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Modification of Critical Current in HTSC Tape Conductors by a Ferromagnetic Layer

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Abstract. In some applications of tape conductors from high temperature superconductors (HTSC) the magnetic field is created by the transported current itself. This is e.g. the case of power transmission cables or current leads. Quite complex distribution of local magnetic field determines then the ability of the superconducting element to carry electrical current. We have investigated how much the critical current of a tape conductor can be changed by putting a ferromagnetic layer in the vicinity of the HTSC material. Numerical procedure has been developed to resolve the current and field distribution in such superconductor-ferromagnet composite tape. Theoretical predictions have been confirmed by experiments on sample made from Bi-2223/Ag composite tape. The critical current of such tape can be improved by placing a soft ferromagnetic material at the tape’s edges. On the other hand, the calculations show that the ferromagnetic substrate of YBCO coated tape reduces its self-field critical current.

1. Introduction
The suggestion to improve the performance of a superconducting (SC) wire by a cover from soft ferromagnetic (SF) material has been proposed by several authors. Theoretical calculations for a flat superconducting tape in Meissner state have shown that a SF half-space or cavity in vicinity of the edge of a superconducting tape could increase its capability to transport DC current [1] and the same was found for a SF wall of finite thickness perpendicular to the tape [2]. Redistribution of Meissner currents and an enhancement of lower critical field have been predicted in SC filament of circular cross-section in vicinity of SF half-space [3, 4].

For a hard superconductor, using the critical state model [5] it was found that the shape of the current-free zone in flat tape changed assuming a SF cover [6]. However, the expected increase of critical current has not been confirmed [7]. This was later explained by more detailed calculation predicting that the increase of critical current by 20% would be reached if each filament were covered by SF [8]. Magneto-optic observation has shown that ferrites near the edges of YBCO thin film increase its critical current density [9]. Increase of critical current of Fe-sheathed round MgB2 wire compared to Cu-sheathed one [10] in magnetic fields up to about 0.6 T has been ascribed to the strong local deformation of magnetic field [11]. Ferromagnetic disks attached to the ends of HTSC winding increased its maximum current [12], and numerical simulations confirmed the experimental data when the dependence of critical current on the local magnetic field has been taken into account [13].
We have performed a series of calculations for two typical configurations of conductors based on high-temperature superconducting (HTSC) materials. In the case of a conductor with flattened elliptic core, an increase of the self-field critical current can be achieved by placing the SF material at the edges. This geometry is representative of a Bi-2223/Ag tape and the theoretical predictions have been confirmed experimentally. On the other hand, for the geometry of a thin SC layer on a SF substrate, that is representative for a YBCO coated tape, the direct experimental verification is not possible because no reference sample with non-magnetic substrate but the same SC layer is available. In difference to the previous case, the ferromagnetic substrate generally lowers the self-field critical current of these composites.

2. Calculation procedure

Our considerations limit to the case when the critical current, $I_c$, is reached in the wire under investigation. The calculations are performed in two-dimensional geometry, assuming an infinitely long wire with perfect translational symmetry placed in magnetic field perpendicular to the wire long axis. The fields are to be determined in the box of cylindrical shape, coaxial with the wire, on which the boundary condition for magnetic field is established.

To perform these calculations, the finite-element code FEMLAB \[14\] has been used. This software allows to resolve a non-linear problem when using magnetic field dependent properties of materials. The governing quantity of the calculation is the solution for the magnetic vector potential, $\vec{A}$, that fulfils the equation

$$\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{j}$$

where $\mu$ is the magnetic permeability and $\vec{j}$ the density of electrical current. The distribution of magnetic field is determined from the calculated $\vec{A}$ as $\vec{B} = \nabla \times \vec{A}$.

We assume $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m for both the free space and the superconductor. The permeability of SF is represented by the empirical expression

$$\mu_{SF} = \mu_0 \left[ \mu_{min} + \frac{\mu_{max}}{1 + \left( \frac{B^2}{B_0^2} \right)^2} \right]$$

containing four parameters to characterize the non-linear $B(H)$ dependence.

The only domain with non-zero current density $\vec{j}$ is the superconductor. According to our previous analysis \[15\], the anisotropic dependence of the critical current density in HTSC materials on magnetic field is reasonably described by the phenomenological expression

$$j_c(x, y) = \frac{j_{c0}}{1 + \left( \frac{k^2 B^2(x, y) + B_z^2(x, y)}{B_0^2} \right)^\delta}$$

that can be considered a generalization of the dependence proposed by Kim et al. \[16\]. When the local magnetic field parallel to the a-b planes of the HTSC, $B_\parallel$, causes less significant reduction of the critical current density than the component perpendicular to these planes, $B_\perp$, then $k<1$. 

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In the calculation, all the cross-section of superconductor, \( S_{SC} \), is filled with critical current density that obeys the expression (2). The critical current is then determined as

\[
I_c = \int_{S_{SC}} j_c(x, y) \, dx \, dy.
\]  

(4)

In this way, \( I_c \) can be calculated for the applied magnetic field with arbitrary orientation with respect to the tape wide face and hence the a-b planes of superconductor.

3. Critical current of Bi-2223/Ag tape with edges covered by Ni

The idea of covering the edges of a commercial Bi-2223/Ag tape by a soft ferromagnetic material was first published by Alamgir et al.[17]. We present here the results for the commercial tape [18] modified by a layer of nickel electrically deposited on the tape edges. The typical sample cross-section is shown in the left-side half of figure 1.

The properties of superconductor have been determined by comparing the calculated and measured values of critical currents for the original (uncovered) tape in magnetic fields from zero to 0.1 T in two basic orientations of magnetic field. Replacement of the filamentary superconducting structure by an elliptic core with effective current density re-scaled according to the fill factor reduces the computing time without a significant influence on the result, as demonstrated by Majoros et al. [19]. Following the procedure that in detail has been described in [20] it was found that the properties of the filamentary superconducting core of the tape can be represented by the expression (3) with the following parameters:

\[
j_0 = 1.64 \times 10^8 \text{ A/m}^2, \quad B_0 = 0.00382 \text{ T}, \quad \beta = 0.468 \quad \text{and} \quad k = 0.12.
\]

The properties of the Ni-layer have been investigated on a sample prepared by depositing a 10 \( \mu \)m layer on a 1 mm thick Ag sheet by the same procedure used for depositing the Ni-layer on the tape. When placed in parallel magnetic field in the SQUID magnetometer, the magnetization loop shown in

\[\text{Figure 1: Cross-section of the multifilamentary Bi-2223/Ag tape covered on edges by 10 \( \mu \)m thick layer of nickel (left half), and the geometry used for the finite element calculations (right half).}\]

\[\text{Figure 2: Magnetization loop measured at 77 K on the 10 \( \mu \)m thick Ni layer deposited on 1 mm Ag sheet by the same procedure as used to cover the edges of Bu-2223/Ag tape. Dashed line is the fit by the expression (2) with parameters given in text.}\]
Figure 3: Examples of the distributions of magnetic field (represented by the lines of constant vector potential) and the density of electrical current (darker area – higher density) calculated by the finite element method. The scales for both quantities are identical in two pictures. In the picture on the left hand side, the U-shaped coverings at the tape edges are considered as ferromagnetic. The picture on the right hand side is the reference case when non-magnetic cover was assumed. Properties of materials used in this calculation are given in the text, the magnetic field of 10 mT is assumed to be applied in the direction perpendicular to the tape wide face.

Figure 2 has been measured. Reasonable fit of the magnetic permeability can be achieved by using the expression (2) with the parameters $\mu_{\text{min}} = 1.5$, $\mu_{\text{max}} = 250$, $B_c = 0.38$ and $\gamma = 2.2$, as shown by the dashed line in figure 2. The effect of the ferromagnetic cover can be understood when comparing the left and right part of the figure 3, where the distributions of magnetic field and current density calculated for the tape with magnetic cover and the reference case with non-magnetic cover are placed side by side. It is clearly seen that diverting the magnetic flux from the sample edges creates larger zone with enhanced current density because of more favorable (parallel) orientation of magnetic

Figure 4: Calculated (lines) and measured (symbols) values of critical current obtained for the tape from figure 1, i.e. with 32 µm layer of nickel deposited at the tape edges leaving the central part of 1.9 mm width uncovered. Improvement of the critical current at low magnetic fields, predicted by finite element calculations (lines) is qualitatively confirmed by experimental data (symbols).
field. This results in the increase of critical current in both the principal orientations of the magnetic field (parallel and perpendicular, respectively), as shown by the full lines in figure 4. Experimental values of critical current obtained on the sample with the cross-section illustrated in figure 1 are in fair agreement with the prediction of the finite element calculation.

4. Effect of ferromagnetic substrate on the critical current of YBCO coated tape

Similar calculation as in the previous section can be performed also for the 2nd generation of HTSC tapes. We used the simplified geometry given in figure 5. Typically, the substrates of YBCO coated tapes are ferromagnetic at liquid nitrogen temperatures [21, 22]. In difference to the previous case of the Bi-2223 tape that was first investigated for its superconductor’s properties and afterwards the ferromagnetic layer was introduced, it is not possible to extract the properties of the YBCO layer itself, without the substrate, from the experimental data. On the other hand, the properties of substrates can be studied e.g on samples with superconducting layer mechanically removed. Then, the superconductor properties can be estimated indirectly, searching for the agreement between the calculated and measured critical current.

In the figure 6 present are the results of finite element calculations for a typical tape with \( w = 4 \) mm, substrate thickness \( h_{SF} = 100 \) µm and YBCO layer of \( h_{SC} = 2.5 \) µm. We assumed the substrate properties defined by \( \mu_{\text{min}} = 1.2, \mu_{\text{max}} = 30, B_{c} = 0.39 \) and \( \gamma = 2 \), and for the superconductor: \( j_{c0} = 1.13 \times 10^{10} \) A/m², \( B_{0} = 0.02 \) T, \( \beta = 0.6 \) and \( k = 0.3 \). There are two features worth mentioning in this graph: in difference to the edge cover, the ferromagnetic substrate generally lowers the critical current at low fields. Also, the parallel orientation yields two distinct cases: when the applied magnetic field and that

![Figure 5: Superconducting layer deposited on the substrate with soft ferromagnetic properties.](image)

![Figure 6: Dependence of critical current on two principal directions of magnetic field, calculated for a superconducting layer placed on soft magnetic substrate (dashed lines) compared with the result calculated for a non-magnetic substrate (full lines). Material parameters used in the calculation are given in text. For the parallel orientation of applied field, the case when the self-field in substrate sums with the applied field (indicated “parallel +”) results in lower critical current.](image)
one produced by the transport current itself are added in the substrate side, the depression of critical current is bigger than in the case when the fields in the substrate subtract.

5. Conclusions
We have found that the presence of a soft ferromagnetic material can significantly influence the critical current of typical conductors from high-temperature materials in magnetic fields below 50 mT. The performance of Bi-2223/Ag tape can be improved by 10 – 20% with the help of covering the tape edges by nickel. On the other hand, the ferromagnetism of substrate used to deposit the YBCO layer in coated conductors would generally lower the critical current in self-field conditions.

It is interesting, that for the parallel orientation of the applied magnetic field there are two cases to be distinguished. If in the space occupied by the ferromagnetic substrate the applied field is added to the field produced by the transport current, the critical current is quickly suppressed. On the other hand, the combination resulting in the subtraction of the applied from the self field results in the increase of critical current with applied magnetic field in certain field interval starting from zero. This effect should be properly taken into account when assembling tape conductors into cables.

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