Development and realization methods for the study of local magnetic and transport characteristics of the superconducting tapes

S.V. Pokrovskiy*, I.A. Rudnev, A.I. Podlivaev

"National Nuclear Research University "MEPHI", 115409, Kashirskoe shosse 31, Moscow, Russia

Abstract

It was developed and realized the method which allows carrying out a non-contact and non-destructive rapid testing of local magnetic and transport characteristics of the superconducting tapes. To investigate local transport characteristics we have to solve the inversion problem Biot-Savart-Laplas equation. We have developed the author's original numerical calculation algorithm. On the base of measurements of the spatial distribution of the magnetic field, induced by passing transport current through the tape we can calculate 2D distribution of the transport current. Such measurements provide a clear way to see the current path, identify weak areas of tapes, to evaluate the homogeneity of current flow and quality of the tape. Since our numerical algorithm is very fast, we can solve the problem of inversion in real time mode. In addition, we have made program for reel to reel system of investigation local transport properties of a long HTS tapes. Proposed method has no specific binding to a model, and the spatial resolution is limited only by the experimental method, which is measured spatial distribution of the magnetic field. There is only one limitation – two-dimensional current flow in the samples.

1. Introduction

Nowadays high-temperature superconductors (HTSC) are increasingly used in various areas of technology. The current level of production allows to a number of companies to produce long-length HTS
tapes with high transport characteristics [1,2]. However, the inhomogeneity in magnitude of the critical current $I_c$ along the length of the tape remains one of the unsolved problems [1].

Magnetometric approaches to study the critical current inhomogeneity in the HTSC film mean inducing currents with values, close to the critical. Then we determine the topology of magnetic field induced by these currents and current paths, including areas with low critical current. The electric current in the samples as can be induced by contact [3] and non-contact [4] methods. In the contact method we pass transport current through the sample. In the non-contact method, the current in a superconductor induced by an external magnetic field.

The most common algorithms enable us to obtain two-dimensional restoration technique of superconducting current (SC) distribution. These techniques need the results of the local measurements of induced magnetic field [4-8]. Determination of the superconductive current is based on the inversion of the Biot-Savart-Laplace equation.

There are two possibilities for studying of currents in the SC tape by the non-contact method. In first case, sample is placed in an external magnetic field, while in second case we study the remanent magnetization of the sample after removal of the magnetic field.

In this paper, we present algorithms for reconstruction of the current distribution in HTS tapes for non-contact and contact methods. The results of applying these techniques to the study defects in the second generation HTSC tapes are discussed. The second method is more interesting. In that case we assume that the tape is removed from the field source which gave rise to screening currents.

2. Two recovery algorithms of the current distribution from the spatial measurements of magnetic induction

2.1. The algorithm for determining the current distribution, induced by the external field in HTS tape

We consider that the tape is removed from the field source which induced screening currents. The external field is zero. To determine the currents in the tape the measurement of the only component $B_z(X,Y)$ of the magnetic field is sufficient. The current in this case is determined up to a constant (uniform current flowing in the plane $Z = 0$ does not affect the field component $B_z(X,Y)$, [8]). If the lines of current flow in the HTS sample are closed (that takes place in case of the remanent magnetization), the usual method of determining $X, Y$ components of the current is a preliminary determination of the density of the magnetic moment of the film $g(X, Y) = (g_x, g_y, g_z)$ [3], followed by determination of the currents by (1):

$$j = \nabla \times g$$  \hspace{1cm} (1)

For the film we assume $g_x = g_y = 0; g_z = g(X, Y)$ [4]. In order to find the solution, an artificial smoothing is needed, which can suppress the high harmonics of the required function after Fourier transformation of the equations [5]. This can be done by using of the smoothing approach proposed by A.N. Tikhonov [9], where the filter function can be represented as:

$$W(k) = \frac{\tilde{K}^2}{\tilde{K}^2 + (k/k_{max})^2}$$  \hspace{1cm} (2)

$k_{max}$ - the regularization parameter. Taking into account the filter function, expression for the Fourier transform of the magnetization can be written as:
\[
\tilde{g}(k_x, k_y) = \tilde{B}(k_x, k_y) \cdot W(k) \left( \mu_0 \tilde{K}(k_x, k_y) \right)
\]  \hspace{1cm} (3)

After a two-dimensional inverse Fourier transform this equation defines the coordinate function \( g(X,Y) \). According to (1), numerical differentiation of this function gives a current distribution in the sample.

The advantage of the non-contact algorithm is that it allows us to investigate not only the good samples, but samples of poor quality. If the studied sample is heterogeneous and strongly superconducting regions in it does not overlap, the algorithm based on the residual magnetization reveal find out the areas of the superconducting phase in this sample. Whereas the contact methods of measurement based on the current flowing through the sample does not give any results. However, if we study the HTS tape of good quality and the critical current in it is almost homogeneous, non-contact detection algorithm for characterization of a tape loses its attraction. This is due to the fact that the magnetization of HTS tapes in its central part has areas of complete screening of the external field at any amplitude of a magnetic field \([10]\). Obviously, in full screening areas the non-contact algorithm is not able to express all characteristics of SC tape. If transport current passes through the tape it will pass through the entire cross section of the tape. This means that the central region of tape will also be available for detection.

### 2.2. Algorithm for determining the transport currents in HTS tape

If the HTS tape has a high enough quality (uniformity of current characteristics along width and length), SC currents in the tape are induced preferable not by magnetic field but by using of an external current source with current terminals. The current distribution in the tape is reconstructed from a single component of the magnetic field \( B_x(X,Y) \). In \([8]\) an algorithm is given which allows to determine both current components \( j_x, j_y \) from the components of the field \( B_x(X,Y) \) without the intermediate determination of the magnetic moment. In the contact algorithm, we use the magnetic moment, representing the total current in form of a sum of closed currents and a uniform background current flowing through the film plane. The amplitude of the background current is selected so that the total current is zero outside of SC tape.

A comparison of numerical errors of the presented algorithm with one described in \([8]\) show the advantage of using of the first one. Results were obtained for the test non-superconducting sample with known configuration \([7]\).

We note an important fact that must be considered in determining whether defects in the film. For SC tapes, current characteristics of which depend only on the transverse coordinates \(X\), the induced current in the contact and noncontact method and will only have component \( j_x \). Therefore current component \( j_x \) is an indicator of a local defect. We carry out detection of defects in SC tapes through the image of level lines for values \( j_x(X,Y) \).

### 3. Experiment

#### 3.1. Methods of measuring the spatial distribution of magnetic induction

Experimental measurements of the magnetic field are produced by the Hall magnetometry. This was done by scanning of the region of space above the pre-magnetized HTS tape \([6,7]\) with mesh size \( \delta = 0.5 \) mm for the coordinates \((X,Y)\). The height of placement of the Hall sensor above the film coincided with the mesh size. In all experiments we use HTS tapes of second generation with a copper cover.
3.2. Test measurements

Before conduction the measurements we want to estimate qualitatively how the current distribution looks for two types of defects: a crack running from edge to center of the tape and non conductive inclusion. A $J_x(x,y)$ near the crack has two extremes (maximum and minimum) which are shifted relative to each other along the center line of the tape. Lines of level of the $J_x(x,y)$ in this case have concentric close-ended form and they are located on opposite sides of the crack. The $J_x(x,y)$ near non-uniform inclusions has four extremes (two maxima and two minima). The level lines of $J_x(x,y)$ in this case are similar to a flower with four petals. We carried out tests using a copper tape with two holes and two edge cuts. The results confirmed the correctness of our approach (Fig. 1).

![Fig. 1. Level lines of the current across the copper tape with artificial defects](image1)

3.3. Indications of cracks and heterogeneous inclusions in SC tape

In the research we are interested in types of defects (e.g.: crack or non-uniform inclusion or low-conducting region) and their forms. Figure 2 show the distribution of current component along the tape of the remanent magnetization of SC tape of second generation in the copper shell of width 1 cm, obtained by a non-contact method.

![Fig. 2. Distribution of current components along the tape of the remanent magnetization SC tape](image2)
The current distribution given in fig. 2 is typical for SC tapes [4]. Closed inducted current is antisymmetric relative to the equator and equal to zero on it. The fuzzy boundaries of current location in the tape are the result of smoothing, required for solving the inverse problem of the Biot-Savart.

There are obvious inhomogeneities in the current flow in the tape as can be seen in fig. 2, but it is difficult to identify the type of the defect visually. In this case the contact method can be applied. The distribution of current components for a transport current of 110 A, is given in figures 3a, 3b, and it is typical for the SC tapes [3]. Here the current flows also in the central part of the tape, showing its inhomogeneity, but the visual identification of these irregularities is complicated. Observation of the current defects in the tape best of all perform by current level lines components $J_x(x,y)$.

Another important element of our methodology is the studying of $J_x(x,y)$ for different values of the transport current flowing through SC tape in the contact method. Cracks extending from the edges of the tape to the center are shown up at any values of transport current. The inhomogeneous inclusions appear only when the current flowing through the tape reaches a critical value for low-conducting region.

This allows us to find the cracks in the tape at low currents. The appearance of structures with four "petals" at certain values of transport current determine the location and the critical current of the low-conducting inhomogeneous inclusions. The size of defects can be obtained from the distance between the centers of "petals". On the Fig. 3c one can clearly see five points of the cracks (three at the top and two at the bottom of the tape) and one low-conducting region. Transport current was 110 A.

![Fig. 3. Distribution of transport current components of the SC tape. Transport current is 110 A. 3a – component along the tape, 3b – component across the tape, 3c - Level lines of the current component across the SC tape (transport current is 110A)](image-url)
The lengths of these cracks are approximately equal to $1 \div 2$ mm. The local current inhomogeneity was observed on the left side in the middle of the tape (Fig 3). It should be noted that it appears when the transport current is above 80 A. Critical current of the tape is 300A.

4. Conclusions

This contribution describes the methods to determine two-dimensional distribution of current in a HTSC tape from the spatial distribution of magnetic induction. It is shown that the contact method has two major advantages. Firstly, it reveals the most weak sections (i.e. sections, preventing the transport current) of the SC tape. These weak sections are revealed when the value of the transport is current is significantly less than the critical. Secondly, the method allows determination of the type and parameters of the defects in the tape. We demonstrate the possibility of determination and identification of various current defects in the HTSC tape.

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