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.

1. Introduction

Large superconducting pellets based on ReBa$_2$Cu$_3$O$_{7-\delta}$ (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
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 \((\mu_0 H_0)\) of about 0.15 T at the sample surface. The penetration depth of the currents into the sample follows roughly [5] \(\Delta z \simeq H_0/J_c\) 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 \(J_c\). 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 \(2 \times 2\) 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 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 from about 3 to \(5 \times 10^8\) 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 \(J_c\) for each area leads to the calibration curve, which is a monotonously increasing function, as shown in figure 4, and thus maps \(B_m\) 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 \((\lesssim 0.3 - 0.6\) 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 \(1 \times 10^8\) A m\(^{-2}\) for \(J_c\) is easily achieved (see figure 4), which is better than usually needed. If future measurements of \(B_m\) 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
magnetoscan signal can be calculated for different values of parameters are known from experiment, so that the equilibrium experimental magnetoscan results quantitatively. All necessary current distribution at the Hall probe position reproduces the magnetoscan. Calculating the magnetic field of that time evolution of the local current distribution during the magnetoscan.

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 \( \pm 0.1 \) 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 \( 1 \times 10^8 \) 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.

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References


