

Suppression of magnetic relaxation processes in melt-textured $\text{YBa}_2\text{Cu}_3\text{O}_x$ superconductors by a transverse ac magnetic field

L. M. Fisher,¹ A. V. Kalinov,¹ I. F. Voloshin,¹ and V. A. Yampol'skii²

¹All-Russian Electrical Engineering Institute, 12 Krasnokazarmennaya Street, 111250 Moscow, Russia

²Institute for Radiophysics and Electronics NASU, 12 Proskura Street, 61085 Kharkov, Ukraine

(Received 7 December 2004; published 12 April 2005)

The effect of the transverse ac magnetic field on the relaxation process in $\text{YBa}_2\text{Cu}_3\text{O}_x$ melt-textured superconductors was studied. A factor of 50 suppression of the relaxation rate could be achieved at the expense of some reduction in the maximum trapped field, with the magnetic-induction gradient being unchanged. This phenomenon is interpreted as a result of an increase of the pinning force after the action of the transverse ac magnetic field that is confirmed by the measurement of the trapped-induction distribution.

DOI: 10.1103/PhysRevB.71.140503

PACS number(s): 74.25.Nf, 74.25.Qt

The electrodynamics of hard superconductors was under study for a long time. A wide variety of interesting phenomena were discovered and interpreted on the basis of the developed concepts. One of them is the suppression of static magnetization under the action of a transverse ac magnetic field. First, this phenomenon was observed and interpreted by Yamafuji and coauthors.^{1,2} If one places a superconducting strip into a perpendicular static (dc) magnetic field \mathbf{H} and then apply an ac magnetic field $\mathbf{h}(t)$ along the strip surface, the critical profile of the static magnetic flux changes noticeably. The short vortices oriented perpendicular to the strip are shown to bend and move in such a way that the static magnetic flux tends to become homogeneous. This phenomenon and its consequences were studied theoretically in detail in recent papers.^{3,4}

The other origin of the suppression of the static magnetization by the transverse ac magnetic field (the collapse phenomenon) was considered in Refs. 5–9. If the vortex length L exceeds significantly the penetration depth of the ac field, the vortex bend does not play an essential role and the flux-line cutting mechanism (the phenomenon predicted by Clem¹⁰) is put in the forefront. As was shown in Refs. 6, 7, and 9, it is the flux-line cutting that provides the homogenization of the static magnetic flux in the wide areas of the sample bulk where the ac field has penetrated (the creation of collapse zone). If the ac amplitude h exceeds the penetration field H_p , the distribution of the static magnetic induction becomes homogeneous in the whole sample bulk and the magnetic moment disappears.^{8,11}

It is well known that the inhomogeneous magnetic-flux distribution is metastable. According to the classical paper by Anderson,¹² such a state of a superconductor relaxes to the homogeneous one following the logarithmic law. Within the existing concept on the collapse, one could expect a noticeable decrease of the relaxation rate of the magnetic moment after the action of the ac field. Indeed, the surface homogeneous region of the sample, the collapse zone, should be filled by the vortices and the critical gradient should be established before the vortices start to leave the sample and the magnetic moment begins to decrease. In the present paper we have checked this assumption and made sure that the relaxation rate of the dc magnetic moment is actually decreased

significantly by the action of the transverse ac magnetic field. Surprisingly, we have observed a striking concomitant phenomenon which appears to be of general interest in vortex matter. Not only does the magnetic moment not change, but the spatial distribution of the static magnetic flux holds the shape without significant relaxation for a long time after the action of ac field. Moreover, this distribution conserves after the moderate temperature increase. This strongly suggests that the critical current density grows after the action.

Melt-textured $\text{YBa}_2\text{Cu}_3\text{O}_x$ (YBCO) platelike samples of $9.3 \times 7.4 \times 1.5 \text{ mm}^3$ (sample *A*) and $8 \times 6.3 \times 1.5 \text{ mm}^3$ (sample *B*) in sizes were cut from a homogeneous part of bulk textured cylinders grown by the seeding technique. The homogeneity was checked by a scanning Hall probe. The c axis was perpendicular to the largest face of the sample. At $T=77 \text{ K}$, the characteristic value of the critical current density J_c in the \mathbf{ab} plane is of the order of 13 and 22 kA/cm^2 for samples *A* and *B* (in self-field), respectively. The “static” magnetization M was measured by a vibrating sample magnetometer in the external magnetic field $\mathbf{H} \parallel c$ created by an electromagnet. The zero-field-cooled sample was exposed to the magnetic field of 12 kOe which was further reduced to 5 kOe; from this point, the relaxation measurement was started. The above-mentioned fields are essentially higher than the penetration field of the sample (1.6 kOe). A commercial Hall probe was fixed on the sample to measure the evolution of the magnetic induction locally. The other Hall probe with the sensitive zone of $0.3 \times 0.3 \text{ mm}^2$ was used to scan the magnetic-induction distribution on the sample surface. The distance from the sample to the sensitive zone of the probe was about 0.2 mm. The Hall measurements were performed in the zero field after exposition of the sample to $H=12 \text{ kOe}$. The ac magnetic field $\mathbf{h} \parallel \mathbf{ab}$ was a computer-generated triangle wave with the frequency $F=140 \text{ Hz}$. The ac field could be applied for a definite number of periods and stopped exactly at the end of the period (at $h=0$). In our experiments we used 999 full cycles of the ac field. Most of the measurements were performed at the liquid-nitrogen temperature $T=77 \text{ K}$.

Figure 1(a) demonstrates the influence of the orthogonal ac magnetic field on the relaxation of M . The conventional (without the ac field) relaxation is shown to follow the loga-

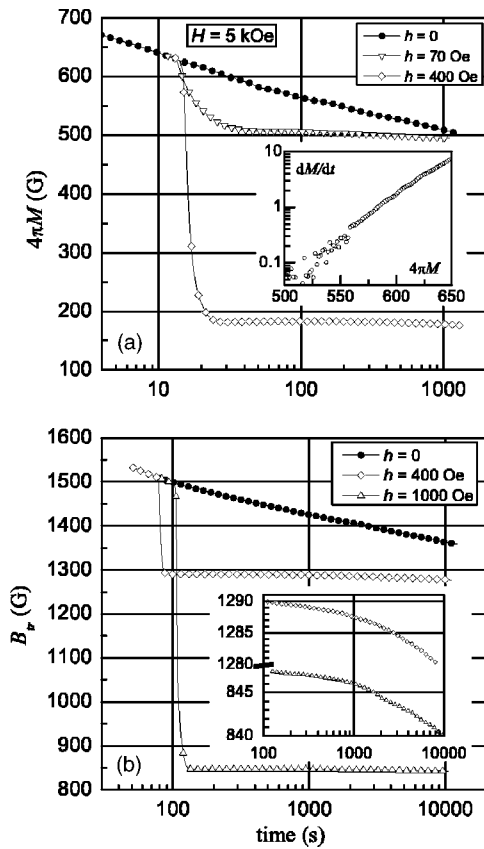


FIG. 1. Relaxation of the (a) magnetization M and (b) trapped magnetic induction B_{tr} without (closed symbols) and with the action of the ac field (open symbols) for sample A. The upper inset shows the dependence of $dM/dt \propto E$ on $M \propto J$; the lower shows the tails of suppressed relaxation in enlarged scale.

rithmic law, that implies an exponential current-voltage characteristic (CVC) $E \propto \exp[-(-U/kT)(1-J/J_{c0})]$ (see inset), where J_{c0} is a depinning current at the zero temperature and U is a pinning-well depth.¹² For the other run, at $t \approx 20$ s the ac field of the amplitude h was applied, followed by the sharp drop in the magnetization due to the collapse effect.⁸ When the ac field action has finished, we can see almost no relaxation for the first 100 s and an essentially reduced logarithmic relaxation rate $S = dM/d \ln t$ for the rest of the observation period.

To reduce the minor effect of the magnetic-field relaxation in the electromagnet on the magnetization we studied the temporal dependence of the trapped magnetic induction B_{tr} in the central part of the sample without any external magnetic field by the Hall probe. Three curves in Fig. 1(b) correspond to the same magnetic prehistory of the sample, but differ from each other because of the action of the ac field with different amplitudes. The upper curve is obtained for the case when the ac field was not switched on during the measurement at all, $h = 0$. Two lower curves demonstrate the influence of the ac field on the relaxation of B_{tr} . All curves in Fig. 1(b) follow the same logarithmic-like law before switching on the ac field. Switching on the ac field results in a giant suppression of the relaxation rate (5–60 times). The inset of Fig. 1(b) shows that the decrease of the relaxation rate de-

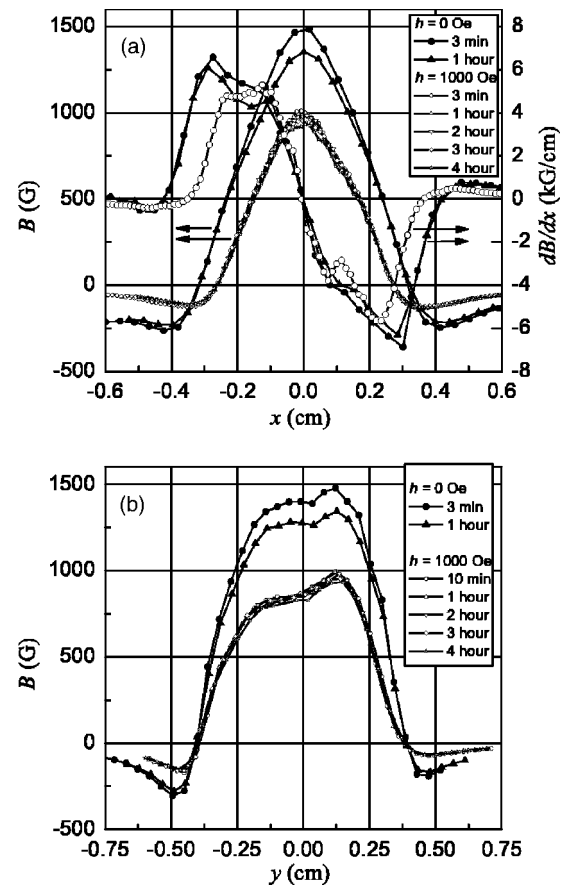


FIG. 2. Relaxation of the magnetic-induction distribution along the (a) x and (b) y directions on the surface of sample A without (closed symbols) and after the action of the ac field (open symbols). Panel (a) (the right scale) also shows derivatives dB/dx .

pends essentially on the amplitude of the ac field and B_{tr} does not follow the logarithmic law for the whole time window.

The abrupt decrease of the static magnetization under the action of the ac field (the jumps shown in Fig. 1) is connected to the suppression of the dc shielding currents in all sample regions where the ac field penetrates. The suppression of the relaxation of M and B_{tr} could be easily interpreted as a result of the collapse: vortices cannot leave the sample before the sufficient gradient of the magnetic induction would be restored in the surface regions of the sample. From the macroscopic point of view, the other explanation looks plausible. As we reduce the magnetization (and current density) significantly, we should get a huge decrease in $dM/dt \propto E$ in accordance with the exponential CVC [see inset of Fig. 1(a)]. However, this explanation will work only in the case of the uniform distribution of the shielding currents. As we will see below this is not the case.

To clarify the real influence of the ac field on the relaxation process we have investigated the temporal evolution of the dc magnetic-field distribution by the scanning Hall probe. The spatial distribution $B(x)$ (across the ac field direction) of the trapped dc magnetic field is shown in Fig. 2(a). The unperturbed curves (closed symbols) demonstrate Bean-like profiles of the magnetic-flux distribution which relaxes obvi-

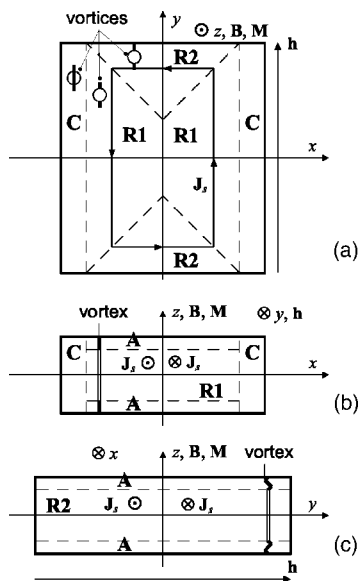


FIG. 3. Schematic view of the cross sections of the sample. Regions marked with “C” are fully penetrated by the ac field; there is no shielding current (J_s) in the xy plane here. The vortices in regions R1 and R2 are partially disturbed (bent or entangled in the zy plane). This disturbance occurs in the A regions corresponding to the ac field penetration depth along the z axis.

ously in $1/h$. After the action of the ac field (open symbols) the relaxation is suppressed significantly in accordance with the data of Fig. 1(b). The change in the profile width along the x axis is due to the collapse of the dc shielding currents in the regions of the sample where the ac field has penetrated (the “collapsed” regions marked with “C” in Fig. 3). Even at a first glance at the curves in Fig. 2(a) one can reveal a very important consequence of the action of the ac field. The magnetic-field distribution in the central part of the sample before and after this action differs by the vertical displacement, with the gradient being the same. Numerically calculated dB/dx curves shown in Fig. 2(a) confirm this observation to be true everywhere except in the most outer regions. This means that the current densities in the R1 regions maintain their initial values in all sample regions where the ac field has not penetrated along the x direction. However, the regions occupied by the currents flowing along the x direction (R2) are not changed. This, together with the decrease of the maximum trapped field, results in the decrease of the current density in the R2 regions [see Fig. 2(b)] that makes them subcritical and suppresses the relaxation in the y direction. This decrease of the local induction itself could affect the relaxation rate S directly, due to an increase of the J_c or a change in the CVC exponent. However, the change of the CVC exponent with the magnetic field is too low to explain the huge change in S .¹³ The influence of local B on S through the J_c change could be estimated comparing the data of Figs. 1(a) and 1(b). The external magnetic field in Fig. 1(a) is well higher than the penetration field and the ac field. In this case, the change of the local B is essentially lower than for zero-field measurement Fig. 1(b), but the effect of the relaxation suppression does exist and is qualitatively the same.

The most interesting feature of the relaxation after the

action of the ac field is the following. Not only the magnetization and the magnetic induction, but the distribution of the dc field gradient, i.e., distribution of the dc shielding currents, stops the relaxation after the action of the ac field. The vortices in the central part of the sample (R1 and R2 regions in Fig. 3) could not move into the collapsed regions (C). This is probably due to the impossibility to overcome the cutting barrier,^{14,15} because the C regions are (at least partially) filled with the vortices aligned with the y axis. However, the other possible origin of the suppression of relaxation has to be considered.

We suppose the penetration of the ac field from the largest (xy) faces of the sample to be of great importance. The first possible reason is an increase in the vortex length accompanied by the pinning energy gain, tending to the increase of the J_c , because the vortices turn out to be “anchored” by their tails (in the A regions). The elongation of the vortices occurs in such a way (along the y axis) that there is no additional Lorentz force directed outside the sample (along the x and y directions). Thus, the shielding currents become subcritical resulting in the exponential decrease of the relaxation rate. However, to explain the significant decrease of S by the vortex-length increase alone, the relative vortex elongation must be of the order of the logarithmic relaxation-rate decrease, which is hardly possible. Moreover, in the collective pinning approach¹⁶ the vortex elongation gives only a sub-linear term in the free energy. The other explanation could be based on the anisotropy of the pinning force in the YBCO superconductors. After the action of the ac field, parts (segments) of the vortices in the A regions can be aligned and locked in in the ab plane leading to an increase of the pinning force. The action of the ac field could also result in the bend or entangling of the vortices in the A regions at the scale of 100–1000 vortex-lattice periods. As a result, a significant increase of the vortex-bundle size can take place. This, in turn, can lead to the increase of the collective pinning potential¹⁶ and to the observed suppression of the relaxation rate.

To check if the action of the ac field does increase the critical current density, the following experiment was done. Suggesting the shielding currents become subcritical after the action we could increase the temperature without decreasing the current density. Our scanning-Hall-probe setup permits only 77-K measurements, so we have to decrease the temperature back to 77 K to investigate the changes. This temperature decrease should not change the magnetic-flux profile in any way in the absence of the external magnetic field, thus we can study a distribution frozen from the higher temperature. The magnetothermal history was as follows. Sample B was cooled to 83 K in the external magnetic field of 10 kOe, then the field was switched off. At this point the ac field was applied (or not applied in the other run). Further, the sample was heated by 3 K to “develop” a difference between perturbed and nonperturbed flux profiles. Before this heating, they should look like the profiles on Fig. 2(a) (the gradients are the same). Upon heating, the nonperturbed profile should follow the J_c changes and the perturbed one will go from a subcritical to a critical state (possibly with a higher J_c). Finally, the sample was cooled down to 77 K and profiles were measured. (Note, that these profiles correspond

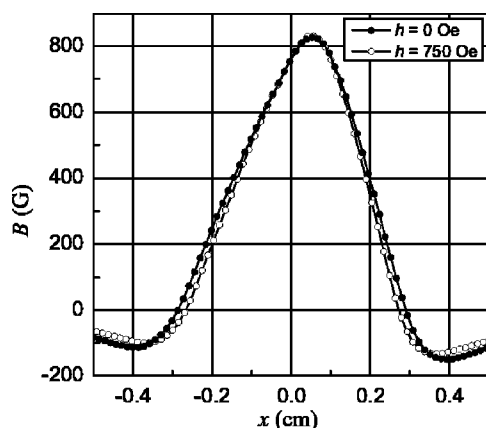


FIG. 4. Distribution of the trapped induction for sample *B* obtained without (closed symbols) and after the action of the ac field (open symbols). The magnetothermal history is described in the text.

to the critical current at $T=86$ K.) These experiments were repeated several times, with the temperatures' reproducibility being better than 0.05 K. The result is shown in Fig. 4. The perturbed profile is seen to keep a narrower form but the

maximum field is the same. This means that the magnetic-induction distribution is steeper and the critical current density in the "perturbed" sample is higher. The crude evaluation gives the J_c increase of at least 8%.

Summarizing, we have observed the giant decrease of the relaxation rate after the action of the transverse ac magnetic field. This effect exists in the relaxation of the "static" magnetization and the local value of the trapped magnetic induction. After this action, the distribution of the magnetic induction across the ac field direction turns out to be frozen with the same current density. This distribution conserves even if the temperature of the sample increased by several Kelvin giving a new critical state with a higher J_c . We suppose the increase of the vortex length accompanied by partial locking of the vortex segments in the **ab** planes could be a reason for this phenomenon. The observed effect can also be a result of the increase of the collective pinning potential due to the increase of the vortex-bundle dimension in the **ab** plane.

We thank A. L. Rakhmanov for helpful discussions. This work is supported by INTAS (Grant No. 01-2282), RFBR (Grant No. 03-02-17169), and the Russian National Program on Superconductivity (Contract No. 40.012.1.1.11.46).

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