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Magnetic Mapping, a way to test and understand current flows in thin and bulk superconductors.

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Abstract. Nondestructive testing of superconducting blocks and thin films is a worth point in their development and their industrial production. The most intrinsic characteristic to be tested is the critical current, so is the maximum current can be carried in the superconducting state. The measurement of the current flowing through the samples could be done by direct transport experiments but this means using specific samples, and only the mean current may be found. Distribution of current density in the sample is more relevant because it yields the map of in-homogeneity of the samples, and its effect in the current density distribution.

Magnetic measurements have been developed by Hall scanning and magneto-optical effect, allowing the mapping of the component of the magnetic field perpendicular to a surface of the sample created by the current distribution. By solving the inverse Biot-Savart problem a map of current densities can be obtained. We will present the status of the magnetic measurements obtained by exploring superconducting bulks and tapes magnetized by an external field and the magnetic map generated by the current carried through superconducting wires.

Introduction

The great expectancy for applications that the HTC superconductivity has opened in the last 20 years, has involved a great effort to produce materials of quality enough to meet the requirements of applications. Manufacture of large and homogenous bulk pieces and wires for electro-mechanics, has posed a great challenge, due to the opposition between the poor mechanical properties of ceramics and the requirements of shape and working. The electrical and magnetic behaviour of the superconducting elements is mostly related with their microstructure, which should be highly distorted by defects, leading to a conflict between mechanics and electromagnetics, between a brittle structure full of defects thus producing a highly stressed microstructure, which on the other hand must have a good mechanical behaviour when high magnetic fields are being applied.

From the point of view of electromagnetics, such a highly inhomogeneous material becomes difficult to predict due to the fact that currents can flow only through well connected paths, and the effect of the magnetic field depends strongly on the type and the distribution of defects or grain structure.

The determination of the electromagnetic behavior of the SC parts is then necessary to investigate the correlation between defects and current distribution, their effectiveness as pinning centers, and also in order to give an adequate certification of the pieces when in production.

Direct measurements of transport currents allow the direct characterization of the intrinsic parameter J_c, critical current density, as well its dependence on the magnetic field or its behaviour in the flux flow regime. However, the direct determination of J_c is suitable only for geometrically

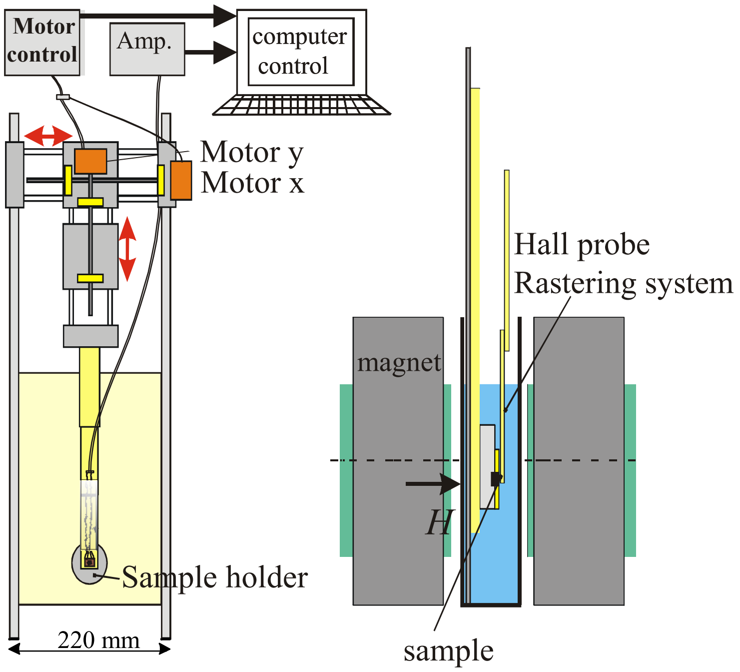


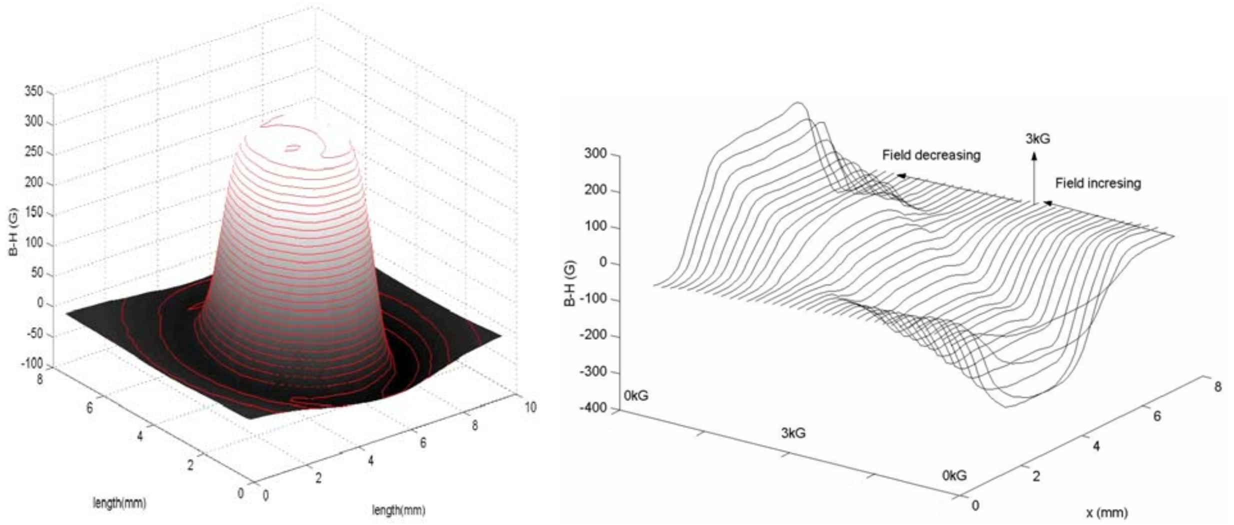
Fig. 1 Sketch of the In Field Sacnning Hall Microscope

simple samples which can support contacts [1] or can be inductively coupled for non contact measurements [2]. For standard samples, this characterization is difficult and usually requires the destruction of the sample, being so very useful only to characterize small bridges made in selected parts of a sample but not applicable as a method to determine the current distribution in a large part of the piece.

Exploration of the electromagnetic behaviour can be done in several ways depending on the range of the applied field and spatial resolution required.

Magneto-optical effect has been extensively used in order to explore the distribution of the modulus of the magnetic field in the surface of samples when an external field is applied, allowing the study of the field penetration in the samples, thus giving a picture of the microstructure near the surface of the sample[3]. The fast response, the high resolution in the range of that of the optical microscopy, are contrasted by the low field saturation of the garnets and the non linearity of the response, which requires systematic calibrations to obtain numerical data.

Hall effect probes are very suitable alternative also largely used. They can sense the field in the direction perpendicular to their sensing areas with a very large dynamic range, from some hundredths of mT up to several T, with a very acceptable linearity. They are used to perform maps of the flux density of the magnetic field by scanning the surface of the superconducting part to be tested [4]. The system can be used for characterization of large pieces, with measurement time as the limiting factor for resolution.



a/ b/

Fig. º2. a/ Hall map of the magnetic contribution of a YBCO ring subjected to an external field of 400G after cooled at zero field. b/ Profiles of cross secction of the Hall maps along a magnetization cycle with H=0...3...0 kG.

The aim of the present work is to show how the magnetic characterization by mapping can easily provide useful information about the superconducting pellets and large pieces, in operating conditions, when subjected to both external fields and transport currents.

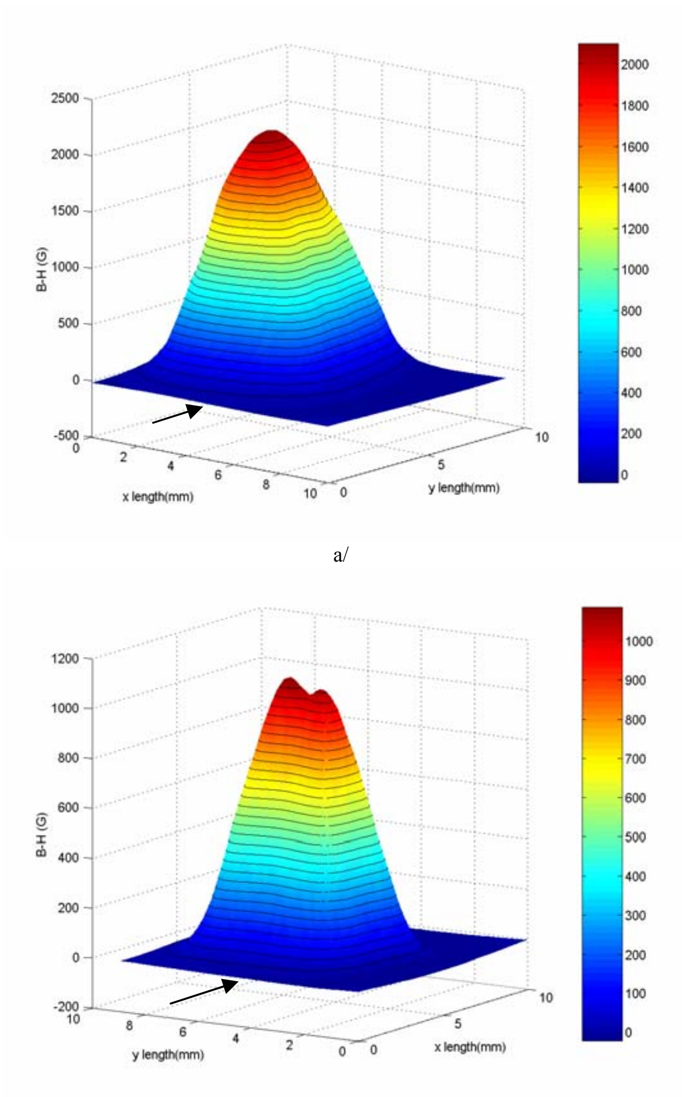
Hall measurements system.

Hall measurements are habitually performed by scanning a hall probe over the surface of the sample to be explored by means of a XY cartesian displacer wihich defines the mechanical resolution of the scans. The magnetic field measurements performed over sample in the superconducting state produce a large difference of temperatures between the sample and the XY displacer. This thermal gradient produces thermal expansion unstabilities which affect to the distance between the sample and the Hall probe. The correction of these introduces a third degree of freedom in the scanner: a third movement, Z, should be considered to compensate any possible misalignements or displacement of the plane of the sample with respect to the XY scanning plane.

A way to simplify the Z correction is just to perform a raster with the probe in contact, lightly pressed, over the surface of the sample, maintaining its sensitive area at a constant distance.

We have built a Hall Mapping Magnetometer for standard characterization and research of the magnetic behaviour of our superconducting samples. The Hall probe is attached to a XY displacer giving a picture of the field after the XY scans are performed. The Hall probe can be selected according to the adequate resolution for the experiment to be performed. The most common has been a THS118 modified in order to diminish the distance between the sensing area and the surface of the sample. It has been adjusted to 80μm. The raster is performed on a XY basis with a pitch of 160μm. The measuring mesh can be made more dense but the limit is fixed by the measuring window of the probe: meshing finer than 100μm requires deconvolution of the window function after measurements and, in fact, only increases the spatial resolution if the noise is smaller than the value of the event to be detected averaged to the window area. For the high resolution measurements it is necessary to consider probes with smaller sensing area, which can be already found, and also maintain or diminish the distance to the surface of the sample.

The sample holder is included in the gap of a magnet, as is sketched in Fig. 1, which can produce a magnetic strength of $H=8x10^5$ A/m allowing a measuring area of $40x40mm^2$.



a/

b/

Fig. °3 3-D representation of the Hall maps of remanence corresponding to welded samples. a/: The critical current of the joint is almost the same than that of the blocks. b/: the critical current of the joint is reduced

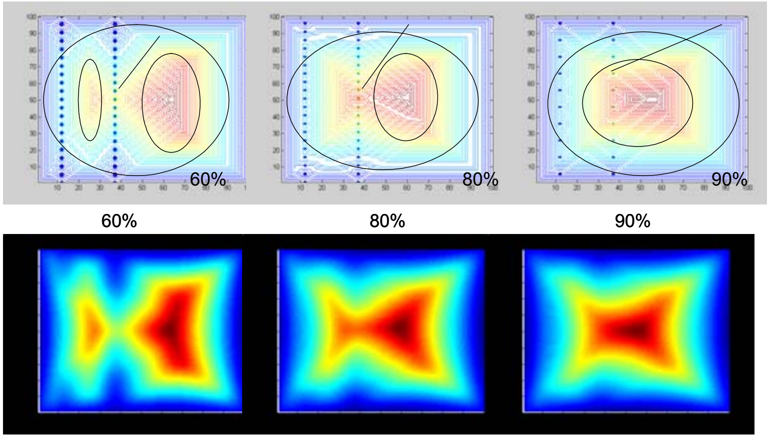


Fig.º4 Simulation of boundaries. In each case, two boudaries are considered, doted lines, with a critical current of 60, 80 and 90% of that of the blocks. Up: the current paths permform inner loops if the boundaries saturate. Down: corresponding magnetic map

Measurements.

Magnetization cycles. The In Field Hall Mapping allows measuring the penetration of the magnetic field in the sample along a magnetization process. In order to show the contribution of the sample we represent in the magnetic maps the difference of the field measured over the explored surface and the applied magnetic field. Fig.º2 shows the magnetic profile generated by the trapped currents in a YBCO ring of an outer-inner diameters of 5mm and 3mm, respectively. The thickness of the ring is 0.5mm. In the figure, the field map corresponds to an external field 400G. When the field is changing (Fig. º2 b), we can detect the redistribution of the trapped field as in the Bean framework, from zero field condition up to the remanent state. Defects or inhomogeneity can be deduced from the deviation of the ideal distribution of currents created in the sample by the external field.

Remanent state

In Fig. º3, a second situation is shown. Two samples have been made by superconducting welding of two YBCO blocks. Both figures show the Hall map in the remanent state, after field cooling with an external field far away of full penetration field (H*). The figures show the difference of the current distribution in both profiles. The first appears (Fig.º3 a) homogeneous with the symmetry corresponding to currents flowing around the sample with no indication of the weld just marked by the arrows. The counterpart can be found in the Fig. º3 b. The profile show clearly two peaks, each one showing the presence of a loop of current which corresponds to each block welded, thus revealing the joint as lower critical current zone.

Simulations agreeing this picture can be done in the Bean framework. In Fig.º4 we can observe the distribution of current loops generated in a system of superconducting material with two joint boundaries, with the constrain of maximizing the area. Neglecting the current dependence on the magnetic field, the corresponding field picture is shown just below each current distribution. The joints of each have been considered of poorer quality so allowing carrying only a 60, 80 and 90 % of the full current. In the pictures we consider only a thin sheet of material so introducing a high shape factor that produces some convexity in the magnetic flux density distribution. The boundaries produce loops of current when they saturate, thus inducing the peaks configuration of the magnetic map. The angle between the current paths and the boundary is also characteristic of the critical current ratio between that on the boundary and the corresponding one in the superconducting block.

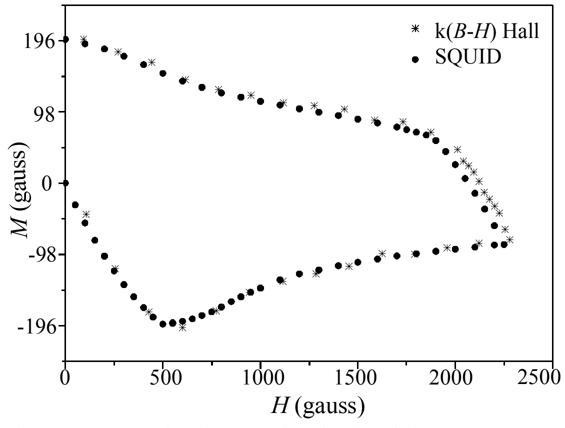


Fig. º5 Magnetization cycle obtained by a SQUID magnetomenter and that obtained by Eq. º1 The correspondence of both is obtained with k=1.

Magnetization.

From Hall measurements of contribution of the sample to the magnetic field ($B-\mu_0H$), we can approach the value of the magnetization by a number proportional to the average of the field over the surface of the sample:

$$\overline{B} - \mu_0 H = \frac{1}{S}\iint \left[B_z(x,y) - \mu_0 H\right]dxdy \qquad (1)$$

where S is the area of the surface of the sample.

In Fig º5 we can find both, the value suggested by Eq.º1 and the standard measurement of the magnetization in a conventional magnetometer. They agree well in shape [5], thus suggesting the proportionality between both, which depends on the shape of the sample but not on the magnetic field. In case corresponding to the ring of Fig. º2 the factor is just 1.95. Hall Mapping allows so performing measurements of the magnetization of large superconducting parts which otherwise cannot be made.

Current distribution

It is also possible to calculate from the Hall map the value of the currents flowing through the superconducting sample, by solving the so called Inverse Problem. It means to solve the Biot–Savart law for currents. A solver has been developed in our group [6] to obtain the current distribution on the basis that only currents flowing in the raster plane XY could be considered and their densities are constant along the Z axis. The map should cover all the area where the currents flow. The assumptions could be not completely fulfilled, but in general are in good agreement with the standard situations. A complete discussion of the procedure can be found at [7]. The software is available for public use at [8].

The Inverse Problem solver allows deeper researching of the behaviour of superconductors. It gives a deeper knowledge of the defects, inhomogeneity or external interactions.

Welding

Characterization of welding of superconducting ceramics requires the determination of the critical current through the join. Hall measurements allow the determination of the current in the joint and also the current in the original bulks. In Fig.º6 we report on the results of the current distribution obtained by solving for currents the Hall map of two welded samples A and B (see Fig º6). The map of currents shows clearly the enhancement of the current path just in the junction. This enhancement corresponds with a diminishing of the current density. In sample A the joint saturates and the current of each block closes in a loop which generates the peaks of the magnetic field map (upper left). Sample B shows a better quality joint which does not saturate, carrying almost all the current induced in both blocks. From the current maps we can distinguish the critical current in the joint, J_c^{GB}, and the current in each grain, J_c^{G}, the ratio J_c^{GB}/ J_c^{G} is the figure of merit of the weld it is of 0.7 for sample A and 0.96 for sample B.

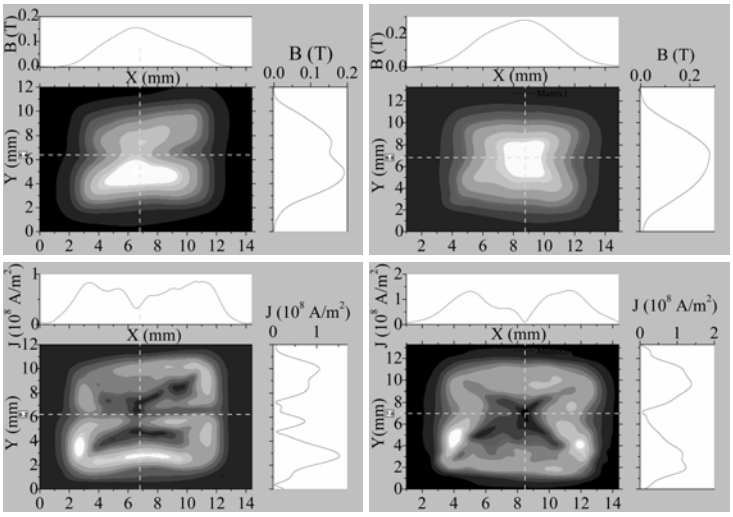


Fig. º6 . Magnetic maps corresponding to a sample A (upper left) and a sample B (upper right). By Inverse Problem calculations we obtain the distribution of current density modulus, shown below. The junction corresponds to the drawn horizontal line.

Tapes

Research on coated superconducting tapes requires a characterization of the current distribution along the tape when carrying current. Losses modelization is strongly dependent on it. The current distribution is also affected by the field existing on the environment, produced by other conductors as in cables. In Fig. º7, a

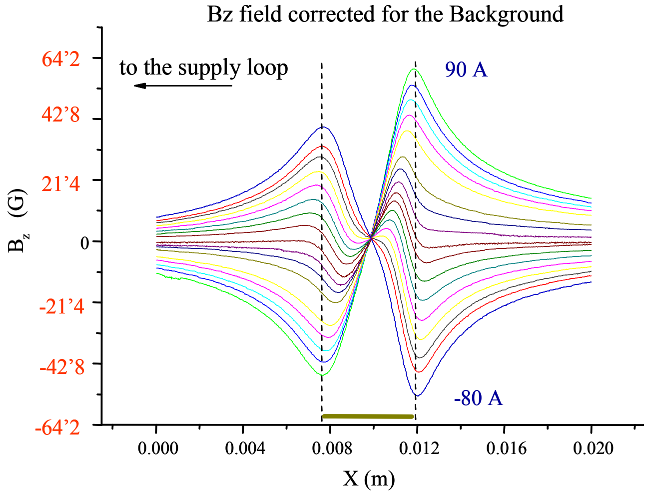


Fig. °7 Bz distribution along a tranversal line over a Coated Superconducting tape of 4mm width (see text)

set of hall measurements is shown. The tape is loaded up to 110A, nearly the quench current, and then the current is reduced by steps of 10A down to zero and reversed up to -80A. The sample is also subjected to the magnetic field created by the powering loop which introduces an asymmetry because the different distance from both parts of the tape and the differences between the field sense. At each step a Hall scan has been performed. We can observe de four peaks structure corresponding to the trapped field when the current is smaller than that of the full penetration of the magnetic self-field. The remanence is also observed at the central line when the current applied is zero. The set of profiles allows the computation of the losses and also the influence of the external field in cable design.

Summary

The combination of simulation in critical state models, the Inverse Problem solvers and the Hall measurements is a very powerful tool for characterization and research of the behavior of superconducting samples and parts. They allow the determination of the magnetization under an external field or by the self-field when carrying current, the determination of the effects of external fields in the distribution of currents, and also of the perturbations in the current distribution induced by defects or inhomogeneities due to the material or the design of the shape of the Superconducting parts.

The drawback is the time required to perform the Hall measurements, but there are reasonable expectations to lower it by improving the sampling rate and the displacers. An effort to optimize the sampling process should be also made.

References

[1] X. Granados, T. Puig, J. Teva, E. Mendoza and X. Obradors, IEEE Trans. Appl. Supercond., vol. 11, 2001, p.2406.

[2] Spyker, R.; Kozlowski, G.; Oberly, C.E, IEEE Trans. on Mag., vol 27. 1991, p.1093

[3] Ch.Joos, J.Albrecht, H.Kuhn, S.Leonhardt and H.Kronmüller, Rep.Prog.Phys. 65, 2002, p.651.

[4] F. Frangi, L. Jansk, M. Majoros and S. Zanella, Physica C 224, 1994, p. 20

[5] X. Granados, S. Sena, E. Bartolomé, A. Palau, T. Puig, X. Obradors, M. Carrera, J. Amorós, and H. Claus, IEEE Trans. Appl. Supercond., vol. 13, 2003, p. 3667.

[6] J.Amorós, M.Carrera, X.Granados, J.Fontcuberta, X.Obradors, in Applied Superconductivity 1997, Inst. of Phys. Conf. Series No. 158, 1998,p. 1639.

[7] J. Amorós, M. Carrera, X. Granados, S. Iliescu, E. Moreno, B. Bozzo, and X. Obradors, EUCAS proceedings 2005, to be published.

[8] Caragol program is available at http://jaumetor.upc.es/caragol