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Non-destructive assessment of the critical current density in large superconducting pellets

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Abstract
We present a new method of rapidly determining the local critical current density (J_c) in large superconducting pellets without destroying the sample. We show that magnetoscan data averaged over a certain small sample area can be mapped directly onto absolute values of J_c. This conclusion and the corresponding calibration curve are based on results from magnetoscan and from SQUID measurements of the same sample regions, which were found to show an excellent correlation. Numerical simulations help to extend the calibration curve, to improve the resolution of the method and to reduce possible errors.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Large superconducting pellets based on $ReBa_2Cu_3O_{7-\delta}$ (Re-123, with Re = Y, Sm, Gd, etc) can carry high remanent magnetic fields of up to 3 T in liquid nitrogen [1] (77 K) and up to 17 T at lower temperatures [2]. Accordingly, such materials have a high potential for many applications, e.g. by replacing conventional permanent magnets in motors or transformers, as magnetic bearings, flywheels, magnetic separators, NMR (nuclear magnetic resonance) devices, etc (see e.g. [3]).

The remanent trapped field (B_{tr}) of a magnetized superconducting pellet is usually measured by a Hall probe slightly above the sample surface. Various kinds of cracks and inhomogeneities usually impede the current flow and reduce B_{tr} considerably, but details of these inhomogeneities do not show up in the field map. Therefore, the assessment of the local critical current density (J_c) is often done by SQUID measurements of small samples cut from different regions of the large pellet. Such a procedure is not only time consuming, but also destroys the pellet. A faster and non-destructive method is therefore highly desirable.

The magnetoscan technique [4–6] allows investigation of the local properties of large superconductors near their surface without destroying them and has been used to detect inhomogeneities and cracks (e.g. [7–9, 6, 10]). In this paper we will show that the absolute values of the magnetoscan signal, averaged over a small sample area, can be used for a fast and non-destructive determination of the local J_c in the pellets. It is obvious that the new method does not reproduce the entire information from SQUID measurements (i.e. J_c versus the magnetic field B) but reveals J_c near the surface at a certain low field value, which is sufficient for characterizing the samples in most cases. To demonstrate the method and acquire a calibration curve, SQUID and magnetoscan results from the same sample regions are compared. Further aspects, especially the resolution and possible errors, are discussed with the help of numerical simulations.

The sample used for the experiments was a Y-123 superconductor with a transition temperature of about 92 K. The pellet has a cylindrical shape with a diameter of about 25 mm and a height of 10 mm and was produced by a top seeded melt growth process [3, 11]. The trapped field in the remanent state has a maximum of about 0.65 T at 77 K and indicates a single grain sample.

2. Magnetoscan

Magnetoscan data were obtained in the following manner (see figure 1). The non-magnetized sample is cooled in liquid nitrogen (77 K). A small cylindrical permanent magnet (with a diameter and height of 2 mm and a remanent polarization of 1 T) is installed in the sensor-head, which is placed slightly

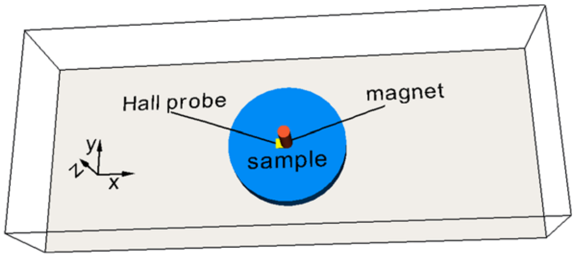

Figure 1. Sketch of the experimental setup.

above the sample surface, and induces a local current flow in the superconductor. The magnetoscan signal (B_m) is the z component of the magnetic field of these local currents measured by a Hall probe, which is attached to the bottom of the sensor-head, i.e. between the magnet and the sample. The field map—$B_m(x, y)$—is obtained by moving the sensor-head over the whole sample surface. Further details on the setup and other aspects of the technique are presented in [4] and [5].

Figure 2 shows the result—$B_m(x, y)$—of the magnetoscan. The distance between the Hall probe and the sample surface was kept at 0.13 mm and that between the magnet and the sample at 1 mm, leading to a maximum applied field ($\mu_0 H_a$) of about 0.15 T at the sample surface. The penetration depth of the currents into the sample follows roughly [5] $\Delta z \simeq H_a/J_c$ which leads to $\Delta z \simeq 1 - 0.1$ mm for typical J_c values between $1 - 10 \times 10^8$ A m^{-2} at 77 K in such samples.

First, we point out that a one-to-one correlation between the field map ($B_m(x, y)$) and $J_c(x, y)$ is not expected, since B_m reflects not only the absolute values of the currents, but also the stray field effects, e.g. peaks in B_m at cracks or defect boundaries caused by an abrupt change of J_c [5]. Thus the signal has to be averaged over some small sample area. Actually, all currents in the sample contribute to B_m at a certain point, but since the signal (B_m) is recorded very close to the sample surface (0.13 mm) only currents within a radius similar to that of the permanent magnet contribute significantly to the field value, as shown in [5]. Accordingly, B_m should be averaged over an area with a diameter comparable to that of the magnet—which is 2 mm in our case. The white rectangles drawn in figure 2 indicate the areas, over which B_m was averaged. They have a dimension of roughly 2×2 mm^2.

3. SQUID

To confirm that the magnetoscan signal averaged over a small area ($\langle B_m \rangle$) can be mapped onto J_c and to acquire the corresponding calibration curve, J_c was evaluated from SQUID measurements. The SQUID samples were cut from the large pellet in such a way that their surfaces agreed exactly with the marked areas, over which B_m was averaged (see figure 2). For each SQUID sample, J_c was calculated from Bean's model for rectangular samples, i.e. $J_c = [m_i/\Omega] \times [12a/(3ab - b^2)]$, where $a \simeq b \simeq 2$ mm are the surface dimensions and $c \simeq 1$ mm is the height, along which the field was applied, $\Omega = abc$. The irreversible magnetic moment m_i was acquired from a field loop at 77 K in the SQUID. This led to J_c values

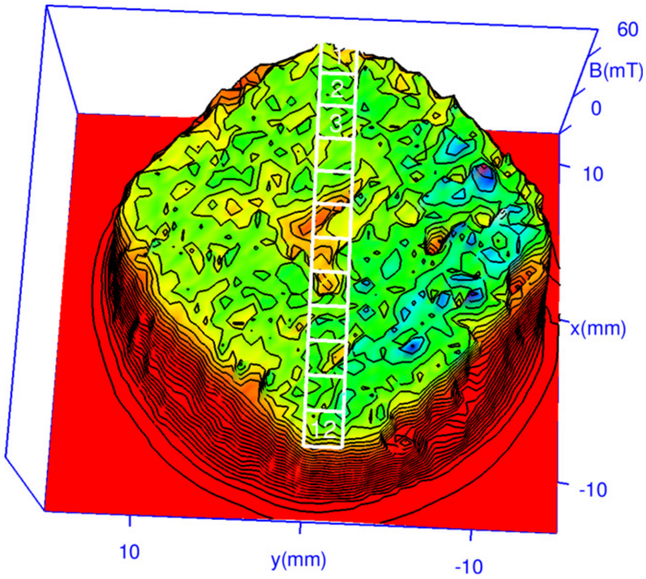

Figure 2. Results of the magnetoscan. The areas labeled by consecutive numbers 1, 2, . . . , 12 mark the areas, over which the magnetoscan results were averaged, and from where the SQUID samples were cut out.

from about 3 to 5×10^8 A m^{-2} in the remanent state. Note that this method works only for single grain SQUID samples.

4. Comparison

Figure 3 demonstrates the good correlation of magnetoscan and SQUID data from the same sample region, when the SQUID J_c is evaluated at 0.15 T, i.e. the maximum applied field during the magnetoscan. Note, that the magnetoscan signal near the sample edge is strongly affected by the electromagnetic boundary conditions. Thus to ensure that the boundary of the pellet does not influence our study, the first two areas at each edge (i.e. numbers 1, 2, 11, and 12) were omitted. Plotting $\langle B_m \rangle$ versus the J_c of each area leads to the calibration curve, which is a monotonously increasing function, as shown in figure 4, and thus maps $\langle B_m \rangle$ unambiguously on J_c. Note that J_c from the SQUID data is averaged over the whole (SQUID) sample volume, whereas the magnetoscan signal is mainly determined by currents close to the surface. Moreover, the penetration depth of the currents in a magnetoscan experiment is smaller ($\simeq$0.3–0.6 mm in our experiments) than the height of the SQUID samples (1 mm). Thus some scatter in the $\langle B_m \rangle$ versus J_c correlation is expected, but a resolution much better than 1×10^8 A m^{-2} for J_c is easily achieved (see figure 4), which is better than usually needed. If future measurements of $\langle B_m \rangle$ reveal data points beyond the available interval, the calibration curve can always be extended by new SQUID experiments, but the curve can also be extrapolated using numerical simulations.

5. Simulation

The principles of simulating a magnetoscan measurement were introduced in [5]. It was shown that solving Maxwell's

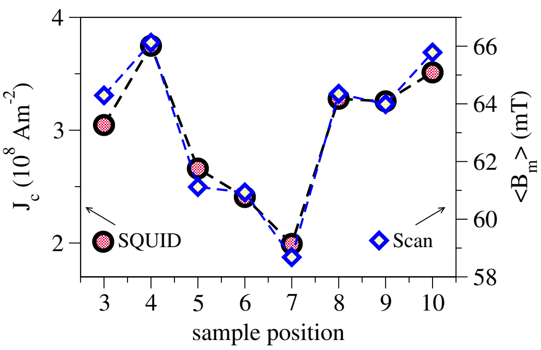

Figure 3. J_c from SQUID and $\langle B_m \rangle$ from magnetoscan measurements as a function of sample position. The sample positions correspond to the marked areas of figure 2.

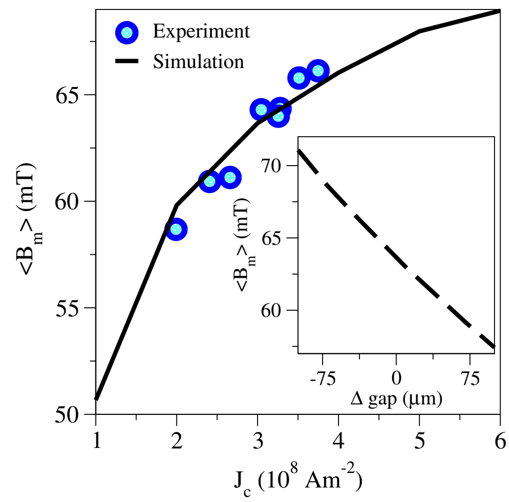

Figure 4. Calibration curve ($\langle B_m \rangle$ versus J_c) from experiment and simulation. The inset illustrates the effect of changing the distance between the sample surface and the Hall probe (Δ gap) at $J_c = 3 \times 10^8$ A m^{-2} (Δ gap = 0 refers to a distance of 0.13 mm).

equations in a three dimensional system and representing the superconductor by the well known power law for the electrical field: $\vec{E} = E_c (J/J_c)^n \vec{J}/J$ (E_c denotes the electric field criterion and J the local current density) leads to the time evolution of the local current distribution during the magnetoscan. Calculating the magnetic field of that current distribution at the Hall probe position reproduces the experimental magnetoscan results quantitatively. All necessary parameters are known from experiment, so that the equilibrium magnetoscan signal can be calculated for different values of J_c. The results are shown by the solid line in figure 4. We find excellent agreement with the available experimental data, which gives confidence in the results also beyond this interval.

The simulations show that the resolution of the method, which is basically the slope of $\langle B_m \rangle$ as a function of J_c (i.e. $d\langle B_m \rangle / dJ_c$) deteriorates with increasing J_c, which is expected and mainly reflects the reduction of the current penetration depth. There are different ways of increasing the slope and thus improving the resolution as demonstrated by simulations [5]. For instance, changing the gap between the Hall probe and the sample surface from the standard 0.13 mm by ±0.1 mm would shift the slope at $J_c = 3 \times 10^8$ A m^{-2} from 3.15 to 3.5 (for a gap of 0.03 mm) and to 2.9 mT/(10^8 A m^{-2}) (for a gap of 0.23 mm). The benefit of a smaller gap becomes more significant at higher critical currents. Another possibility is to increase the applied field, either by reducing the distance between the magnet and sample or by using a stronger magnet. The higher field leads to a larger current penetration depth and therefore to a larger magnetoscan signal and a larger slope, e.g. from about 3 to 9 mT/(10^8 A m^{-2}) at $J_c = 3 \times 10^8$ A m^{-2} when the applied field is doubled. Moreover, repeating the magnetoscan experiment in various applied fields reveals the field dependence of J_c.

We point out that the calibration curve is only valid when the parameters of the setup are not changed. It is most important to keep the gap between the sample surface and the Hall probe constant, since the magnetoscan signal is highly sensitive to a variation of this value as shown in the inset of figure 4. For instance, increasing the gap accidentally from 0.13 to 0.23 mm would result in an underestimation of J_c by about 40% in our case. In our setup, the sensor-head is pressed onto the sample surface by a spring, which ensures constant distances as long as the sensor-head (which has a diameter of 3 cm) and the sample surface are parallel. A small angle would increase the gap and therefore lead to errors. In our case, however, a small angle between the sample surface and the sensor-head is almost immediately detected by a constant slope of the magnetoscan signal along a particular direction due to the similar diameters of sample and sensor-head. Alternatively, this error source can be strongly diminished by reducing the diameter of the sample head (e.g. up to a size slightly larger than the diameter of the magnet, which is 2 mm).

6. Summary

In summary, we have shown that magnetoscan data, averaged over a small sample area with a size similar to the surface of the permanent magnet, can be unambiguously mapped onto absolute values of J_c. The calibration curve is obtained by comparing magnetoscan data with J_c from SQUID measurements at the same sample regions. Thus, this method allows a rapid determination of the local critical current density distribution near the surface of a large superconducting pellet at small fields at 77 K without destroying the sample. A resolution much better than 1×10^8 A m^{-2} in J_c is easily achieved and can be further improved by modifying the setup as shown by numerical simulations. The success of the method is essentially based on the stable and reproducible parameters of the setup.

Acknowledgments

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