Simulations of local field inhomogeneities of magnetic tracks and their impact on the magnetization of HTSs with defects

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Abstract. Using the Monte Carlo method, the full and partial magnetization loops of a YBCO superconductor have been studied. The partial loops simulated field inhomogeneities occurring on magnetic tracks in levitation systems. The influence of temperature and defect concentration on the shape and area of the full and partial hysteretic curves has been studied. The highest considered defect concentration provided the least partial curve area which meant less hysteresis energy losses and greater levitation stability.

1. Introduction

One of the possible ways of creating high-speed transport is the use of magnetic levitation devices based on high-temperature superconductors (HTSs). The effect of magnetic levitation in such systems can be achieved due to the stable interaction and movement of the transport trolley containing an HTS material over a track of permanent magnets that create a gradient magnetic field [1]. The inhomogeneity of this magnetic field along the direction of movement of the trolley causes magnetization reversal of the HTS and, accordingly, leads to the occurrence of hysteresis energy losses, which, under certain conditions, may lead to overheating of the superconductor and to the loss of stability of the entire system [2]. Thus, the study of cyclic magnetization reversal processes in HTSs is an urgent problem.

In this work, using the continuum Monte Carlo method within the framework of the layered HTS model [3], we have calculated the magnetization loops of samples of a YBa₂Cu₃O₇₋ₓ (YBCO) HTS in the range ±0.15 T of external magnetic field H at two different temperatures T. In addition, partial loops were calculated simulating the possible field inhomogeneities that may occur on a magnetic track. The samples under study contained two different concentrations n_def of randomly distributed point defects.

2. Computational model

In this paper, a two-dimensional version of the model of a layered HTS was implemented for the YBCO superconductor placed in an external magnetic field perpendicular to the superconducting CuO₂ layers. In this case, at high enough temperatures and in strong magnetic fields, a three-dimensional sample is treated as a set of independent, non-interacting layers so that the results of magnetization for one HTS-layer can be interpreted as an averaged response of the whole sample, and the Abrikosov vortices inherent in type-II superconductors, are treated as two-dimensional “pancakes”. The Gibbs energy potential for an HTS in a 2D geometry can be considered as a sum of the vortex
own-energies, and the interactions of vortices with one another, the sample boundary, external magnetic
field, and the pinning centers (defects). The Monte Carlo (MC) algorithm used for the presented
computations minimizes the Gibbs potential over the course of approx. $10^6$–$10^7$ steps by means of a
standard Metropolis algorithm [4]. For a more detailed description of the computational model and
method see [5].

The considered HTS material (YBCO) had the following typical parameters: $\lambda = 120$ nm (the Lon-
don penetration depth), $\xi = 2.2$ nm (the coherence length), $T_c = 92$ K (the critical temperature). The
samples were 5 μm in width (along the x-axis) and 3 μm in length (along the y-axis) and contained
randomly distributed pinning centers. The defects were represented as point-like local potential wells
of width $2\xi$ and depth $\alpha = 0.05$ eV (which corresponds to medium pinning force).

3. Results

Figure 1 presents a set of full and partial hysteretic magnetization curves for two samples: subfigures
a) and c) correspond to the case of $n_{def} = 2.0\cdot10^9$ cm$^{-2}$ (302 defects) and subfigures b) and d) – to
$n_{def} = 2.7\cdot10^9$ cm$^{-2}$ (403 defects). The first row corresponds to the temperature of 4.2 K, and the second
one – to $T = 10$ K. All subfigures have the same scale along the vertical axis for convenience.

Let us first analyse the full curves shown in thick orange lines. The presented figures show how the
residual magnetization changes with the increasing number of defects: for the case of 4.2 K (top row)
the difference between the zero-field value of $-4\pi M$ for two defect concentrations slightly exceeds
28%, whereas for $T = 10$ K (bottom row), this difference is about 0.5% smaller. Changes in the irre-
sversibility field $H_{irr}$ values (which set the threshold such that in fields higher than $H_{irr}$, the magnetiza-
tion curve repeats itself when the field ramping is reversed) can also be observed. This can be clearly
seen when comparing the magnetization of identical samples at 4.2 K and 10 K: whereas curve a)
demonstrates a hysteretic behavior at the highest considered fields, curve c) becomes thread-like at
0.13 T $< H < 0.15$ T. The changes in $H_{irr}$ with the increasing defect concentration can be traced by
comparing the thickness of the curves at high fields: e.g., for 302 defects, the rightmost part of the
loop is much narrower than for 403 defects at 4.2 K, and at the higher temperature, the field range, in
which the loop becomes thread-like, is roughly 3 times smaller for subfigure d) than c). Another thing
to mention is the change in the overall area enclosed in the magnetization loops (which indicates the
change in the critical current density $j_c$): it clearly increases with the rising $n_{def}$ and decreases with the
rising $T$. All the mentioned features are in agreement with the predictions based on various experi-
mental and theoretical results.

Now let us turn to the more interesting partial curves. It should be noted that in each of the four
cases, the field ranges in which the partial curves were calculated were identical. This allows us to
compare the area enclosed in the partial curves, and it can be seen that in the considered cases, the area
predictably decreases with the increasing temperature (in sync with the full curve), but at the same
time, the partial curve area also decreases with the increasing defect concentration. Normally, the
magnetization loop area is used to determine the hysteretic losses occurring upon remagnetization of
the sample, so a reduced loop area means that less energy is lost due to the changing external field and
the sample gains less heat. In practice, this would mean that the sample containing 403 defects
($n_{def} = 2.7\cdot10^9$ cm$^{-2}$) would grant the levitation system greater stability than the sample with a lesser
defect concentration.

Let us compare the behaviour of vortices in these two cases. For illustrative purposes, we shall only
demonstrate the vortex configurations at $T = 4.2$ K. Figure 2 shows two instant vortex distributions (on
the right) with the corresponding magnetization curves (on the left), on which the point corresponding
to the presented vortex picture is denoted with a cross-mark. Here, subfigure a) corresponds to the
sample with 302 defects and b) – to 403 defects. Each picture containing the magnetization curves
shows the current number of vortices in the top right corner and the current external magnetic field
value in the bottom right corner. Both partial curves started at the bottommost point (corresponding to
$H = 0.04$ T), then $H$ was ramped up to 0.14 T and after that – down to 0.04 T again, thus completing
the loop.
Figure 1. The full and partial magnetization curves of two samples with different defect concentrations at two different temperatures: \( n_{\text{def}} = 2.0 \times 10^9 \, \text{cm}^{-2} \) and \( 2.7 \times 10^9 \, \text{cm}^{-2} \) for the left and right columns, \( T = 4.2 \, \text{K} \) and \( 10 \, \text{K} \) for the top and bottom rows.

It can be seen from the left column of images that at first, as the external field increases, the magnetization “curve” is linear. From the point of view of the vortex system this means that the number of vortices is constant. The increasing magnetic field is not strong enough for the new vortices to overcome the near-edge potential barrier created not only by the Meissner current (as in the case of a vortex-free sample) but also by repulsive potential from the pinned vortices. Such state, in which no new vortices enter the samples with the increasing field, persists until \( H \) reaches 0.09 T. The fact that this threshold field is identical in both samples may mean that the vortex density near the sample boundaries is almost the same in both samples. This can be visually deduced from comparing the vortex images in Figure 2. However, despite the similar near-edge vortex densities, the sample in b) contains a greater number of vortices than a) from the very start of the partial curve (this is due to a greater number of pinning centers, so the difference is close to 100). On the other hand, there is much more “free” space for the newly entering vortices to occupy in sample a) than b) – the former contains more vortex-free spaces. For this reason and due to the repulsive nature of the vortex-vortex interaction, as the magnetic field increases, the rate at which new vortices enter two samples are different: this process occurs much slower in the more defective sample than in the less defective one. This is why the bottom partial curve converges to its corresponding full one at a greater angle than in subfigure a).
Figure 2. The scaled parts of the full and partial magnetization curves (on the left) and the instant vortex configurations (on the right) for two samples containing a) 302 and b) 403 defects. The turquoise cross-marks denote the points to which the vortex pictures correspond.

Then, as the external field begins to decrease, the vortices exit the sample. In this case, both partial curves coincide with their corresponding full ones for the most part. However, in the bottom case it takes a bit longer for the partial curve to converge. This too can be attributed to the behaviour and density of vortices. Due to the smaller size of areas with low defect density in this sample, it takes much higher fields to “squeeze” a certain number of vortices in these areas. Since the partial curve field-range did not reach the maximum full-curve field (0.15 T), less vortices were trapped in the inter-defect areas and more stayed near the boundaries, so when the external field began to decrease, more vortices were able to leave the sample. This explains why the partial curve deviated from the full one until \( H \) reached 0.1 T.

The resulting data on the hysteresis energy losses in the considered samples can be summed up in a normalized bar chart presented in Figure 3. Here, the areas of the partial curves are presented in the descending order, normalized to the minimum value. The captions to bars contain information on the temperature and defect concentration for which they were obtained. For example, “T4d302” (the blue-coloured bar) corresponds to a sample with 302 defects at 4.2 K. Thus, the first two bars correspond to \( T = 4.2 \) K and the last two – to \( T = 10 \) K. At the same time, the odd bars correspond to the sample with 302 defects. And the even ones – with 403 defects. The chart clearly demonstrates that the energy losses upon remagnetization decrease with the rising temperature (at 10 K, the normalized losses for both samples are close to 1). The losses also decrease with the rising number of defects, although the difference between neighbouring bars (1–2 and 3–4) seems to lessen with the rising temperature. This indicates that (among the considered values) a higher operating temperature would be more applicable to the levitation devices since it allows for 50–75% less hysteresis losses than the liquid helium temperature does. A 30% increase in the defect concentration at \( T = 10 \) K leads to an additional 15% drop in the hysteresis losses.

The overall vortex behaviour in the 403-defect sample gives reason to believe that a higher concentration of defects could provide even better results in the considered conditions. However, the chosen
defect parameters were restricted to a medium pinning potential and a random defect distribution, which leaves a question as to how a different (higher or lower) potential-well depth $\alpha$ and a different (periodic or gradient) pinning distribution would influence the obtained results.

![Normalized bar chart demonstrating the hysteresis energy losses for the two considered samples at two temperatures.](image)

Figure 3. The normalized bar chart demonstrating the hysteresis energy losses for the two considered samples at two temperatures.

4. Conclusion
The magnetization of a YBCO superconductor with different concentrations of point-like defects has been studied in different temperatures. The changes in the areas of hysteretic magnetization curves (and therefore, the critical current density) with defect concentration and temperature have been demonstrated. The obtained partial magnetization loops which were meant to model the way the samples would behave in a locally inhomogeneous magnetic field in levitation devices showed that the sample with the highest considered defect density would provide the highest results and experience less energy losses, both in liquid helium and at 10 K. A higher operating temperature has provided approximately 50–75% less losses than 4.2 K. Further studies are needed to determine the influence of pinning parameters on the remagnetization behavior of HTSs with defects.

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