



## The low-field peak in magnetization loops of uniform and granular superconductors in perpendicular magnetic fields

T. H. Johansen<sup>a</sup>, D. V. Shantsev<sup>a,b</sup>, M. R. Koblishka<sup>a</sup>, Y. M. Galperin<sup>a,b</sup>, P. Nalevka<sup>c</sup> and M. Jirsa<sup>c</sup>

<sup>a</sup>University of Oslo, P.O.Box 1048, Blindern, 0316 Oslo, Norway

<sup>b</sup>A.F. Ioffe Physico-Technical Institute, Polytechnicheskaya 26, St. Petersburg 194021, Russia

<sup>c</sup>Institute of Physics, ASCR, Na Slovance 2, CZ-18821 Praha 8, Czech Republic

The present work aims to explain the anomalous position of the low-field peak in magnetization loops in Bi-2223 tapes, where the peak is often seen shifted to a positive field on the descending field branch. We prove theoretically that for an infinitely thin and long strip placed in a perpendicular field, the central peak occurs exactly at 0 T, for any function  $J_c(B)$ . This general result is shown to be in excellent agreement with experimental data. After introducing granularity in such a film into a lattice of small weakly-overlapping disks, the peak becomes shifted to positive values. We conclude that this anomalous behaviour in the magnetization is a definite signature of granularity.

The low-field peak in a magnetization loop (MHL) is formed at  $B_p$  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. 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]. Two factors are known to cause a shift of  $B_p$  toward positive values: decreasing sample thickness [4] and increasing its granularity [3].

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,

$$B_z(x) - B_a = -\frac{\mu_0}{\pi} \int_0^w \frac{J_c[B_z(u)]}{x^2 - u^2} u du, \quad (1)$$

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 [5]

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

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 [5]:

$$\partial M/\partial B_a = 0 \quad \text{at} \quad B_a = 0. \quad (3)$$

Consequently, on a major MHL the magnetic moment has an extremum in the remanent state for *any*  $J_c(B)$ -dependence. 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

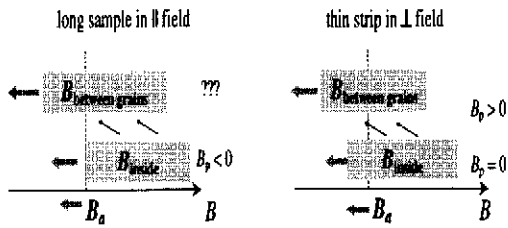


Figure 1. A drawing illustrating the main conclusion of the paper.

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; see 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. (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 position may be found close to zero field, even though its geometry predicts  $B_p < 0$  [6]. 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 (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 [7]. As shown in (d), also this sample exhibits the anomalous peak position.

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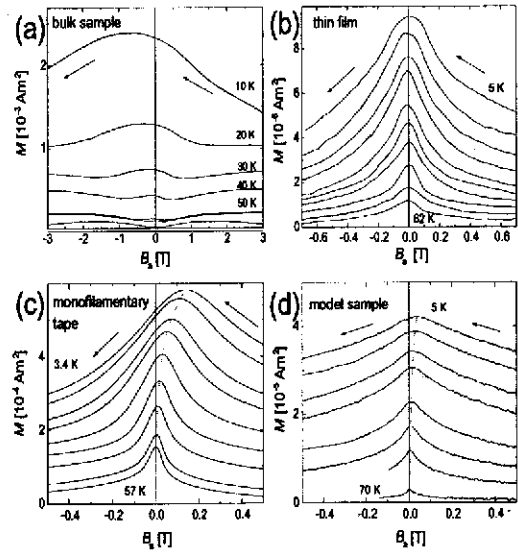


Figure 2. The descending branches of the MHLs (arrows indicate the direction of the field sweep): (a) bulk sample (thickness 300  $\mu\text{m}$ ),  $10 \leq T \leq 40$  K. (b) a very homogeneous YBCO thin film. The peak is located exactly at 0 T; (c) monofilamentary Bi-2223 tape with *anomalous*  $B_p$  (dashed line); (d) model sample with *anomalous*  $B_p$ .

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