the localized magnetic field in these regions. The results are compared with measurements of SPs wound at Ricor LTD and show a close match between the calculated and measured critical currents.

2. Experimental

Commercial reinforced BSCCO tapes purchased from American Superconductor Corp. [3] have been used for forming SPs. Fig. 1 shows a representative SPs. Each SP consists of 100 turns of BSCCO-2223 tape with 100 and 180 mm inner and outer diameters respectively. After epoxy vacuum impregnating each SP, 14 SP units were connected in series to form a single HTS coil. A full description of the coil will be given elsewhere.

I–V curve measurements were carried out using a 0–8 V, 0–580 A Agilent power supply, Keithly 2182 nanovoltmeter and Keithly 7000 scanner. For the tape measurements, 5 voltage taps were attached 20 mm apart to detect variations along the length of the tape if any. The contact area occupied the 10 cm central region of a 25 cm tape. The external magnetic field, 1% homogeneous over the region of interest, was generated by a large homemade Helmholtz coil. For measurements between 65 and 77 K we used liquid nitrogen pumped by a vacuum controlled rotary pump. Temperatures down to 20 K have been achieved using Ricor made GM cryocoolers.

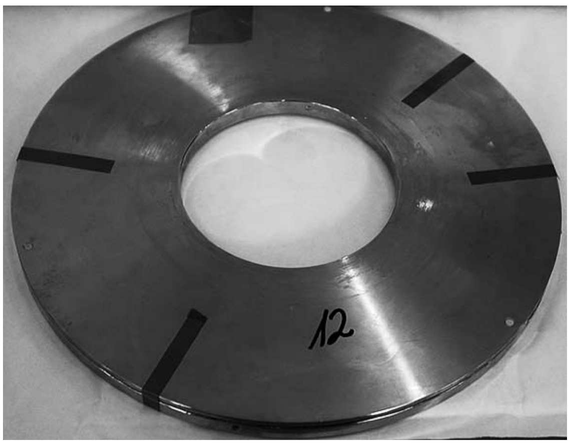

Fig. 1. A Ricor made SP. Inner diameter = 100 mm, outer $D = 180$ mm, 100 turns, 44 m of BSCCO reinforced wire.

3. Results and discussion

Fig. 2(a) exhibits *I–V* curves of the reinforced BSCCO tape in various external perpendicular magnetic fields at 77 K. Data presented here are averaged over the 5 voltage taps and represent the voltages of a 1 cm tape. All curves are well described by the power law dependence

$$E = E_0(I/I_c)^n, \qquad (1)$$

where I_c is the critical current related to the generally used criterion $E_0 = 1$ μV/cm. Fig. 2(b) presents the I_c values obtained by fitting the data to Eq. (1). As expected, I_c decreases sharply with increasing field except for the first 100 G where weak field dependence is observed. We explain this plateau in $I_c(B)$ by a shift of the local magnetic field profile towards the edge of the tape induced by the external field [4].

Fig. 3 exhibits the *I–V* curve of a representative Ricor made SP. Being composed of 44 m length HTS wire, the 1 μV/cm criterion for I_c determination is equivalent to a voltage of 4.4 mV across the SP ends. The critical current obtained for the presented pancake is 71.5 A, and the variation of the measured I_c among all the pancakes is about ±2 A.

The transition from the *I–V* characteristics of a straight tape to the *I–V* characteristics of the SP is not simple. With the increase of the current, the wire is exposed to an increasing self-field of the SP, which is much higher than the wire self-field. In the process of sweeping up the SP current, the wire actually "travels" horizontally across the *I–V* curves of a straight wire presented in Fig. 1. Moreover, while the data presented in Fig. 1 are obtained for a uniform perpendicular field along the wire

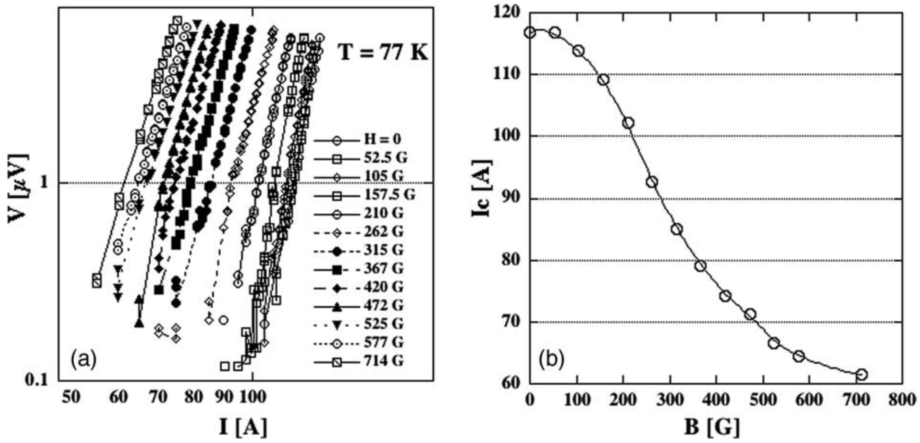

Fig. 2. (a) Log–log plot of the I–V curves of reinforced BSCCO tape in perpendicular magnetic fields in the range of 0–714 G, (b) extracted I_c vs. B values.

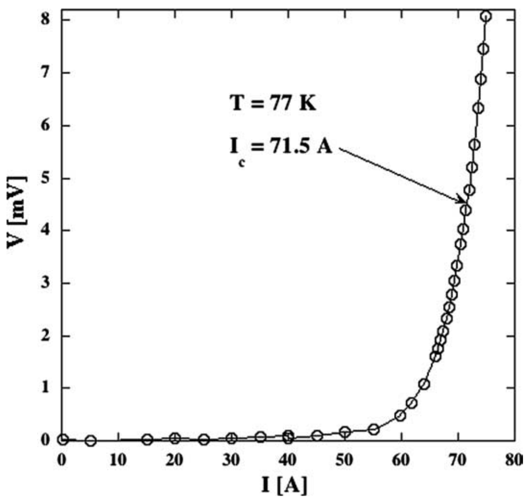

Fig. 3. I–V curve of a representative SP. I_c is defined as the appearance of 4.4 mV at the coil ends corresponding to the 1 μV/cm criterion.

cross-section, in the SP case the field varies sharply along the wire cross-section and along the SP windings.

Fig. 4(a) and (b) respectively present the radial (B_r) and axial (B_z) self-field components of the SP configuration, normalized to the current. The results shown have been obtained under the assumption of homogeneous current distribution in all the windings and by using Vector Fields' PC Opera finite element software.

As seen in Fig. 4(a), B_r peaks at the top and bottom ends of the SP's mid winding. At this winding B_r changes from approximately 18 G/A at one side to −18 G/A at the opposite side passing through zero at the center of the wire cross-section. B_z is maximal, +25/−25 G/A, at the inner/outer windings of the SP, crossing zero B_z value at the center of the SP (Fig. 4(b)). Because of the high anisotropy in the field-dependent characteristics of the BSCCO wire, in this SP configuration B_r is the dominant field component determining I_c of the SP. Therefore, we neglect the role of B_z for the determination of I_c and assume that B_r distribution is approximately equal in all the windings.

The dashed line in Fig. 5 is the I–B characteristic of the SP assuming that B_r is homogeneous throughout the wire cross-section and equals its maximal value of 18 G/A. in this case, the I–B curve of the SP crosses the $I_c(B)$ curve of the tape (re-plotted from Fig. 1(b)) at I_c values lower than 50 A. This clearly indicates that the maximal self-field value, to which a segment of the SP is exposed, does not determine the critical current value of the whole SP. In the solid line of Fig. 5 the I–B characteristic is calculated under the assumption that the wire cross-section is exposed to a uniform field equals the average field value i.e. approximately 9 G/A. In this case, the I–B line meets with the $I_c(B)$ curve at about 64 A, namely a 90% match with the actual measured 71.5 A I_c of the SP.

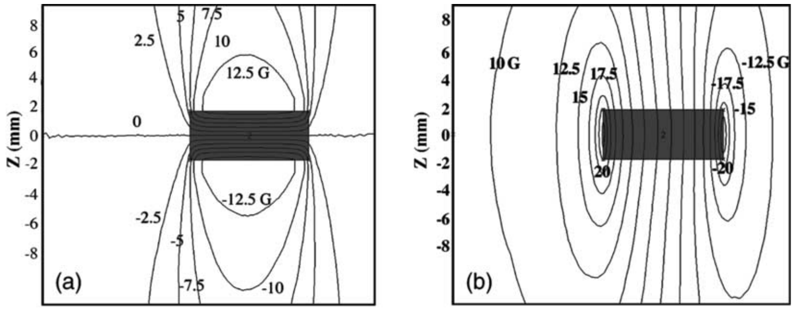

Fig. 4. (a) The radial component of the self-field, B_r, of the SP for a current of 1 A, (b) the axial self-field component, B_z.

In order to further improve the calculated I_c value and to account for complex coil geometries, we numerically solve the recursive non-linear Biot–Savart equation:

$$B = \frac{1}{c}\int \frac{J(B, r') \times (r - r')}{|r - r'|^3}\, d^3r', \qquad (2)$$

where $J(B)$ is the local field-dependent current density inside the wire. In principle, any winding in the coil might present a different J distribution depending on the localized field at the winding position [5,6]. The current will redistribute itself to minimize the electric and magnetic fields inside the superconductor.

To simplify the problem we take a second approximation approach where we assume that all windings have an identical field distribution and the wire cross-section is divided into 10 sub-sections at which we assume constant current. The starting point for this approximation is the magnetic field profile obtained for the last approximation i.e. the magnetic profile of homogeneous total current of 64 A. In the next iterations, the current density in each sub-section is selected close to $I_c(B)$ corresponding to the average field value of the sub-section and a new field profile is recalculated. The process continues until a convergence of

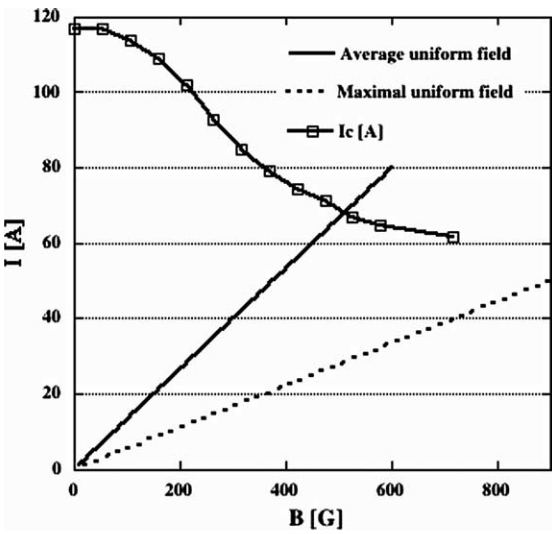

Fig. 5. I–B characteristics of the SP. Solid line: a uniform field that equals the average field value over the wire cross-section is assumed; dashed line: a uniform field that equals the maximal field value.

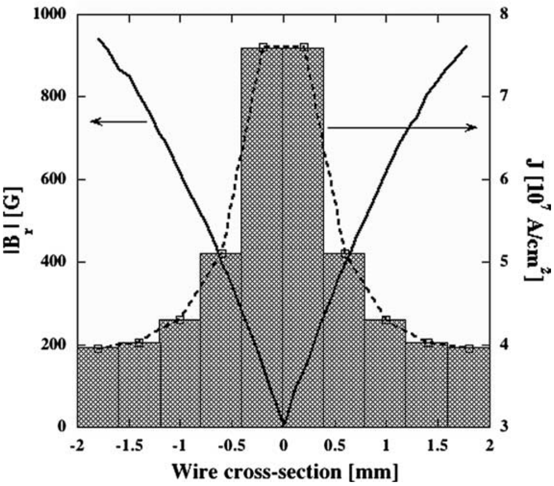

Fig. 6. Magnetic field profile (solid line) and current density distribution (dashed line) along the winding cross-section. Rectangles represent J in each sub-section.

I in all sub-sections is obtained. Fig. 6 shows the final values of the current density, J, in each sub-section along with the resulting field profile along the wire cross-section. The central sub-sections, experiencing lower fields, carry larger currents. The situation is reversed at the edges where the field is maximal and the current is minimal. The resulting I_c of the SP for this final iteration is 69.8 A, about 98% of the actual measured I_c. This good matching between the calculated and measured critical currents suggests that inside the SP the central regions of the wire cross-section experiencing the lowest magnetic fields carry most of the current.

4. Summary and conclusions

Field-dependent I–V curves of BSCCO reinforced wires and of Ricor made SP have been measured. The data show that I–V curves of HTS pancakes and coils are highly affected by the self-field distribution. Analysis of the data implies that the non-homogeneous magnetic field experienced by the windings of the SP results in a non-homogeneous current flow across the wire cross-section. Central regions, experiencing the lowest field values, carry the highest current density and most of the wire current. Subdividing the wire's cross-section into 10 sub-sections, carrying different current densities, gives a 98% match between the calculated and the measured I_c value of the SP. The analysis suggested here could serve for an estimation of the critical current of more complex HTS coils and windings configurations.

Acknowledgements

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