UvA-DARE (Digital Academic Repository)

Anisotropy of perpendicular field penetration into high-T_c superconductors induced by strong longitudinal field

Indenbom, M.V.; Forkl, A.; Ludescher, B.; Kronmuller, H.; Habermeier, H.U.; Leibold, B.; D'Anna, G.; Li, T.W.; Kes, P.H.; Menovsky, A.A.

DOI

[10.1016/0921-4534\(94\)90212-7](https://doi.org/10.1016/0921-4534(94)90212-7)

Publication date

1994

Published in

Physica C

[Link to publication](#)

Citation for published version (APA):

Indenbom, M. V., Forkl, A., Ludescher, B., Kronmuller, H., Habermeier, H. U., Leibold, B., D'Anna, G., Li, T. W., Kes, P. H., & Menovsky, A. A. (1994). Anisotropy of perpendicular field penetration into high-T_c superconductors induced by strong longitudinal field. *Physica C*, 226, 325-332. [https://doi.org/10.1016/0921-4534\(94\)90212-7](https://doi.org/10.1016/0921-4534(94)90212-7)

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (<https://dare.uva.nl>)

Anisotropy of perpendicular field penetration into high- T_c superconductors induced by strong longitudinal field

M.V. Indenbom *, A. Forkl, B. Ludescher, H. Kronmüller

Max-Planck-Institut für Metallforschung, Institut für Physik Heisenbergstr. 1, 70506 Stuttgart, Germany

H.-U. Haberman, and B. Leibold

Max-Planck-Institut für Festkörperforschung Heisenbergstr. 1, 70506 Stuttgart, Germany

G. D'Anna

IGA, Department of Physics, EPFL, CH-1015 Lausanne, Switzerland

T.W. Li, P.H. Kes

Kamerlingh Onnes Laboratorium, Leiden University, PO Box 9506, Leiden, The Netherlands

A.A. Menovsky

Physics Department, University of Amsterdam, 1018 XE Amsterdam, The Netherlands

Received 7 March 1994

Abstract

The geometry of penetration of a magnetic field oriented perpendicular to the surface of a superconductor is changed by the presence of a longitudinal field. This is studied directly by means of the magneto-optical technique in different high- T_c materials. In $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals Brandt's mode of magnetization is observed, namely, penetration of an AC field *only* along the longitudinal field even if the corresponding dimension of the sample is much longer than the other two. This anisotropy is the evidence that the force-free configuration of current and vortices cannot be destroyed by cutting and reconnection of the vortices in this 3D superconductor. On the contrary, the absence of the induced anisotropy in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals reveals the independence of pancake vortices in CuO layers from longitudinal field which makes a realization of the force-free configuration impossible in the layered 2D superconductor. An intermediate effect in thin films indicates that vortices are almost normal to the film surface even if the applied field is nearly parallel to it. The described experiment can be used as a new tool to study the internal vortex structure in superconductors.

1. Introduction

The magnetic-flux behavior in superconductors is the key phenomenon for its current-carrying proper-

ties useful for applications [1]. Usually, measurements of magnetic properties give only integral data with some ambiguities of interpretation. Direct study of the magnetic flux structure by means of the magneto-optical technique provides us with much more detailed information [4]. In the last few years this technique was further developed and successfully applied to high-temperature superconductors (HTSC's)

* Corresponding author. Permanent address: Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Moscow distr., Russian Federation.

[5–8]. We present here observations of perpendicular-field profiles by means of the unique high-sensitivity and high-contrast magneto-optical garnet indicator [8] which shows that the flux motion can be qualitatively changed in the presence of an additional strong longitudinal field. The latter geometry is often encountered in transport and magnetic measurements in both high- T_c and traditional superconductors. The additional constant field is a characteristic feature in torque, vibrating-reed and torsion-pendulum experiments [9–11] because of the necessity to transform the induced magnetic moment into a measured mechanical moment. The effects of the qualitative change of the flux motion in this geometry have been discussed only very recently [2]. In the theoretical description of the vibrating-reed experiments in a linear diffusion approximation it was supposed that flux cannot move at the sample edges where no Lorentz force occurs because the flux lines are parallel to the vibration-induced screening currents.

The configurations in which currents are parallel to the vortex lines, the so-called force-free configurations, have been very actively investigated since their first experimental observations [12,13] but mainly as a problem of purely academic interest and not in conjunction with any practically important phenomena [14,15]. So far, the problem of the force-free configuration has remained very controversial and numerous special experimental and theoretical works (see, for example, Refs. [16,17] and references therein) do not answer the question whether stable force-free configurations exist or if these will be destroyed by flux-line cutting and reconnection. Usually the investigations are devoted to looking for the latter processes and their phenomenological description. A different instability of the force-free configurations starting from the edges, where already initially the magnetic field and current are not parallel [18], as a rule is neglected. The possible role of the internal structure of the superconductors in this problem in fact has not been seriously discussed. The direct visualization of the flux behavior in the force-free configuration can solve these problems.

The geometry with an additional longitudinal field allows us to *directly* resolve the peculiarities of the flux microstructure in the high- T_c superconductors. Namely, we show that $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) is not

layered enough and behaves as a three-dimensional (3D) medium, where vortices form lines and perpendicular AC fields penetrate only along the direction of the longitudinal field, as was predicted by Brandt [2]. On the other hand, in the strongly layered $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO) flux exists in the form of pancake vortices which may independently move in the layers and do not feel the longitudinal field [3].

2. Experimental

The description of modern magneto-optical techniques can be found elsewhere [6–9]. Two kinds of the magneto-optical layers for the magnetic flux structure visualization are currently used for investigations: Thin films of europium chalcogenides directly deposited onto the superconductor surface and thus yielding high spatial resolution of 1 μm [5,6], and industrially prepared special ferrimagnetic garnet films having a high field sensitivity and providing non-destructive testing of samples [7,8]. In this work we use a garnet film with in-plane magnetic anisotropy which has no coercitivity for perpendicular magnetization and can reveal fields from 10 μT to 0.3 T. The essential idea of the technique is as follows. The magnetic field B_z normal to the sample surface (x, y) is mapped by Faraday rotation of polarized light reflected from an aluminium mirror on the bottom surface of the indicator film which contacts the sample. Dark areas on the presented photos are Meissner phase areas with $B_z=0$. In the bright areas, into which the normal component of the field has penetrated, a higher intensity of images corresponds to higher absolute values of B_z . The constant in-plane magnetic field, $B_x=175$ mT, is generated by a permanent magnet and is directed horizontally on all figures. The normal component of the field, B_z , is applied by a coil and can exceed 200 mT.

We chose three different samples for the demonstration of our novel effect. The first is the same partly detwinned $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystal, $2 \times 1 \times 0.1$ mm³, (Fig. 1(a)) with $T_c=87.7$ K on which many-peak losses have been measured [11]. The second is a BSCCO ($\text{Bi}_{2.10}\text{Sr}_{1.89}\text{Ca}_{0.99}\text{Cu}_2\text{O}_x$) big single crystal, $5 \times 2 \times 0.09$ mm³, of very high quality ($T_c=86$ K). The third is a 1.5×1.5 mm² YBCO thin film with a thickness of 680 nm, the crystallographical c -axis

Fig. 1. Penetration of a perpendicular magnetic field B_z into an YBCO single crystal observed by means of a magneto-optical garnet film with in-plane anisotropy at $T = 61$ K as described in Ref. [8]. Regions of $|B_z| > 0$ appear as bright domains: the higher is $|B_z|$ the higher is the image intensity. Dark areas are where $B_z = 0$ (Meissner phase). (a) Photo of the basal surface (ab) of this crystal with twin structure revealed in polarized light [19]. (b) Remanence after application of $B_z = 100$ mT and switching it off ($B_x = 0$). (d) Penetration of flux at $B_z = 68$ mT and (e) remanence after switching $B_z = 100$ mT off in the presence of a longitudinal field $B_x = 175$ mT applied before cooling the crystal. (c,f) Schematic current distributions during flux penetration (density of the thin lines represents the current density j): (c) without B_x , current saturates and flux equally penetrates from all sides; (f) in the presence of a strong B_x this flux penetration takes place only in the x -direction. The vertical current lines are parallel and equidistant in the domains of constant $j_y = j_c$ in which perpendicular flux has penetrated along x from the left and right edges. The flux front is indicated by bold lines. Screening currents (curved current lines behind the flux front) maintain $B_z = 0$ in the Meissner phase.

perpendicular to its surface and prepared by laser ablation on TiSrO_3 substrates ($T_c = 89$ K). Some other samples of each type also investigated demonstrate the same results.

3. Results and discussion

If we apply a magnetic field perpendicularly to the (ab) surface of the YBCO single crystal, this field typically penetrates almost equally from all sides, forming a double-Y figure which is characteristic for rectangular superconductors in the critical state. After

switching off the field, the flux partly escapes also isotropically (Fig. 1(b)). So, even in a crystallographically anisotropic detwinned YBCO crystal the pinning-force density is approximately isotropic in the basal plane (ab).

The situation drastically changes with application of a permanent field B_x along the basal surface. The perpendicular field now penetrates (Fig. 1(d)) and escapes (Fig. 1(e)) *only* in the direction of the *in-plane field* (x -direction), similarly as was predicted by Brandt for the flux diffusion in this geometry [2]. So, in the presence of an additional in-plane field we obtain an extreme anisotropy of the flux motion, as can be clearly seen from comparison of the two remanent states (b) and (e) in Fig. 1. The latter clearly demonstrates that even after application of B_z higher than the constant B_x no flux penetration occurs across the in-plane field. A small amount of penetrated flux along the long edges would be observable in Fig. 1(b) as a strip of captured flux.

The anisotropy in this new critical state can be explained as follows. The application of B_z generates a screening current in the xy plane which is partially parallel and partially perpendicular to B_x (see Fig. 1(e)). In the former case there is no (or at least a much smaller) driving force on the longitudinal vortices while in the latter case there is. The former is analogous to the force-free current configuration which was first discussed 30 years ago (see references in Ref. [14]) and which is still a topical problem now [15,16]. Thus, contrary to the case $B_x=0$ where the supercurrent density j in any direction is limited by its critical value j_c (isotropic current limiting), in the presence of B_x , the component j_x does not produce a large enough driving force and can be much larger than j_c (anisotropic current limiting). The pictures of the corresponding current distributions are presented in Figs. 1(c) and (f), where the transformation of the double-Y structure of magnetic flux, occurring without an additional field, into a H-shape structure in the presence of B_x is shown.

In the same experiment on the BSCCO single crystals no decrease of the flux flow perpendicular to the longitudinal field is observed (Fig. 2). Contrary to the case of YBCO, penetration of the perpendicular field in BSCCO is independent of the presence of the in-plane field. This effect is clear and direct *evidence for the existence and independent motion of pancake*

vortices in this layered superconductor (see the model below).

Thin films can be treated as an intermediate case. The c -oriented square YBCO thin film exhibits a much lower current-limiting anisotropy (Fig. 3) than the YBCO crystal. Application of B_x splits the characteristic cross of lines dividing the sectors of uniform current flow of density j_c along the square sides (Fig. 3(a)) into an anisotropic current configuration (Fig. 3(b)). Such a configuration looks similar, but evidently is of quite a different nature, as that described in high- T_c single crystals which have anisotropic j_c values in the plane parallel to the c -axis [20]. The anisotropy induced by B_x is more pronounced at higher temperatures as follows from the temperature dependence of the length b defined in the inset of Fig. 3(c) which was measured in the remanent state after applying a field $B_z=200$ mT. The length b characterizes the difference of the longitudinal ($j_{c\parallel}$) and transversal ($j_{c\perp}$) critical currents since one can show that $b/a=1-j_{c\perp}/j_{c\parallel}$ where a is the size of the square. The observed increase of b is not only caused by the temperature change of the superconducting parameters, but also is due to the trivial decrease of the captured normal-field component with decreasing j_c compared to the constant B_x . This is evident by a decrease of b during further increase of B_z after reaching the critical state. The thickness of the present YBCO film is larger than λ . In thin-film structures with thicknesses less than or approximately equal to λ the induced anisotropy was not detected. A similar reduction of the effect of the force free current configuration in thin films was already observed in transport measurements [21,22].

The difference between the three investigated cases is illustrated in Fig. 4. The usual Abrikosov vortex lines in a thick slab are parallel to the field, and a current flowing along the longitudinal-field component affects only the perpendicular parts of the vortex lines, whereas the pinning force acts on the whole vortex lengths (Fig. 4(a)). In thin films, the appearance of in-plane vortices is energetically not favorable: The vortices are almost perpendicular to the surface even if the field is nearly parallel to it and the superconductor itself is isotropic (Fig. 4(b)) [23]. In BSCCO, pancakes are independently pinned, and Josephson strings connecting them do not feel pinning centers (Fig. 4(c)). So, in the two last cases, the penetration

Fig. 2. Penetration of $B_z = 30$ mT into a BSCCO single crystal at $T = 32$ K: (a) $B_x = 0$, (b) $B_x = 175$ mT. Only a part of the crystal is shown. It is revealed by a flux concentration near the crystal edge.

of B_z should be *independent* of B_x . The corresponding independence of B_x was detected in numerous integral measurements (see e.g. Ref. [3]), but it should be pointed out that the same effect was sometimes observed in YBCO, whereas in *our* experiments (performed at relatively low fields) the vortices behave as strongly coherent vortex *lines*.

The latter discrepancy can be explained by considering the effect of the anisotropy on the magnetic moment. For example, in an isotropic square with sides

a and thickness d , the maximum magnetic moment is $\frac{1}{6}j_c da^2$. For the same square in the presence of B_x , longitudinal-current densities up to the depairing current are in principle allowed (see Fig. 1(f)) resulting in a magnetic moment which is only slightly higher, $\frac{1}{4}j_c da^2$. Thus, our magneto-optical observations reveal the dimensionality of the vortex lattice more clearly and with higher precision than the traditional measurements of integral quantities, i.e. magnetization, torque.

Fig. 3. Critical-state configurations in an YBCO thin film square: (a) a symmetrical one without B_x ($T=50$ K, $B_z=159$ mT) and (b) the appearance of asymmetry in the presence of $B_x=175$ mT ($T=85$ K, $B_z=31$ mT). (c) Temperature dependence of the anisotropy of the remanent flux pattern induced by $B_x=175$ mT. The inset shows the splitting b and corresponding anisotropy of j_c induced by B_x .

4. Conclusions

The direct observation of flux motion in the force-free configuration and investigations of its dependence on the structure of superconductors are reported for the first time. In a 3D superconductor like YBCO the force-free configuration can be very stable and the perpendicular-field component will not penetrate through the existing array of longitudinal vor-

tices, contrary to some integral measurements [16]. Such a cross-penetration can take place in materials with some internal weak connections like BSCCO, where vortex lines can easily be cut and reconnected or are already decomposed into independent pancake vortex lattices and Josephson vortices. In finite samples of a 3D superconductor there is only one way for the transverse component to penetrate, namely, the penetration from the ends where the force-free

Fig. 4. Schematic vortex structures in inclined fields: (a) In nearly isotropic thick crystals the vortices coincide with the field lines. (b) In films thinner than λ the vortices are perpendicular to the film surface and their density is defined by the normal component of the field only. (c) In layered structures the vortex lines dissolve into two-dimensional pancake vortex lattices which move independently in the layers. Φ_0 marks the positions of the vortex cores.

configuration is not realized. Finite-size effects can also lead to the destruction of the force-free effect as is found in our thin films.

Force-free configurations are not an artificial concept, but do occur in numerous routine experiments. Their sensitivity to vortex-line cutting and reconnection can be used as a powerful tool to study this phenomenon and obtain additional information about the effective flux dimensionality in high- T_c superconductors, which is presently one of the most actual problems. This method is physically analogous to the transport measurements in the flux transformer geometry which also reveal decomposition of the vortices into pancakes in BSCCO [24] and continuous vortex lines in YBCO [25], but does not need electric contacts.

Acknowledgements

The authors thank E.H. Brandt for numerous helpful discussions and A.V. Antonov and M. Yu. Gusev (firm "Gamma", Moscow) for the unique garnet magneto-optical indicator. MVI is grateful to the Alexander von Humboldt-Stiftung for financial support. GD would like to acknowledge financial support from the Fonds National Suisse de la Recherche Scientifique (FNPNR30). Production of the BSCCO crystals was carried out at ALMOS and supported by the Dutch Foundation for Fundamental Research on Matter, FOM.

References

- [1] Concise Encyclopedia of Magnetic & Superconducting Materials, ed. J. Everts, (Pergamon, Oxford, 1992).
- [2] E.H. Brandt, Phys. Rev. Lett. 68 (1992) 3769.
- [3] P.H. Kes, J. Aarts, V.M. Vinokur and C.J. van der Beek, Phys. Rev. Lett. 64 (1990) 1063.
- [4] R.P. Huebener, Magnetic Flux Structures in Superconductors (Springer, New York, 1978).
- [5] N. Moser, M.R. Koblishka, H. Kronmüller, B. Gegenheimer and H. Theuss, Physica C 159 (1989) 117.
- [6] Th. Schuster, M.R. Koblishka, B. Ludescher, N. Moser and H. Kronmüller, Cryogenics 31 (1991) 811.
- [7] M.V. Indenbom, N.N. Kolesnikov, M.P. Kulakov, I.G. Naumenko, V.I. Nikitenko, A.A. Polyanskii, N.F. Versinin and V.K. Vlasko-Vlasov, Physica C 166 (1990) 486.
- [8] L.A. Dorosinskii, M.V. Indenbom, V.I. Nikitenko, Yu.A. Ossip'yan, A.A. Polyanskii and V.K. Vlasko-Vlasov, Physica C 203 (1992) 149.
- [9] D.E. Farrell, S. Bonham, J. Foster, Y.C. Chang, P.Y. Jiang, K.G. Vandervoort, D.L. Lam and V.G. Kogan, Phys. Rev. Lett. 63 (1989) 782.
- [10] C. Duran, J. Yazzyi, F. de la Cruz, D. Bishop, D.B. Mitzi and A. Kapitulnik, Phys. Rev. B 44 (1991) 7737.
- [11] G. D'Anna, W. Benoit, W. Sadowski and E. Walker, Europhys. Lett. 20 (1992) 167.
- [12] P. Grassmann and L. Rinderer, Helv. Phys. Acta 27 (1954) 309.
- [13] S.T. Secula, R.W. Boom and C.J. Bergeron, Appl. Phys. Lett. 2 (1963) 102.
- [14] A.M. Campbell and J.E. Everts, Adv. Phys. 21 (1972) 198.
- [15] J.R. Clem, Transport Currents and Force-Free Current Flow, in: Ref. [1], p. 612.
- [16] M.A.R. LeBlanc, S. Celebi, S.X. Wang and V. Plecháček, Phys. Rev. Lett. 71 (1993) 3367; M.A.R. LeBlanc, D. LeBlanc, A. Golebiowski and G. Fillion, Phys. Rev. Lett. 66 (1993) 3309; G. Fillion, R. Gauthier and M.A.R. LeBlanc, Phys. Rev. Lett. 43 (1979) 86.

- [17] A. Perez-Gonzalez and J.R. Clem, *Phys. Rev. B* 31 (1985) 7048.
- [18] E.H. Brandt, *Phys. Rev. B* 25 (1982) 5756.
- [19] L. Dorosinskii, B. Farber, M. Indenbom, V. Nikitenko, A. Polyanskii and V. Vlasko-Vlasov, *Ferroelectrics* 111 (1990) 321.
- [20] E.M. Gyorgy, R.B. van Dover, K.A. Jackson, L.F. Schneemeyer and J.V. Waszczak, *Appl. Phys. Lett.* 55 (1989) 283.
- [21] W.C.H. Joiner and G.E. Kuhl, *Phys. Rev.* 168 (1968) 413.
- [22] M.G. Blamire and J.E. Evetts, *Appl. Phys. Lett.* 46 (1985) 1181.
- [23] E.H. Brandt, *Phys. Rev. B*, to be published; E.H. Brandt and M. Indenbom, in: *Proc. of the LT20*, Eugene, Oregon, 4–11 August 1993, ed. R.J. Donnelly, *Physica B* 194–196 (1994) 1803.
- [24] R. Busch, G. Ries, H. Werthner, G. Kreiselmeier and G. Saemann-Ischenko, *Phys. Rev. Lett.* 69 (1992) 522; H. Safar, E. Rodriguez, F. de la Cruz, R.L. Gammel, L.F. Schneemeyer and D.J. Bishop, *Phys. Rev. B* 46 (1992) 14238.
- [25] H. Safar, P.L. Gammel, D.A. Huse, S.N. Majumdar, L.F. Schneemeyer, D.J. Bishop, D. López, G. Nieva and F. De la Cruz, *Phys. Rev. Lett.* 71 (1994) 1272; R. Busch et al., to be published.