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Physics Procedia 36 (2012) 1625 – 1630

Physics
Procedia

Superconductivity Centennial Conference

Current distribution in wide YBCO tapes

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Abstract

The need of a better mechanical behaviour and the stabilization of coated conductors for applications, as Magnets, cables or Fault Current Limiters, has motivated the lamination of tapes with stainless steel or copper alloys, increasing so the elastic modulus of the conductors and their mechanical performance. Some of the stainless steels used are magnetic, thus introducing some perturbations of the current flow when energizing the conductor. In order to detect these possible perturbations, the magnetic self field in the surface of the tape has been explored by Hall mapping technique at several current loads in a monotonically driven cyclic sequence. By increasing current steps when loading up, crossing the critical field threshold, and decreasing down to remanent state. Deviation from the expected magnetic map has been observed. In this work, we will report on the resulting measurements, and the current flow is calculated by solving the inverse problem for a 12 mm wide stainless steel reinforced Coated Conductor tape. We discuss on the likely origin of the observed perturbations.

Keywords: YBCO tapes, Hall mapping, inverse problem

1. Introduction

The application of the superconducting tapes at the commercial level in different devices requires a precise characterization of the electrical properties, and the magnetic, mechanical and thermal behaviour. Hall scanning microscopy has revealed as a powerful method for evaluation of HTS tape properties, including homogeneity at the millimetric scale, local evaluation of the current flowing through the tape and local evaluation of the critical current [1]. The development of the appropriate algorithms has allow also to perform these measurements at speeds so fast as 20 cm/s, speed that could be reduced by the bottleneck of the data acquisition to 2 cm/s with the designs in development. In the tapes which include

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doi:10.1016/j.phpro.2012.06.319

magnetic materials, however, these features can be affected by the magnetic contribution of such materials as is the case of the stainless steel lamination used to enhance the mechanical performances of some tapes. Works done concerning HTS tapes, partially coated with ferromagnetic material, demonstrated influence over the critical current [2] by modifying the magnetic field. This modification of the field distribution could affect the Hall measurements and also the values obtained. In the present work, we study the effect of this perturbation of the magnetic field, generated by the flowing current, on the precision of the calculated currents along a cycle from zero-field condition to saturation by achieving a current higher than the critical, closing the cycle by diminishing the current up to obtain the remanence condition.

2. Computation model

The current on the tapes has been computed using the discretization and inversion procedure of the authors [3,4,5] adapted to tapes as described in [1].

The measured stretch of tape is subdivided in a discretization grid of small rectangular elements, where the magnetization M is assumed to be constant. The discretization grid is completed with virtual elements to allow the closure of the current circuit achieving so the conditions of validity to apply the inverse problem solver [4,1]. In addition, at both ends of the measured we impose that the current flows parallel to tape along its axis [1]. The resulting variation of magnetic field is appreciable only at the ends of the measured tape, and the computed current map remains valid in the central stretch of the tape, away from its ends. The size of the lateral elements is large enough so that the circuit-closing current supported by them generates a magnetic field on the tape which is smaller than the resolution of the Hall probe. The inversion of the resulting linearized system yields values for the magnetization M and circulating current J, which are valid in the central section of the measured tape.

Successive, overlapping discretization grids with the same geometry can be used to cover any length of tape. The overlap between the successive discretization grids allow their central areas, where the current map is valid, to cover the entire tape. The use of the same geometry in all successive discretization grids allow the inversion of the linearized system for only the initial grid, and the resulting Moore-Penrose pseudo inverse matrix can be applied to solve all the subsequent linear systems. This piecewise, symmetrical approach allows the computation of current maps for tapes of any length, with a resolution of 0.25 mm (across the tape) x 0.5 mm (along the tape), at a typical speed of 20 cm/s using a PC computer [1].

3. YBCO tapes

Commercial grade YBCO tapes have been studied, with a width of 12 mm and 3 different structural configurations:

(a) A tape manufactured by American Superconductor, henceforth called "tape 344". It has an YBCO layer with thickness 1 μm, sandwiched between two layers of stainless steel soldered to the sides of the tape. Each stainless steel layer complete with solder has thickness of about 75 μm. The width of the superconducting layer is only 10 mm. At 77K has been found I_c= 210.7 A (1 μV/cm criterion).

(b) A second tape manufactured by American Superconductor, henceforth called "Amperium tape". It has a 1 μm thick YBCO layer, sandwiched like tape 344, but with a thinner layer of stainless steel and solder material so that total thickness of each stainless steel layer is 50 μm. The outer surface is therefore closer to the YBCO layer. At 77K has been found I_c= 248 A.

(c) A tape manufactured by SuperPower, henceforth called "SP0". Its structure is different from the two previous ones, and thinner: a 1 μm thick YBCO layer is covered above by a layer 3 μm thick of Ag, and supported below by a layer made of Hastelloy of 100 µm thickness, and a second layer of Ag 3 µm-thickness. At 77K has been found I_c= 313 A.

A stretch of about 16-17 cm of each tape was inserted in a transport current circuit by fixing the beginning and end of the tape to blocks of Cu. The tape was then dipped in liquid N_2 at 77K. The circuit was designed so that the current outside the tape was symmetrically distributed on both sides of the tape and far enough to avoid magnetic coupling with the tape. The explored area of the tapes is more than 3 cm far from the current feeding contacts.

The tape was subjected to a ZFC process, and a transport current was applied then to the circuit, with total intensity varying from zero to reach 3-5 times the critical field (1 µV/cm) crossing so the I_c threshold as warranty of full penetration. The distance between the contacts used to measure I_c and the blocks of current supply is always 2 cm or more. Then, the intensity was decreased to zero. The vertical magnetic field B_z was measured at different intensities throughout this cycle.

A Hall probe was rastered in parallel rows, crossing the tape, at a height of 80 µm above the tape surface, so the distance above the superconducting layer is: 140 µm in the 344, 130 µm in the Amperium, 86 µm in the SP0 tape. The probe had an active area of 100 x 100 μm^2, and the vertical magnetic field B_z above the tape was measured on each row with a steps of 5 µm. Typically the dimensions of the measured Hall maps are 40 mm x 50 mm (main axis), but maps up to 100 mm have been measured in some samples.

4. Magnetic field distributions and computed current distributions

Figures 1-3 show a typical magnetic map corresponding 344 samples. The measured magnetic field is not homogeneous along the axis of the tape. After full penetration, inhomogeneities are clearly revealed for the lower currents and in the remanent state (Fig 2).

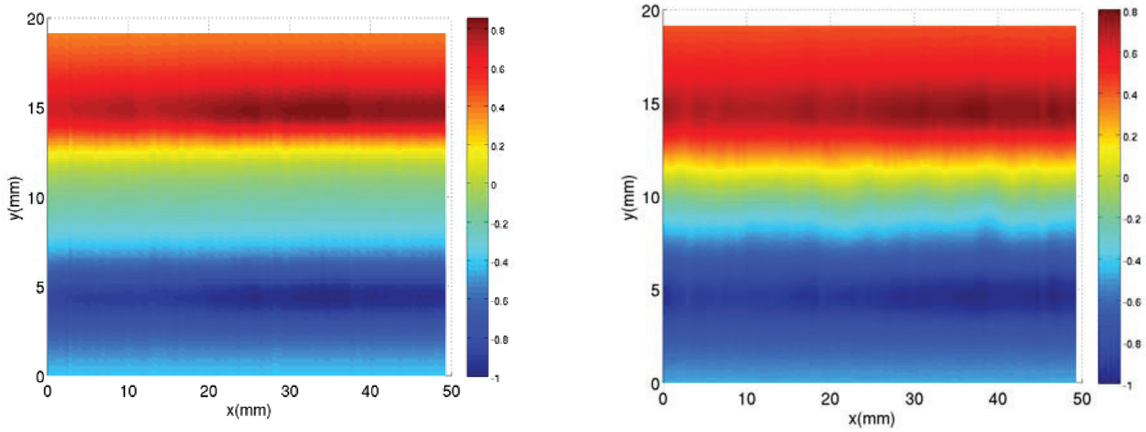

Fig. 1. Vertical magnetic field measured in the increasing current cycle, with an applied current intensity of: (left) 50 A, (normalized -1=-28G); (right) 200A, (normalized; -1=-87G).

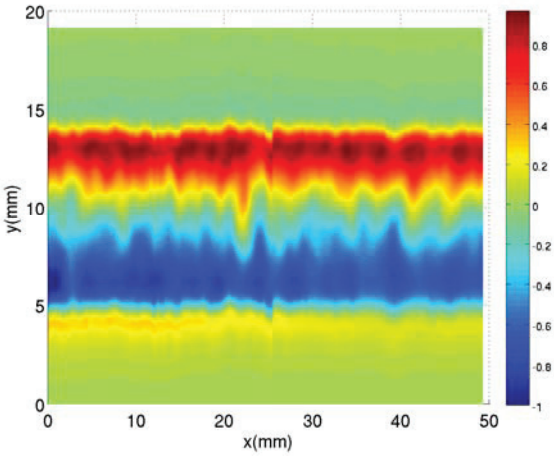

Fig. 2. Vertical magnetic field measured (normalized; -1=-39G) in the remanent state, after a current of 218 A was applied.

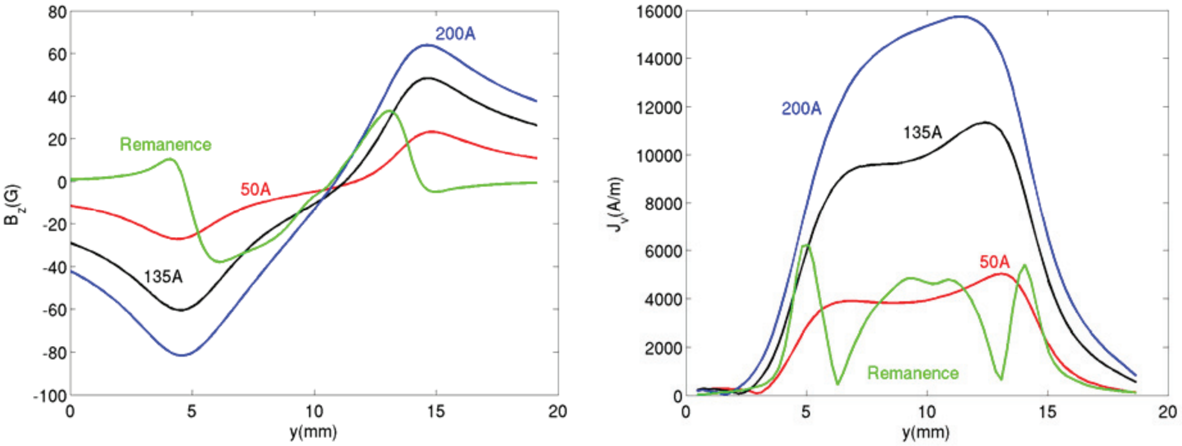

Fig. 3. (Left): Vertical magnetic field on a central cross-section of the tape 344 under different transport currents; (Right): Current density on a central cross-section of the tape under different transport currents

A maximal transport current of 218 A was reached. This is greater than the critical current supported by the tape which was found, with the 1 μV/cm criterion, to be 210.7 A. The calculated current density per width unit reaches a maximal value of 16535 A/m in the remanent state as shown in Fig. 2.

The computation of the map of currents, by Biot-Savart inversion of the measured magnetic field, shows a width density of current which is asymmetrical, higher on one side of the tape (Fig. 3).

The total intensity transported by this computed current map may be compared with the actual transport of current in the circuit. For a range of currents from zero to maximum applied current, the computed intensity of current has values which are 77-90% of the actual transport. The underestimation of the transported current is caused by the attenuation, due to the magnetic properties of the stainless steel layers, of the magnetic field generated by the current on the HTS tape.

The results in the Amperium tape (not shown here) reveal a measured magnetic field that is symmetrical and fairly homogeneous along the tape. The current map computed by Biot-Savart inversion of the magnetic field is also symmetrical, and the computed transport of current agrees with the measured transport within margins of error of 1-5%, the expected error margin of the computation.

Fig. 4 and 5 summarize the behavior of tape SP0. The field distribution of Fig. 4 (left) corresponds to a transported current of 300A, very close to the critical current supported by the tape, which has been found using the 1 μV/cm criterion to be 313A. The measured magnetic field is symmetrical and homogeneous along the tape axis, even in the remanent state (Fig. 4 right). Biot-Savart inversion of this magnetic field yields current maps which are also symmetrical, homogeneous along the tape axis, and the computed current transport agrees with the actual transport within a margin of error of 3-10%, attributable to the computational method.

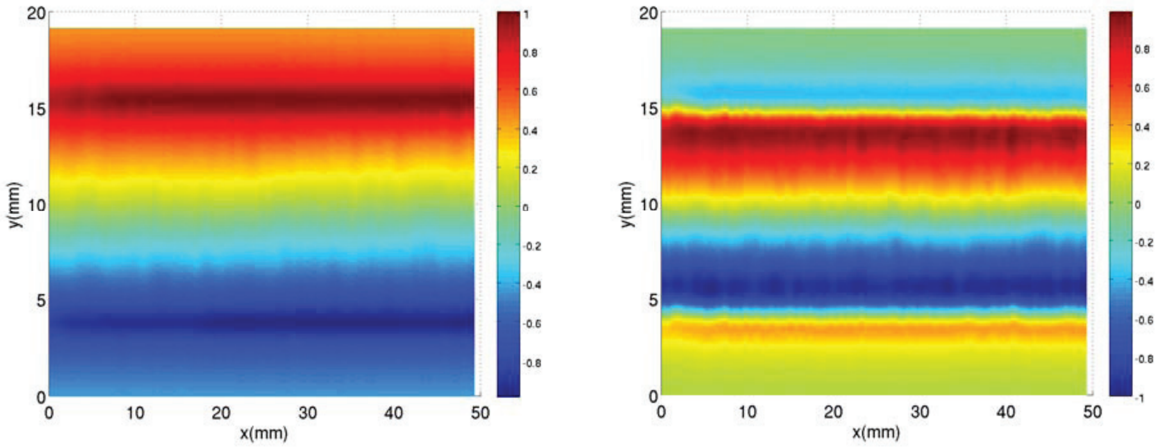

Fig. 4. Vertical magnetic field measured: (left) in the increasing current cycle, with an applied current intensity 300 A (normalized; 1=200G); (right) in the remanent state, after the application of a current transport up to 339A (normalized; -1=-88G)

5. Conclusions

The coating of HTS tapes with soldered layers of stainless steel susceptible to magnetization may affect the distribution of current and the magnetic field generated by the circulating current attenuating it and creating irregularities,. The latter effect results in undervaluation of the transported current when it is computed from the magnetic field by Biot-Savart inversion.

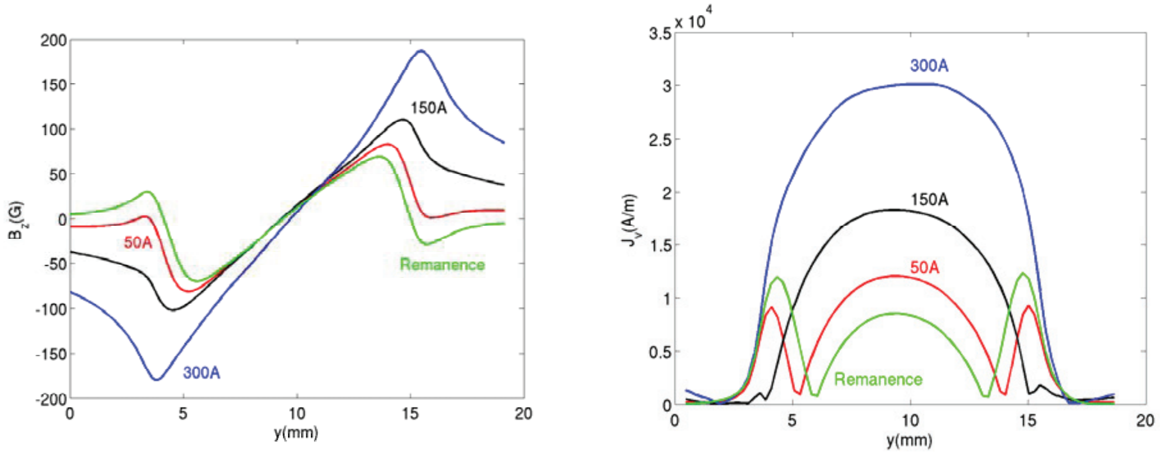

Fig. 5. (Left) Vertical magnetic field on a central cross-section of the tape SP0 under different transport currents, and in remanent state after cancelling the transport.(Right) Current density on a central cross-section of the tape SP0 under different transport currents.

Acknowledgements

We would like to acknowledge the support of Nanoselect project of the CONSOLIDER program, and EU-FP7-ECCOFLOW project, and Xermae.

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