The published version of this preprint appeared in IEEE Transactions on Applied SupercondThis ASC 2012 manuscript 3MPQ-03 was submitted to IEEE Tr

Field mapping for characterization of superconducting tapes, as a function of the position and magnetic flux density

J. Leclerc, K. Berger, B. Douine, and J. Lévêque

***Abstract*—We propose a useful contactless method for the characterization of superconducting tapes. It consists of imposing a constant flux density to a tape, with the use of permanent magnets. A magnet assembly measuring 500x50x10 mm^3, which can impose to the tape a flux density varying from 7 to 180 mT, with an inhomogeneity smaller than 3%, was used by us. The superconductor being cooled at zero field, currents are induced in the conductor. A map of the flux density is then measured over the tape, using a Hall effect probe mounted on an x-y-z table. Using these measurements and with the help of an inverse problem calculation, the distribution of the current flowing through the tape can be computed. This operation has to be repeated for different applied flux densities, by varying the distance between the tape and the magnets, in order to obtain the field dependence of the current distribution. The result will allow the tracking of any defects in the superconductor, as well as their field dependence. Moreover, by fitting measurements by a current distribution model, a value for the critical current density can be obtained, as a function of the flux density and of the position on the tape. This method has been tested experimentally on an YBaCuO tape of 300 mm length. The main advantage of this method is that it cannot only detect eventual defects in superconducting tapes, but it can also quantify them and their field dependence can be obtained.**

***Index Terms*—characterization, current distribution, inverse calculation, magnet, superconductor, tape.**

I. Introduction

THE quality control of superconductors after their fabrication is of high importance for their producers. Particularly during the fabrication of superconducting tapes of great sizes, it is often the case that a defect is localized on one segment of the tape. The manufacturer has to verify therefore the quality and the capacities of the tapes he produces, before sending them out to the clients. The control method has to be, obviously, a nondestructive one. This is why we propose a useful contactless method for the verification and characterization of superconducting tapes. It allows the determination of the current distribution in the tape, as a function of the magnetic flux density B and of the position on the tape x. The method consists in imposing a constant flux density to the tape. The superconductor being cooled at zero field, currents are induced in the conductor. A map of the flux density is then measured over the tape. From these measurements and thanks to a numerical calculation (inverse calculation), the distribution of the current flowing through the tape is obtained. By fitting the result by a current distribution model (for example the "Bean model"), we get a value of Jc as a function of x. The operation is then repeated for different applied flux densities and the field dependence of Jc is obtained. A $Jc(B, x)$ characteristic is thus obtained. We also compared our results with those obtained by using the traditional method of the current transport measurement. Our method has the advantage of not only detecting defects in superconducting tapes, but also of quantifying them. Moreover, a field dependence of the current distribution is obtained.

Manuscript received October 4, 2012.

The authors are with the Groupe de Recherche en Électrotechnique et Électronique de Nancy - EA 4366, Université de Lorraine - BP 70239, 54506 Vandoeuvre-lès-Nancy Cedex, France (e-mail: julien.leclerc@univ-lorraine.fr; kevin.berger@univ-lorraine.fr; bruno.douine@univ-lorraine.fr; jean.leveque@univ-lorraine.fr).

II. Presentation of the method

A. General description

Our new method rests on field mapping. It consists in measuring a map of the flux density in the proximity of a superconducting tape, which has a current flowing inside. Then, using a calculating method called "the inverse calculation", the distribution of the current is computed. To ensure that the method is contact-free and so non-destructive , we chose to use a magnetic field to induce currents in the tape. The superconductor is cooled in zero field (far from the magnets), then brought in the vicinity of the magnets. Currents, aiming to expel the magnetic field, start circulating in the tape. A map of the flux density of size n by m points is then measured, with the help of an Hall effect probe, set up on an x-y-z table. m and n are respectively the number of points measured in the width and in the length of the tape (Fig. 1). Only the component Bz of the flux density perpendicular to the tape is measured. Bz, represents the sum of the induction Bz_m, produced by the magnets and of the one produced by the tape Bz_t. A 1D inverse calculation is then performed. For this, the superconducting tape is supposed to be infinitely thin. We therefore consider that it is traversed by a surface current density expressed in A/m. In this article, surface current densities will be denoted as j (in lowercase letters), in contrast to the areal current densities, which will be marked as J (in uppercase letters). Each line of measures (Fig. 1) will be treated independently. For each line, we dispose of the measurement of Bz, as a function of y. Let us consider the line of measures situated in $x = x_i$. The inverse calculation allows determining, starting from $Bz(x_i, y)$, the value of j_x as a function of y, marked as $j_x(x_i, y)$, with j_x being the x component of the current density flowing through the tape.

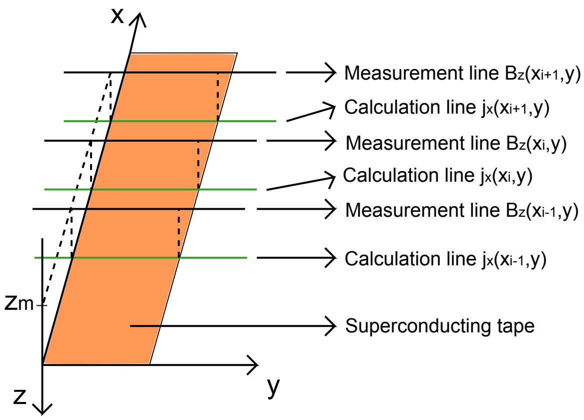

Fig. 1. Representation of the measurement layout.

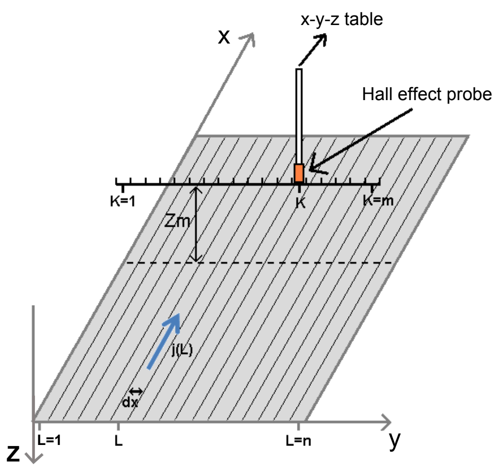

Fig. 2. Representation of the grid used for the inverse calculation.

The curve $j_x(x_i, y)$ is then fitted using a current repartition model. jc being a parameter of the model, we obtain a value of jc, at $x = x_i$. The operation is repeated for each measure line, that is for each value of x_i. A $jc(x)$ characteristic is thus obtained.

B. The Inverse Method

The inverse calculation is a very important part of our method. It allows calculating the distribution of the current in the tape, starting from the measurement of the flux density. We used the method described in [1]. The calculation area is divided, according to y, in m rectangles of width dy and of infinite length, as shown in Fig. 2. We will assume that, in each rectangle, there is a current flowing, which is constant and oriented along x. The induction $B0z(k, l)$ produced by the current circulating in the rectangle located at $y = y_l$ on the point located in $y = y_k$ and in $z = Zm$, can be calculated thanks to the Biot-Savart law (1).

$$B0z(k,l) = \frac{j(l)}{10^7} ln \left(\frac{(y_k - y_l - \frac{dy}{2})^2 + Zm^2}{(y_k - y_l + \frac{dy}{2})^2 + Zm^2} \right) \quad (1)$$

$$B0z(k,l) = j(l)f(k,l) \quad (2)$$

The total flux density Bz at the point located in $y = y_k$ and in $z = Zm$ can be calculated thanks to (3).

$$Bz = \sum_{l=1}^{m} j(l)f(k,l) \quad (3)$$

We can write the system on a matrix form:

$$\begin{bmatrix} Bz(1) \\ Bz(2) \\ ... \\ Bz(n) \end{bmatrix} = \begin{bmatrix} f(1,1) & f(1,2) & ... & f(1,m) \\ f(2,1) & f(2,2) & ... & ... \\ ... & ... & ... & ... \\ f(n,1) & ... & ... & f(n,m) \end{bmatrix} \begin{bmatrix} j(1) \\ j(2) \\ ... \\ j(m) \end{bmatrix}$$

$$\mathbf{Bz} = \mathbf{f}.\mathbf{j} \quad (4)$$

To obtain the repartition of the current in the superconductor, we just have to reverse the matrix $\mathbf{f}$ and to multiply it by the vector $\mathbf{Bz_t}$, which is built on the basis of the effectuated measurements. $\mathbf{Bz_t}$ is obtained by subtracting $\mathbf{Bz_m}$ to $\mathbf{Bz}$. To determine $\mathbf{Bz_m}$ two methods are available to us. The first is to perform a measurement of the flux density without superconducting tape. So the measured field map corresponds to $\mathbf{Bz_m}$. The second solution is to approximate $\mathbf{Bz}$ by a 5th order polynomial. This polynomial is then considered equal to $\mathbf{Bz_m}$. We tested both methods and shown that they are equivalent. We chose to use a 5th order approximation. Indeed, this method is faster because it does not require further measurements. However, it is not possible to inverse directly $\mathbf{f}$. As a result, the problem is ill posed, and $\mathbf{f}$ is not well conditioned. This is why we have chosen to regularize the system, by using the well-known Tikhonov regularization [2], [3]. The choice of the regularization parameter was made via the classic method of the plot of the ”L curve”.

C. Experimental apparatus

The experimental apparatus is composed of three parts: the permanent magnets which impose the magnetic flux density to the superconducting tape, the support for the tape and the flux density measurement system. We placed 5 NdFeB permanent magnets of size of 100x50x10 mm^3 each, side by side and installed them on an iron plate, to build an assembly with a surface of 500x50 mm^2. They allow imposing a flux density varying from 7 to 180 mT to a superconducting tape long of 300 mm, all with an inhomogeneity of less than 3%. The superconducting tape is fixed on a G11 epoxy plate and covered with a plastic sheet. Everything can be moved vertically, for varying the distance between the tape and the magnets in order to change the flux density imposed to the tape. The flux density mapping system is, for its part, composed of an Hall effect probe, fixed on an x-y-z table. This system achieves a spatial resolution of 2.5 µm and has a flux density precision measurement which is less than 0.1 mT. The Hall effect probe is encapsulated in a small Teflon cube. This cube is in contact with the plastic sheet during the measurements. This allows maintaining the Zm distance constant.

The published version of this preprint appeared in IEEE Transactions on Applied SuperconThis ASC 2012 manuscript 3MPQ-03 was submitted to IEEE Tr

Fig. 3. Comparison between the theoretical curve of the current distribution (j_{th}) and that obtained by inversion of the flux density map (j_{calc}). The j_{calc} curve corresponds properly to the j_{th} curve despite some undulations due to the regularization.

III. Validation of the Method

In order to verify the accuracy of the method, we chose to effectuate 2 tests: a theoretical one, to validate the inverse calculation method and an experimental one, to test the method's efficiency on real measures.

A. Validation of the inverse calculation method

In order to verify the inverse calculation method, we presupposed a certain pattern of the currents repartition in a conductor (Fig. 3). We calculated the flux density which this current should produce, using the Biot-Savart law, on the Hall effect sensor at an altitude of $Zm = 420$ µm. We added a noise of ± 10 µT to this result. The obtained result, noted as $Bz(y)$, represents a theoretical measure. The advantage of disposing of a theoretical measure, contrary to the real measure, is that we know precisely the repartition of the current that we aim to determine, by using the inverse calculation method. Hereby, we will be able to check the efficiency of the method. The obtained result by inversing $Bz(y)$ is presented in Fig. 3. The result is satisfying. As we can notice, the inversed curve corresponds properly to the curve we were searching for. Some undulations appear due to the regularization.

B. Validation of the experimental method

The experimental validation of our method was effectuated by imposing a transport current I_{tr} to a superconducting tape, using a power supply. The flux density map was measured with our experimental device and the repartition of the current was calculated with the help of the inverse method. By integrating this result along the width of the tape, we can obtain the value of the current I_{inv}. It is therefore possible to evaluate the correct operation of our method, by comparing I_{inv} to the value of the imposed current I_{tr}, which was effectively flowing through the tape. The experimental tests were made at 20, 40, 60 and 80 A, at increasing current, and then at 60, 40, 20 and 0 A, at decreasing current. Results of the field inversion are presented in Fig. 4.

Fig. 4. Current distribution inside a YBaCuO tape subject to different transport currents.

TABLE I
Comparison between the values of the current imposed experimentaly to the tape and the values obtained after inversion of the flux density map

	Increasing current			
Imposed current (A)	20	40	60	80
Current obtained by inversion (A)	17.7	35	53.5	73.9
Difference (%)	11	12	11	7
	Decreasing current			
Imposed current (A)	60	40	20	0
Current obtained by inversion (A)	56.3	38.4	19.9	1.8
Difference (%)	6	4	0.5	

Firstly, we can note that the repartition of the current is close to the one obtained by the theoretical calculations, in [4]. The shape of the center of the curve is almost identical to the theoretical calculations. However, on the edges, the constants flat parts which should appear are missing.

In order to verify the values of current obtained with our method, the table I allows comparing the values of I_{tr} and I_{inv}. We note that the values are close one to another. The biggest difference is of 12%, which is very acceptable. We can therefore conclude that this method allows us to obtain an accurate value of the current flowing through the superconducting tape.

IV. Test of the Method

A. Description of measurements made

The method has been tested on an YBaCuO tape of 300 mm long, 4 mm wide and cooled into liquid nitrogen. Measurements were carried out on the 200 mm located at its center in order to overcome the sides effects (in the inverse calculation, the tape is assumed to be infinite). The resolution in the length direction is 10 mm, which corresponds to 21 measurement lines . Each measurement line has a length of 60 mm with a resolution of 0.1 mm, which corresponds to 601 measurement points per line. Measurements were made for tape-magnets distances equals to 47.5, 77.5 and 107.5 mm, which corresponds to imposed flux densities to the tape B_{app} equals to 38, 18 and 10.5 mT, respectively.

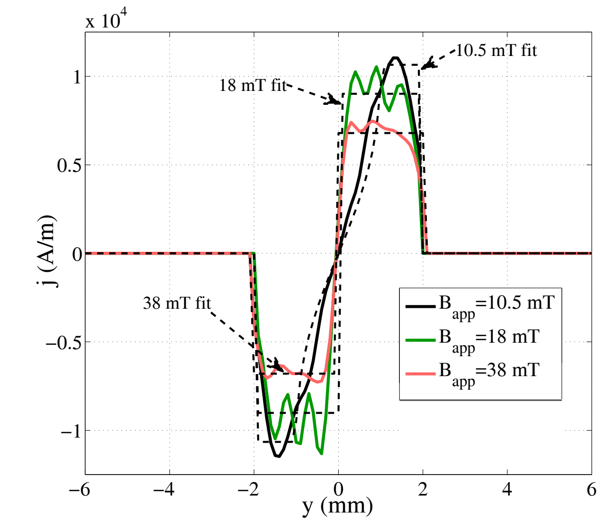

Fig. 5. Distribution of the current induced in the superconducting tape by the permanent magnets for different applied flux densities.

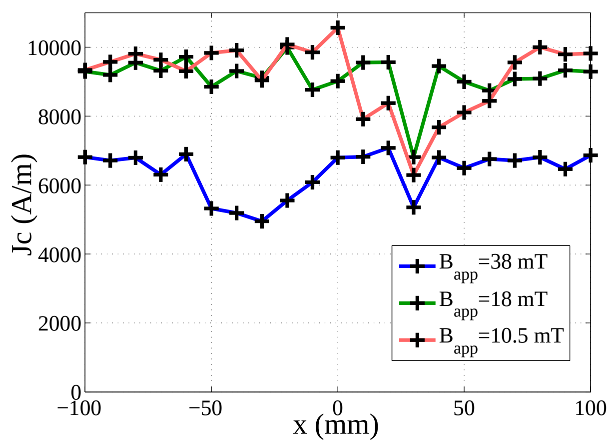

Fig. 6. Critical current density, for differents applied flux densities, as a function of the position on the tape.

B. Experimental results

The plot of the current distribution for the calculation line located at the middle of the tape is shown in Fig. 5. We can see that for the measurements performed at B_{app} = 18 and 38 mT, the current has completely penetrated the superconductor. This is not the case for the measure at 10.5 mT where the current has only partially penetrated. We also note that the curves obtained have the same shape as those obtained by Brandt, in theoretical calculations [4]. In addition, the current value decreases as the applied magnetic flux density increases. This is due to the decay of the critical current when the flux density increases. Due to the complete penetration of the current, curves at 18 and 38 mT have been fitted by a constant $j = \pm jc$. The curve measured at 10.5 mT has been approximated by the results of the calculations of Brandt [4], because these ones takes into account the incomplete penetration. Fits of curves are shown in Fig. 5. This operation was carried out for the 21 measurement lines. This allowed us to determine $jc(x)$. The results are shown in Fig. 6.

We note that, overall, the critical current density decreases with the increase of the flux density. Some points do not satisfy this assertion, between curves at 10.5 and 18 mT. One possible explanation for this is presented later in this section. Moreover,

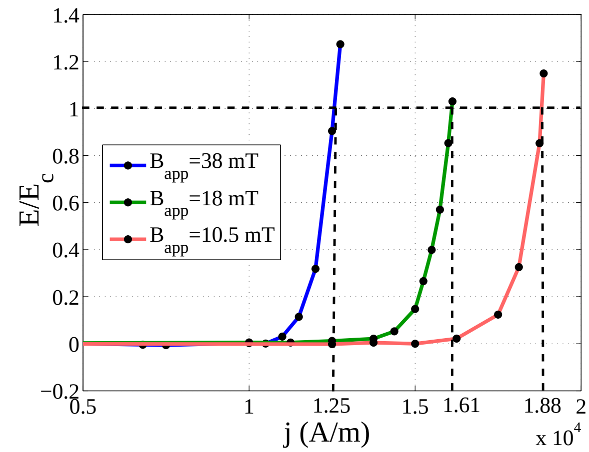

Fig. 7. Normalized electric field as a fuction of the current for differents applied flux densities. These curves were measured by the current transport method.

we note that the critical current density strongly decreases at $x = 30\ mm$. This decrease appears very clearly in the three curves. So we are in the presence of a defect in the superconducting tape.

To check the results, we performed a measurements of jc by the transport current method (Fig. 7). We note that the values obtained by this method are much higher than in our new method.

We assumed that the behavior of the superconductor corresponds to the Bean model (Brandt calculations are based on the Bean model), but this is not exactly the case. The critical current density is usually defined as the current density required to obtain an electric field of 1 μV/cm. This value is an arbitrary criterion. However, in our new method, we are never considering this criterion. The definition of the critical current measured by our method is rather ”the maximum current that can flow through the tape for a few hours (time of measurement) without observable atenuation”. The fact that the tape does not respond well to the Bean model can also explain that some value of jc at 18 mT are superior to those at 10.5 mT. Indeed, it is possible that two reactions are opposed. As the flux density is increased it is plausible that the value of the currents flowing in the tape increases, while penetrating further into the tape. But at the same time, the value of the critical current decreases. So we see a gradual increase of the current at low flux densities, until the decrease of jc becomes predominant and decreases the value of the currents. This explanation is an assumption and has to be verified.

V. Conclusion

We developed and implemented a new method for measuring the critical current of superconducting tapes. This one, in addition to being contactless, allows to measure the critical current density as a function of the position on the tape. It is based on the measurement of a map of the flux density and on an inverse calculation. Permanent magnets were used in order to induce currents in the superconductor. However, we shown that the critical current density obtained does not satisfy the usual criterion of 1 μV/cm. This method has been tested on an YBaCuO tape and allowed us to detect a defect in it.

VI. Acknowledgement

We wish to thank F. Grilli from KIT for the courtesy of having provide the YBCO tape used in our experimentations.

References

[1] T. Johansen, M. Baziljevich, H. Bratsberg, Y. Galperin, P. Lindelof, Y. Shen, and P. Vase, "Direct observation of the current distribution in thin superconducting strips using magneto-optic imaging," *Physical Review B*, vol. 54, no. 22, pp. 16 264–16 269, Dec. 1996.

[2] G. H. Golub, P. C. Hansen, D. P. O'Leary, and Dianne, "Tikhonov regularization and total least squares," *SIAM J. Matrix Anal. Appl*, vol. 21, pp. 185–194.

[3] R. Kress, L. Kuhn, and R. Potthast, "Reconstruction of a current distribution from its magnetic field," *Inverse Problems*, vol. 18, no. 4, pp. 1127–1146, Aug. 2002.

[4] E. Brandt and M. Indenbom, "Type-II-superconductor strip with current in a perpendicular magnetic field," *Physical Review B*, vol. 48, no. 17, pp. 12 893–12 906, Nov. 1993.