Granularity and the central peak in magnetization loops of thin superconductors

D. V. Shantsev$^{1,2}$, M. R. Koblishka$^3$, T. H. Johansen$^1$, and Y. M. Galperin$^{1,2}$

$^1$ University of Oslo, P.O.Box 1048, Blindern, 0316 Oslo, Norway
$^2$ A.F. Ioffe Physico-Technical Institute, Polytechnicheskaya 26, St. Petersburg 194021, Russia

Abstract: Magnetization hysteresis loops of type-II superconductors are characterized by a peak occurring at an applied field $B_p$ near zero. This central peak is formed due to a field-dependence of the critical current density, $J_c(B)$, monotonously decreasing at small fields. The present work focuses on how the peak position is influenced by (i) the sample thickness, and (ii) the sample granularity. Theoretically we prove that in the limit of an infinitely thin and long strip placed in a perpendicular field, the central peak occurs at $B_p = 0$, for any function $J_c(B)$. This result is shown to be in excellent agreement with experimental data.

Key words: magnetization loops, central peak, perpendicular geometry, granularity

INTRODUCTION

The investigation of magnetic hysteresis loops (MHLs) is a widely used tool to characterize superconducting samples, and in particular, to estimate the critical current density and its dependence on magnetic field. An ever-present feature of the MHLs is a peak in the magnetization located at an applied field $B_p$ near zero. This so-called central peak is formed due to a field dependence of the critical current density, $J_c(B)$, monotonously decreasing at small fields. When the sample is a long cylindrical body placed in a parallel applied field, the peak position can be calculated analytically within the critical-state model for several $J_c(B)$ dependences [1]. One always finds on the descending field branch that $B_p < 0$, and similarly $B_p > 0$ on the ascending branch of large-field loops. In simple terms the shift in a consequence of the local flux density, $B$, lagging behind the applied field. However, in some experiments one finds $B_p$ very close to zero or even shifted to the positive side so that the peak occurs before the remanent state is reached. This latter case is, e.g., commonly observed in mono- and multifilamentary Bi-2223 tapes [2,3]. Two factors are known to cause a shift of $B_p$ toward positive values: decreasing sample thickness [5] and increasing its granularity [3,4]. However, quantitative predictions for the peak position with account of these effects are lacking and the present work aims to fill this gap.

RESULTS AND DISCUSSION

Consider a long thin uniform superconducting strip with edges located at $x = \pm w$, the y-axis pointing along the strip, and the z-axis normal to the strip plane. The magnetic field, $B_a$, is applied along the z-axis, so screening currents flow in the y-direction. Assume that the strip is in a fully penetrated state, i.e., the sheet current is everywhere equal to the critical one, $J(x) = \text{sign}(x) J_c[B(x)]$. This state can be reached after applying a very large field, and then reducing it to some much smaller value. The field distribution, $B_z(x)$ then satisfies the integral equation,

$$B_z(x) - B_a = -\frac{\mu_0}{\pi} \int_0^w \frac{J_c[B_z(u)]}{x^2 - u^2} u \, du,$$

(1)
Fig. 1. Upper: A drawing illustrating the main conclusion of the paper. Lower: The descending branches of the MHLs (arrows indicate the direction of the field sweep): (a) bulk sample (thickness 300 μm), temperatures are between 10 and 40 K. (b) a very homogeneous YBCO thin film. The peak is located exactly at zero field; (c) monofilamentary Bi-2223 tape with a very pronounced anomalous peak position indicated by the dashed line; (d) model sample, the peak is found here at positive fields as well.

which follows immediately from the Biot-Savart law. This equation does not have an analytical solution for $B_z(x)$ in case of general $J_c(B)$. However, in the remanent state, $B_a = 0$, its solution always has an interesting symmetry [6]

$$B_z(x) = -B_z(\sqrt{w^2 - x^2}) .$$

Moreover, a similar symmetry relation holds for the function $\partial B_z(x)/\partial B_a$. This symmetry leads to an important result for the magnetic moment of the strip [6]:

$$\frac{dM}{dB_a} = 0 \quad \text{at} \quad B_a = 0 .$$
Consequently, on a major MHL the magnetic moment has an extremum in the remanent state for any \( J_c(B) \)-dependence. Note that the extremum in \( M(B_a) \) is a maximum for a decreasing \( J_c(B) \), and a minimum if \( J_c(B) \) has a pronounced second peak, the so-called fishtail behavior.

Based on this, we arrive at a following general scenario concerning the central peak position, as illustrated in Fig. 1. For long samples in parallel magnetic field the field inside superconductor everywhere lags the applied field. Hence, the peak in magnetization also lags, i.e., it is observed after passing through the remanent state. This corresponds to \( B_p < 0 \) on the descending field branch. A typical example of an MHL for a bulk YBa\(_2\)Cu\(_3\)O\(_{7-x}\) (YBCO) sample with fishtail is shown in Fig. 1(a). As the sample thickness decreases, demagnetization effects come into play and there appear regions inside superconductor where the field goes ahead of \( B_a \). As a result, the peak position is shifted towards zero. It is located exactly at \( B_p = 0 \), in the limiting case of a uniform strip of infinitesimal thickness. This is illustrated in fig. 1(b) for an homogeneous YBCO thin film.

In granular samples the magnetization is often determined by inter-grain currents which depend on the magnetic field at the grain boundaries. This field is affected by demagnetization effect of the grains and always changes ahead of the average local field as the applied field changes. As a result, granularity leads to a shift of \( B_p \) in the positive direction on the descending field branch for all thicknesses. Thus, for a granular bulk (or a bulk with several crystal defects) the peak position may be found close to zero field, even though its geometry predicts \( B_p < 0 \) [7]. For a granular thin strip the peak is always located at a positive field, i.e., before the remanent state is reached. This situation is typically realized in mono- and multifilamentary Bi-2223 tapes Fig. 1(c). This concept is proven by the measurements of a "model sample", which is made from a YBCO thin film by patterning an array of hexagonally-close packed disks [8]. As shown in (d), also this sample exhibits the anomalous peak position.

Acknowledgments. We thank Y. Shen (NKT Research Centre, Brøndby, Denmark) for the excellent uniform YBCO thin film as well as B. Nilsson and T. Claeson (Chalmers, Göteborg, Sweden) for the film with artificial granularity. Financial support came from the Research Council of Norway (NFR), and from NATO via NFR.