The change in tape current distribution during gradual current ramping up over $I_c$ and down to zero

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Abstract. The procedure of the local magnetic field mapping of Bi-2223 tape was applied to receive self field data for the current gradually increasing from zero level up to over critical current of the tape in zero external magnetic field. The measurement was repeated for several currents, the same as were used in current increase, but during phase of current decrease to zero level. The Tichonov method of regularization was applied in solving Biot-Savart inverse in calculation of current distribution across the tape width. The distribution pattern changes rather irregularly during the increase of the current. On the other hand there is no significant difference in the shape of the current distribution profiles for transport currents 20% over $I_c$ and the $I_c$. Comparison of up and down profiles show that changes in the current take place predominantly at edges of the tape, remaining central parts in retard. The same trend was observed in Nb$_3$Sn tape where however most of current flows at edges (non saturated state) contrary to Bi-tapes where central parts are dominant. The method was applied also for frozen currents in Bi-2223/Ag tape. The role of the external magnetic field in the change of the current distribution was studied too.

1. Introduction
For practical reasons, it is interesting to know the transport current distribution across the width of a superconducting tape. Simple physical models based on critical state model are used to calculate current density distribution within the cross-section of a tape [1], i.e. the current distribution across the tape width. However, it is questionable whether these models can be employed to assess real thin and broad tapes which exhibit intrinsic inhomogeneity in $j_c$. Moreover, the inhomogeneity influenced by local values of the self-field and by corresponding effects related to the anisotropy as demonstrated not only in the windings [2-5] but present even within the tape width [6].

Unfortunately, there is no direct way to measure a current distribution in the tape itself. There have been attempts to cut mechanically the tape into longitudinal parallel pieces and to measure the critical currents in the individual pieces [7]. The results have been interpreted in the form of histograms of the current carrying capacity distributed within the width of the original tape. But this approach does not answer the question about the role of the strong perpendicular component of the self field within the edges in the case of the local anisotropy resulting in a current distribution favoring the central parts of the tape where the perpendicular component is much smaller. Hence, the local anisotropy has profound influence on the interpretation of measurement for the saturated regime at which the overall transport current reaches the critical current level. Thus in this situation, the real current distribution of
an original non-destroyed tape may give smaller values of the current at the edges compared with the critical current of the individual pieces cut from the edge parts.

Moreover, this approach gives no information about the current distribution at an unsaturated state, in which the transport current is much smaller than the critical current of the tape, e.g. at AC regime when the transport current passes through the zero current level. The interference of this destructive method with the original parameters of the tape can not be neglected either.

The magnetic knife method was successfully applied for measurement of intrinsic critical current distribution across the tape width [8],[9]. This method, however, does not feel self field of the tape at full transport current nor can it be applied for under critical current (e.g. frozen current) distribution.

2. The method of measurement

To avoid the destructive approach for the investigation of the current distribution at the unsaturated regime it is necessary to use characteristic tape geometry, and to relate a current density distribution within the tape to its self-field distribution around the tape. At first the distribution of the self-magnetic field component perpendicular to the tape plane is mapped across its width. The scanning is carried out in a distance from the tape which is comparable with the tape thickness. Then the inverse problem is solved to determine the distribution of the longitudinal component of transport current within the tape width. This procedure is reliable provided the tape transport properties exhibit translational invariance. However, it can also be applied locally with a reasonable precision, as there is a rapid decrease in the input of distant parts in the longitudinal direction. Hall probes are obviously used as sensors [10].

In a discretization process, the tape was virtually cut longitudinally (z) into a finite number of k sub-tapes of the same width (x direction). It was supposed that the current within each sub-tape was homogeneous. The perpendicular component of the magnetic field was mapped in a finite number of k points over (y) the tape plane along the line (x), which was perpendicular to the tape axis (z). The measured values of \( B_{yi} \) (i=1 to k) were used to calculate the values of current in the sub-tapes \( I_{xi} \) (i = 1 to k). Details are in [11]. The transformation matrix which correlates the current in sub-tapes with the field values in measured points was ill conditioned. A very small error in the localisation of a field probe or in its read-out can lead to a very large error in the calculation of a current distribution. To avoid this problem in real measurements where finite level of errors is inevitable, the Tichonov method of regularization [12],[13] had to be applied.

In DC regime the transport current through the tape is constant. The current distribution across the tape width, as well as the self-field distribution around it, are constant too. The mapping procedure can be performed in a stepwise way from point to point gathering all the \( B_{yi} \) data (i = 1 to k). Then these data can be used to calculate the current distribution within the k sub-tapes.

3. Results

![Figure 1](image1.png)

**Figure 1.** The current distributions during ramping up and down can be compared at 15 A and 4.7 A levels. The parts closer to center are in retard

![Figure 2](image2.png)

**Figure 2.** The current distribution flattens with increasing external magnetic field. Central parts are more sensitive to increase of external magnetic field than edges
The current in BSCCO-2223/Ag tape in LN2 bath at 77 K was gradually increased from zero level to \( I_c \) and than 20% over \( I_c \). The condition for achieving \( I_c \) was standard voltage criterion \( E_0 = 1\mu \text{V/cm} \) (also other methods are possible [14]). Current distribution across the width of the tape during gradual ramping up and down is compared on Figure 1. The current is expressed as the current on unit length of the width.

In figure 1 we can see that there is no remarkable difference between the shape of current distribution at critical current (20 A) and 20% over critical current (25 A). Comparison of distributions during ramping up and down (15 A and 4.7 A levels) reveals that change in current during gradual ramping of transport current takes place predominantly at edges keeping central parts in retard. Higher currents at central parts are intrinsic feature of the Bi-2223/Ag tape and are only partly influenced by self field (i.e. higher perpendicular component of self magnetic field at edges). This can be proved by comparing figure 1 with the critical current distribution achieved by destructive method (cutting the tape into longitudinal pieces and measuring currents of the pieces) at figure 2. The destructive method was limited to critical current distribution only but allowed to make measurements in external magnetic field applied perpendicular to the tape plane. Tapes used on figure 1 and figure 2 are different concerning critical currents and producer but the trend of the current distribution with dominant central parts is the same, i.e. it is intrinsic, not self field induced.

This feature of central predominance concerning the current distribution in BSCCO-2223/Ag tapes is quite different to the current distribution measured on Nb\(_3\)Sn tape at 4.2 K in self field conditions as can be seen on figure 3. Because of unsaturated regime, the current in Nb\(_3\)Sn tape is distributed mostly at edges. However, again the change of the current takes place predominantly at edges during ramping, leaving the parts closer to center in retard. All the measurement was done under critical current level.

To show how powerful is the method based on Hall probe magnetic field mapping in tape vicinity and to test the calculation capabilities for currents different of transport critical current conditions as are the frozen currents induced in tape by external magnetic field, the same procedure was applied to the published [15] graphs of \( B_{\parallel}(x,y_0) \) measured over an Ag – sheathed BSCCO tape (with zero transport current) after the linear increase and decrease of ambient field \( (B_{\text{peak}}=0.3 \, \text{T}) \). The resulting linear current density distribution in prolonged loops corresponding to frozen magnetic flux is shown in figure 4. The frozen current loops are not simple. Again the intrinsic higher critical current densities at central parts of Bi-2223/Ag tape shape the current distribution to secondary opposite maxima at the central parts in parallel with the main maxima at edges (up to 8000 A/m).

4. Conclusions

The transport current distribution in BSCCO-2223/Ag tapes was measured for several tapes using Hall probe magnetometry at vicinity of the tape with transport current and solving Biot-Savart inverse. Maximum of the current is flowing at central parts of the tape, no matter whether the transport current is over critical or under critical. The change in current during ramping takes place predominantly at edges leaving central parts in retard. Contrary, at unsaturated Nb\(_3\)Sn tapes the current flows predominantly at edges with minimum between. However, the character of the change of the current at edges during ramping is similar as in Bi-2223 tapes (the change is in advance at edges).

The predominance of central parts in current distribution in Bi-2223 tapes can be only partly explained by self magnetic field influence. Destructive measurements (without role of self field of full current in maternal tape) reveal that it is intrinsic property of the multifilament tape. The current capacity of the central parts is simple higher. The distribution flattens with increasing field \( B_{\parallel} \).

The method could be applied even for frozen currents in the form of prolonged loops in Bi-2223/Ag tape and the level and distribution of these currents could be determined at least in one cross section at the middle of the tape.
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