Peculiarity of magnetization relaxation in finite size superconductors.

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Abstract. Magnetization relaxation in superconductors is under the study from the very beginning of superconductivity. Now the knowledge about the nature of flux creep is suggested and confirmed by many experiments, but mainly by macromeasurement of average magnetization. Studying the relaxation in finite size superconductors, melt textured and single crystals YBCO, we have found the relaxation is determined not only by material properties, pinning center sizes, dimensionality and distribution, but sample size and shape as well as magnetic flux distribution. Magneto-optic technique, used to visualize the spatial magnetic flux distribution and redistribution in superconductors during relaxation, allowed us to understand the origin of these effects.

1. Introduction
The problem of reduction of magnetization relaxation is very important for bulk superconductor applications like levitation devices, bearing, motors, generators etc. Naturally, it was widely studied since the discovery of superconductivity and is still under discussion [1], despite the fundamental knowledge about the nature of flux pinning and flux creep is obtained. Finite size platelets or rings are mostly used in applications. Therefore we have to understand some particular features of flux relaxation in finite size elements, not only time dependence of flux creep and the way to reduce, but flux redistribution during relaxation, which happens in such elements. All these are very important for optimizing devices construction.

Here are presented the results of magneto-optical study of magnetization relaxation in YBCO finite plates and rings. This well known method allows us to determine average magnetic flux and critical current relaxation as well as spatial variations of flux distribution, to distinguish the flux reduction due weak links and common relaxation, and to find out some very special features of relaxation in thin plates.

2. Flux relaxation in thin and thick plates
The average magnetization relaxation in studied YBCO thin plates measured by macro-method, magnetometer, shows typical logarithmic decay with time. The same we obtain by our MO measurements for full flux penetration into thin plates and for partial flux penetration. However, the analysis of images of magnetic flux distribution taken at different time moments after switching off of magnetic field shows that special flux distribution in thin and thick plates reduces in different manner, figures 1-3. In thick plates the relaxation happens everywhere in sample volume, figure 1. The magnetic flux reduces by logarithmic law and critical current, which flow in occupied by magnetic flux volume, decays by logarithmic law too, figure 3. In thin plates the flux reduces by the same law,
but current decays mainly on external flux boundary, while there is very small relaxation on interior boundary, figures 1-3. The effect is observed in wide temperature range and does not depend upon the field value. Simple explanation of such difference in relaxation process in thick and thin plates was suggested in [3] based on simple power function dependence of critical current upon magnetic field and Maxwell equations.

Figure 1. Trapped flux distribution transformation during relaxation following ZFC and magnetization by $H_z$: a – 50 μm thick plate, full flux penetration, $T = 24$ K; after $H_z = 2000$ Oe; b – the same plate, partial flux penetration, $T = 24$ K; after $H_z = 1000$ Oe; c – 500 μm thick plate, partial flux penetration, $T = 80$ K, after $H_z = 2000$ Oe. There are shown flux distributions in 2 seconds after field switching off, in 1000 seconds and difference image between first and second one. White arrows show the direction, in which profiles of induction distribution were taken.

Figure 2. Transformation of induction distribution during flux creep. Profiles correspond to shown above images and are taken along white arrows shown on figure 1. For full flux penetration the relaxation occurs everywhere in the sample volume, for partial flux penetration the relaxation is on outer flux front for thin sample and everywhere for thick sample.

Figure 3. Relative relaxation of trapped magnetic flux in thick and thin plates. 1 – relaxation of magnetization and critical current everywhere in thick sample and current on external flux front in thin sample, curves practically coincide, 2 - magnetization relaxation in thin sample, 3 – weak relaxation of critical current in thin sample on interior flux front.

So, magnetic flux relaxation is slower in thin plates than in thick plates made from the same material, which coincides with our results on flux relaxation in bulk melt textured YBCO [4]. However micro-cracks across c-axes, which are often observed in bulk melt textured YBCO, would not help to reduce the relaxation, as their existence cause concentration of magnetic field in near cracks area, which lead to relaxation enhancement. Besides, these micro-cracks play the role of weak links, which reduce critical current and enhance relaxation [5].

Another important consequence of found specific feature of relaxation in thin plates is – it is possible to reduce relaxation “closing” trapped flux by small flux with reverse magnetization. It should be pointed out that fast logarithmic relaxation begins very often not at the moment when the field is switched off, figure 3, but for a while, after 0.1 – 2 seconds, which is determined by particular pinning center distribution. It means that one can not extrapolate measured after 10 seconds logarithmic dependence to very short time trying to find initial trapped flux value, which could be found in some publications.

In thin single crystal plates there is one more source of relaxation delay. Turbulence development, the traces of which are seen near thin sample edges in figure 1a, 1b, causes flux concentration near the boundary between magnetic flux with opposite direction [6] and prevents flux exit.
3. Relaxation in superconducting rings

Special attention in our study was paid on trapped magnetic flux relaxation in superconducting rings, as they are supposed to be used as elements of bearings or as permanent magnets with flat profile of induction distribution near their surface. Such rings are rarely made from perfect material, so weak links or microcracks could cross rings, or just some segments of a ring could be made from the material with worse quality that the rest part of the ring. Therefore we made our model rings from relatively perfect material and from material with defects and perform study of flux relaxation in both important for application cases, FC and ZFC magnetization.

Figure 4. Magnetic flux distribution in YBCO ring with diameter=4.2 mm, hole=2 mm, thickness=2 mm, a - after ZFC and magnetization by pulse magnetic field of 1200 Oe, b - 3000 Oe, c - after field cooling under 3000 Oe; the field was applied along to the ring symmetry axis; T = 80 K.

Figure 5. Profiles of magnetic flux distribution and their relaxation, corresponding to induction maps in figure 4. Trapped magnetic flux after FC in 3000 Oe and switching off the field is higher than after following ZFC pulse magnetization in the same field, but relaxation is higher too.

Figure 6. Relaxation of trapped magnetic flux at T = 80 K. Curves 1-4 – after ZFC and 1200 Oe magnetization, curve 5– ZFC and 3000 Oe pulse magnetization., curves 6-7 – after FC under 3000 Oe. Curves 1,5,6 correspond to average relaxation of trapped flux, curves 3,4 to local relaxation over the ring body, curves 2, 7 correspond to relaxation of magnetic flux over the hole of the ring.

The distribution of trapped magnetic flux in the ring made from melt-textured YBCO is shown in figure 4. The material quality, despite the ring is small, only 4 mm in diameter, varies along the ring. For this reason trapped in the ring magnetic flux is inhomogeneous in the ring, near the ring and even over the hole, figure 5. The flux relaxation is also different, figure 6. The highest relaxation is over the ring in places with poor material quality, curve 4, but it influence only a little on summary trapped flux relaxation. Summary magnetic flux shows smart nonlinear relaxation, even possible with short-time enhancement of trapped flux, which turns into long-time logarithmic relaxation. Long time relaxation following FC magnetization is higher than the relaxation after ZFC magnetization.
Figure 7. Trapped flux configuration for ring with weak link marked by black arrows, a – flux distribution after $H_{pulse} = 230$ Oe, b – the same after $H_{pulse} = 470$ Oe, c – after $H_{pulse} = 700$ Oe, d – after $H_{pulse} = 1000$ Oe; non-linear variation of trapped flux value with magnetized pulse strength, 1– mean induction over the ring, 2– induction over the ring hole; 3– nonlinear flux relaxation after pulse magnetization by $H_{pulse} \sim 600$ Oe

Weak links in superconductive rings cause additional flux relaxation (the same as in plates) [5], complicated law of relaxation (which is determined by field strength, FC or ZFC of magnetization, prehistory), nonlinear dependence of trapped magnetic flux upon applied field, and essential redistribution of trapped flux configuration during relaxation, figure 7. Cutting rings along weak links with following joining can reduce this enhanced relaxation; it was shown that joined rings hold the field upto 3000 Oe, [7]. The highest trapped magnetic flux is obtained at a middle, not maximum field.

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References

[1] Kaoru Yamafuji et al, Journ. Ten Physical Society of Japan, 39, 581 (1975); J.R.Cave, M.A.R.LeBlank, Journ. Appl. Phys., 53, 1631 (1982); A.Gonzalez, Phys.Rev.B, 31, 7048 (1985); A. Riise et al., Appl. Phys. Lett., 60, 2294 (1992); R.Boyer, M.A.R.LeBlank, Solid State Commun., v.24, 261 (1977); M.A.R.LeBlank,J.Lorrain, Journ. Appl. Phys., 55, 4035 (1984); I.R. Clem, Physica C, 153-155, 55 (1988); A. Gurevich, H. Brandt, Phys. Rev. Lett., 73, 178 (1994); A.L. Kasatkin et al., Physica C, 310, 296 (1998); G. Mikitik, E.H. Brandt, Phys.Rev.B, 64, 92502 (2001); I.Babich, G.Mikitik, E.H.Brandt, Phys. Rev.B, 68, 052509 (2003)

[2] L.Uspenskaya, V.Vlasko-Vlasov, V.Nikitenko, T.Johanson, Phys.Rev.B 56, 11979 (1997)

[3] L. Uspenskaya, K. S. Korolev, P.N.Yarykin, Physica C 423 181 (2005)

[4] L. Uspenskaya, reports of ISSP RASc on BMBF project 13#6854A “HTS-motor <500 kW", (1999-2002)

[5] A. B. Surzhenko, M. Zeisberger, T.Habisreuther, W.Gawalek, L. S.Uspenskaya, Phys. Rev. B, 68, 64504 (2003)

[6] L.S. Uspenskaya, I.G. Naumenko, A.A. Zhokhov, Physica C, 402, 188-195, 2004

[7] T A Prikhna, W Gawalek, et.al., Supercond. Sci. Technol., v.18, p.s153, 2005