Development and realization methods for the study of local magnetic and transport characteristics of modern nanostructured superconducting materials

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Abstract. It is well known that the Hall probe magnetic imaging represents a powerful technique for the investigation of the magnetic field distribution in nanostructured superconducting materials of many different types and geometries. We present a new method of the evaluation of current distributions in thin nanostructured superconducting tapes and films from the data of two-dimensional magnetic field profiles measured over the sample surface. We have analyzed the different conditions of magnetic flux trap of external magnetic field and the magnetic field distribution of a superconductor at the flow of transport current. Based on the standard algorithm was developed original method of non-contact investigation of local transport properties of modern nanostructured superconducting materials.

1. Methods
The superconducting tapes were investigated in two modes: the penetration and trap of an external magnetic field, the flow of transport current. Using method of local Hall magnetometry were obtained the 2D spatial distribution of trapped magnetic flux or field component of the transport current perpendicular to the surface of the tape $B_z(x,y)$. On the basis of these data is possible to calculate the spatial distribution of currents corresponding to the magnetic field.

The solving of this problem is resulted in the inversion of Biot–Savart law. We have analysed standard approaches of solving the problem [1] and have developed a new modified calculation algorithm 2D distribution of supercurrents in thin superconducting tapes and films [2].

The new algorithm of calculation allows correct solve inversion problem using experimental data of the magnetic field only over the sample, whereas standard algorithm requires that the scanning area of the field was several times larger than the size of the sample. In addition, optimal filter input data allows to detect the inhomogeneities of current flow which typical dimensions on the order of magnitude lower step of the experimental grid scanning the magnetic field.

2. Materials
Have been investigated various modern high-temperature superconducting tapes based on nanostructured thin films of superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10-\delta}$. 

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3. Results
Tapes of various architecture and characteristics, both new and earlier used have been investigated. In this paper we demonstrate only the most typical observed experimental data and the corresponding calculations.

Figure 1 show the distribution of trap magnetic flux in HTS 2G tape and restored surfaces of currents (across and along the tape see figure. 2,3). Architecture of the tape: substrate Ni-5%W alloy (deformation texturing), buffer stack Y$_2$O$_3$/YSZ/CeO$_2$ (~75 nm, high rate reactive sputtering), YBCO (~1 μm, metal organic deposition of TFA), Ag (DC sputtering).

![Figure 1](image.png)

Figure 1. a) distribution of trap magnetic field in high-temperature superconducting tape b) distribution of magnetic field generated by transport current in high-temperature superconducting tape

The magnetization surface profile corresponds to the Bean model. Note that magnetic flux distribution displays moderate inhomogeneity which corresponds to the inhomogeneity of the current distribution in the tape. Surfaces of currents distribution testify to the circular course of the induced currents.

Let's consider separately components of the current along ($J_y(x,y)$) and across the tape ($J_x(x,y)$) (figures 2). Distribution $J_y(x,y)$ non-uniform, that in turn results in nonzero distribution $J_x(x,y)$. That is owing to imperfection of the tape, non-homogeneity of its properties, arise overflows of currents, flows (appearance of nonzero component of the current across the tape). Similar results have been received for other tapes. Also, results were obtained in the mode of transport current flow (figure 3).

Analysis of the results allows us not only describe the homogeneity of the magnetic and transport properties that determine the quality of the finished tape or tapes on the stage of production, but also to determine the fault location and area of redistribution and the flow of current (current domains) in the superconducting tape, by which one can conclude about the defectiveness of tapes, and also to find a region with small current-carrying characteristics. These regions lead to the decreasing of the critical current of the tape, and modern data falling current-carrying capacity can reach 30% [3].
In addition, our method allows to study a local characteristics of current-carrying superconducting tapes during the flow of transport current. Similarly carry out the spatial distribution of the magnetic flux, but induced by passing transport current through the tape. Such measurements provide a clear way to see the current path, identify weak areas of tapes, to evaluate the homogeneity of current flow and efficiency of the superconducting tape.

Figure 2. Spatial distribution of the current components a) \( J_y(x,y) \) – along the magnetized superconducting tape, b) \( J_x(x,y) \) – across the magnetized superconducting tape

Figure 3. Spatial distribution of the transport current components a) \( J_y(x,y) \) – along the superconducting tape, b) \( J_x(x,y) \) – across the superconducting tape

The 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 component perpendicular to the plane of current flow. There is only one restriction – it can be studied objects with
a two-dimensional current flow. Such a limitation follows from the possibility of a correct solution of the inversion problem Biot-Savart-Laplas equation. For today we carried out measurements using the Hall probe as a sensor of magnetic field. As a result of accurate testing and work through the entire procedure it can be possible to detect the region of current flow (defect HTSC film) an order of magnitude smaller then the sensitive area of the Hall probe.

Our approach can be implemented not only with respect to HTS films, but also to other nanoobjects with two-dimensional current flow. On the redistribution of current flow one can conclude about, for example, the presence of defects or damage to the object of research. Moreover, using magnetic atomic force microscope will allow to explore the processes of percolation and redistribution of power in the objects of nanoscale.

4. Conclusions
It was developed a noncontact method for investigation of local transport characteristics of modern nanostructured superconductors.

The calculation method allows us investigate any nanoobjects with two-dimensional current flow.

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