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Temperature-dependent scaling of pinning force data in Bi-based high-T_c superconductors

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Abstract. The scaling of the normalized volume pinning forces, $F_p/F_{p,max}$, versus a reduced field $h = H_a/H_{scale}$ has proven to be a very informative tool to study the origin of the flux pinning in superconductors. Remarkably, on $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) data were mostly analyzed only in a narrow temperature range around 77 K. Here, we present a study of the pinning forces in various Bi-2223 samples at temperatures between 18 K and 80 K. The measurements clearly reveal that there is an apparent non-scaling of the pinning force data; instead, two clearly different temperature regimes for the scaling can be recognized, which are found to be in direct relation to a second step observed in the $m(T)$ curves obtained upon field-cooling and -warming.

PACS. 74.25.Qt Vortex lattices, flux pinning, flux creep – 74.25.Sv Critical currents – 74.72.Hs Bi-based cuprates

1 Introduction

The scaling of data of the normalized volume pinning forces, $F_p/F_{p,max}$, versus a reduced field $h = H_a/H_{scale}$ has proven to be a very informative tool to study the origin of the flux pinning in superconductors [1–5]. Earlier publications [5–8] have shown that in the case of the high-T_c superconductors, the appropriate scaling field is not the upper critical field H_{c2}, but instead the irreversibility field, H_{irr}, which denotes the upper limit of strong flux pinning. Such a pinning analysis was performed on a variety of high-T_c superconductors in literature [5–8], but on $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) data were mostly analyzed only in a narrow temperature range, typically around 77 K.

In this paper, we present a study of the pinning forces in Bi-2223 samples of various shapes (intact silver-sheathed tapes, extracted individual filaments and bulk samples) at temperatures ranging between 18 K and 80 K. The present measurements clearly reveal that there is an apparent non-scaling of the pinning force data; instead, two different temperature regimes can be recognized, which are in direct relation to the second step in the $m(T)$ curves as reported earlier [9].

2 Experimental details

Details of the sample preparation are given elsewhere; silver-sheathed Bi-2223 tapes were prepared by the standard powder-in-tube method as mono- and multifilaments with up to 55 filaments [10,11]. Table 1 gives the superconducting properties of four selected tapes ("1" – "4") which stem from multifilamentary tapes with 37 filaments. The critical current density j_c(fil.) is the maximum current density of a filament as obtained from magneto-optic images of cross-sections of the tapes [11]. Individual filaments were extracted from the tapes by means of an etching procedure [12]. Bulk samples of Bi-2223 were prepared using a melt-quenching technique [13]. A total of 20 different samples was investigated in order to obtain a clear trend. Measurements of $m(T)$ as a function of applied field were performed in various magnetometers (SQUID, VSM) allowing to perform measurements with different sweep rates of the external magnetic field. The scans of $m(T)$ were performed using a SQUID magnetometer in a continuous sweep mode with a sweep rate $dT/dt = 35$ mK/min in the transition region [14,15]. This ensures a large number of datapoints even in a sharp superconducting transition.

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3 Results and discussion

For the scaling of F_p in Bi-2223, there is an useful relation, as the law

$$H_{irr}(T) \sim (1 - T/T_c)^3 \quad (1)$$

holds [16] over a wide temperature range for the tapes and bulk samples as observed by various authors. Therefore,

Table 1. Parameters of the four different Bi-2223 tapes studied as cross sections. j_c(fil., 10 K) gives the maximum current density of a filament obtained from the MO images.

tape	I_c(77 K) [A]	j_e(77 K) [KA/cm^2]	j_c(fil. max., 10 K) [A/cm^2]
1	35	5.1	0.8×10^5
2	62	10	2.1×10^5
3	56	10	1.5×10^5
4	59	7.2	2.0×10^5

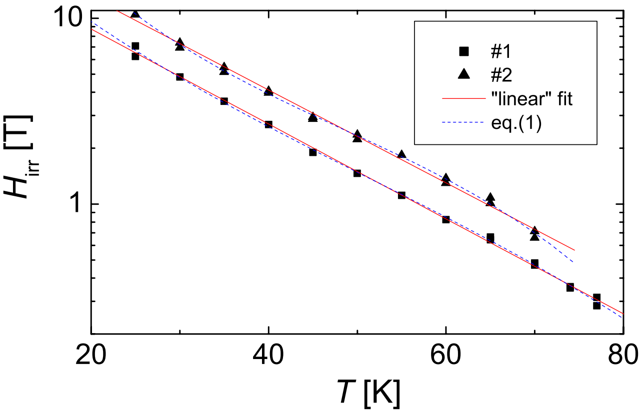

Fig. 1. The irreversibility lines, $H_{\rm irr}(T)$ for two selected samples "1" and "2". Two points at a given temperature are measured using a different sweep rate, i.e. 0.25 T/min and 2 T/min. The dashed lines show the fits using equation (1). In the intermediate temperature range, a simple "linear" fit on the semilogarithmic scale can be made to the data to describe $H_{\rm irr}(T)$.

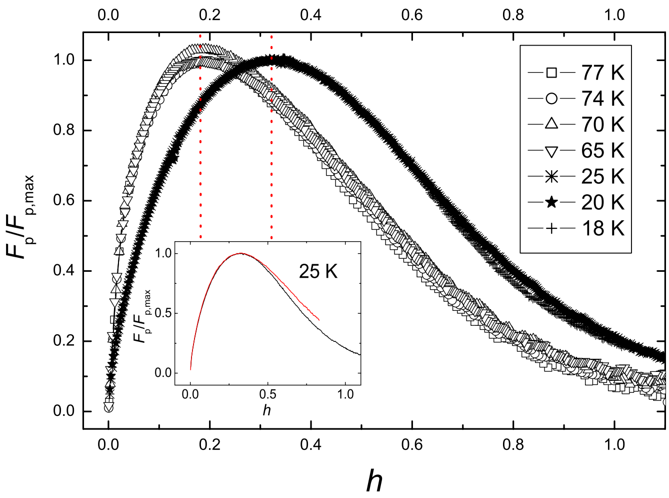

Fig. 2. Plots of the scaled volume pinning forces, $F_{\rm p}/F_{\rm p,max}$, versus the reduced field, $h = H_a/H_{\rm irr}$, for extracted filaments from a Bi-2223 tape. A good scaling is obtained in two clearly distinct temperature regimes, around 77 K and at around 20 K. The inset presents scaled F_p data at $T = 25$ K, measured at two sweep rates, 0.25 T/min and 2 T/min; illustrating that the peak position, h_0, is not affected by creep.

there is no free parameter to improve the scaling behaviour, and furthermore, $H_{\rm irr}$ can be predicted reasonably well for cases where the available magnetic field is too small for a direct determination of $H_{\rm irr}$. Throughout this study, $H_{\rm irr}$ was determined using a criterion of 10^4 A/cm^2. Figure 1 also illustrates that the irreversibility line in the temperature range 30−77 K can be described by a simple "linear" fit in the semilogarithmic representation; this is useful for the quick prediction of $H_{\rm irr}(T)$ from measurements performed at 77 K. This holds well for all samples investigated here.

Figure 2 presents the scaling of the pinning forces for one selected sample; in this case filaments from a multifilamentary tape with 55 filaments. In the temperature range around 77 K, the scaling is reasonably good, and a peak position, $h_0 \approx 0.18$ is obtained. In strong contrast to this, the scaling of the data at 15, 20 and 25 K is also reasonably good, but h_0 is shifted to ≈0.32. Data lower than 18 K do not reach h_0 anymore within the available field range. The inset presents scaled data measured at two different sweep rates of the external magnetic field; clearly indicating that h_0 does *not* depend on the sweep rate. Therefore, the peak position h_0 is an important parameter to discuss the underlying microscopic pinning mechanism. The other samples studied exhibited essentially the same behaviour, only the transition region is different as illustrated in Figure 3.

Figure 3 shows the determination of h_0 as function of temperature for two samples "1" and "2". Note that the filaments from sample "2" exhibited the highest maximum current density as indicated in Table 1. On both samples, we find a well-developed scaling behaviour at high temperatures around 77 K and at low temperatures up to 30 K. The intermediate part is a transition regime, where the flux pinning mechanism gradually changes. Furthermore, the curves for the two selected samples are markedly different. This is an indication of microscopic differences in the pinning landscape of the two samples. All the data obtained on samples "3" and "4" and on various other samples just fall in between the two graphs indicated. Furthermore, it is remarkable that the tape "2" (and a also investigated *monofilamentary* tape) shows the best pinning properties in the intermediate temperature range from all samples studied here.

Figure 4 presents finally the $m(T)$ measurements on a monofilamentary tape. The full symbols give the field-cool cooling (FCC) data, the open symbols the data obtained after zero-field cooling and subsequent warming (ZFC-W). The field-cool warming (FCW) data are practically identical to the FCC data and omitted for clarity. The arrows point to the secondary transition, which becomes visible in fields above 0.5 T. This onset is clearly depending on the applied magnetic field. At very low temperatures, the $m(T)$ curves are bent upwards due to the paramagnetic moment of copper.

The drastic change of the dominating pinning mechanism in the Bi-2223 samples is directly linked to our earlier observation that there is a second step in the

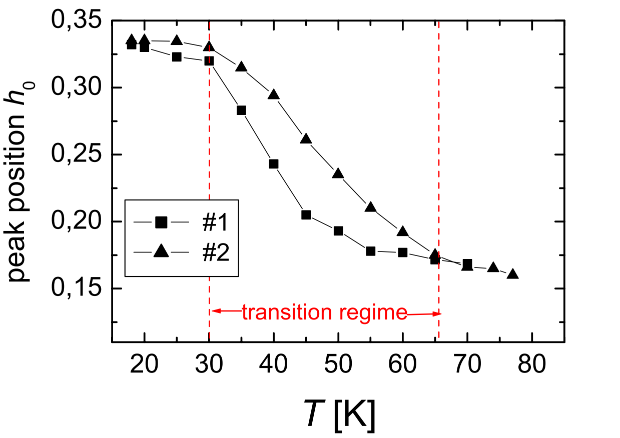

Fig. 3. The peak position of the pinning force scaling, h_0, as a function of temperature for two selected samples "1" and "2". The lines are guidelines to the eye.

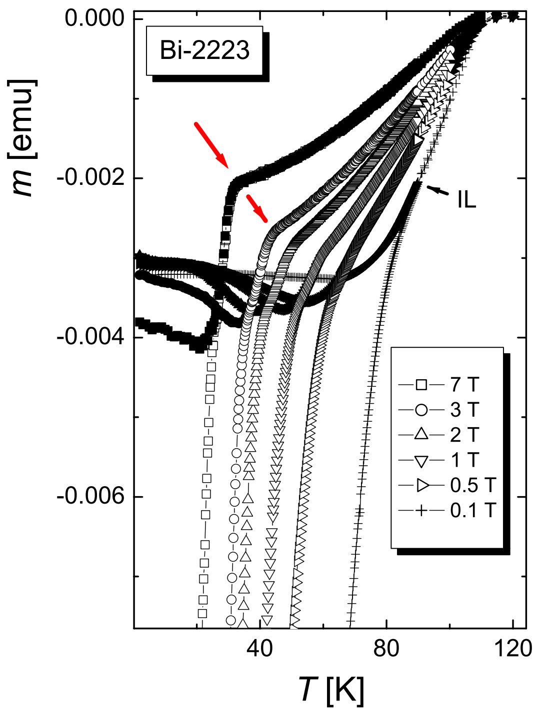

Fig. 4. The temperature dependent scan of the magnetization of a monofilamentary Bi-2223 tape. The full symbols give $m(T)$ after field-cool cooling and the open symbols after zero-field cooled warming. The merging of both datasets gives the irreversibility (IL) field. The arrows point to the secondary transition, which becomes visible in applied fields above 0.5 T.

$m(T)$ curves at high applied magnetic fields (see Fig. 4). This step is also seen in Bi-2212 single crystals [9,17] as well as in Bi-2212 bulks [18,19], only in these materials at slightly lower temperatures. This step may indicate the breakdown of the Josephson-coupling between superconducting clusters, due to the presence of Bi-2201 with a T_c of ≈20 K. This would imply that even the best single crystals of Bi-2212 are spatially inhomogeneous. The presence of such intergrowths were observed by TEM in all Bi-based systems [20].

The peak position $h_0 = 0.33$ implies according to reference [1] a flux pinning at small ($v \sim \xi^3$) normal-conducting or insulating particles. This peak position is also found in various experiments on $YBa_2Cu_3O_x$ (YBCO) samples [5,21]. As at low temperatures even in a layered superconductor the pancake vortices are strongly coupled together, there is no visible difference between the pinning behaviour of Bi-2223 and YBCO. However, at elevated temperatures, the peak position $h_0 \approx 0.18$ indicates a dominant flux pinning of a two-dimensional type like e.g. grain boundaries or dislocations. In this case, the bending experiments of tapes should have shown some increase of j_c at small bending strains. This was, however, never observed [22]. Another possibility is that the vortices in the Bi-2223 material dissociate into pancakes at a temperature of about 30 K; in this case, the effective pinning landscape will change for the resulting pancake vortices. Furthermore, it is clear that the point defects which are operating well at low temperatures, are not suitable to pin effectively the pancake vortices. This dissociation of pancake vortices may also cause the secondary transition as found in the $m(T)$ scans. Following de Lima et al. [17], the secondary transition in the $m(T)$ curves is caused by Josephson coupling of strongly superconducting islands, which would not change the basic flux pinning mechanism, but the lengthscale on which the superconducting currents are flowing. If the secondary transition is caused by embedded Bi-2201 material, then these superconducting areas would become normal-conducting at around 30 K, thus the number of effective pinning sites could even increase. A δT_c-pinning due to such superconducting areas will only be effective just below the secondary transition temperature – this is indeed the region where the peak or butterfly effect in Bi-2212 crystals is observed [23].

A final decision on which transition takes place in the Bi-2223 samples can, at the moment, not be reached from a scaling analysis as the pinning functions of Dew-Hughes are not describing a situation like the dissociation of vortices into pancakes. Here, further studies including theoretical modelling are required. However, some important conclusions can be drawn from the data presented here:
(i) In the low-temperature range, Bi-2223 is similar to YBCO but with higher irreversibility fields,
(ii) at temperatures around 30 K a secondary transition takes place, which is the reason for a drastic change in the pinning mechanism, and
(iii) for a further increase of j_c in Bi-2223 superconductors, it is essential to extend the range of the F_p-scaling at a peak position of 0.33 towards higher temperatures.

From this scaling analysis, it is clear that from measurements at $T = 77$ K, one cannot predict the behaviour of the sample at temperatures lower than 40 K correctly. For example, measurements on monofilamentary tapes show a much stronger increase of j_c and F_p at low temperatures as compared to multifilamentary tapes and the extracted filaments.

The present observation also explains why the attempts to introduce pinning sites into the Bi-2212 or Bi-2223 matrix by adding MgO nanoparticles [24,25] or CrO_3 [26] have failed to increase j_c at $T = 77$ K. If there is an effect of these particles to be observed, then it must be at low temperatures and/or in the intermediate temperature range between 30 and 70 K, i.e., the peak position at $h_0 = 0.33$ should be maintained towards higher temperatures. Very recent experiments, however, show an increase of j_c by adding nanoparticles of Al_2O_3 to bulk Bi-2223 samples [27] and by adding small amounts of Ni to Bi-2223 tapes [28]. The latter doping of Ni on the Cu site would provide a flux pinning of the δT_c-type, also leading to an increase of the peak position in the F_p-scaling.

Irradiation experiments of tapes, where columnar or quasi-columnar defects are introduced, should lead to a peak position h_0 which is maintained to higher temperatures as compared to non-irradiated samples.

4 Conclusions

To conclude, we have found that the pinning force scaling in Bi-2223 works well in two narrow temperature regimes around 70 K and below 20 K. In the intermediate temperature range, the peak position shifts towards 0.18 on increasing T, manifesting a change in the basic pinning mechanism.

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References

1. D. Dew-Hughes, Philos. Mag. **30**, 293 (1974)
2. E.J. Kramer, J. Appl. Phys. **44**, 1360 (1973)
3. H. Ullmaier, *Irreversible Properties of Type II Superconductors* (Springer-Verlag, Berlin 1975), Chap. 3
4. A.M. Campbell, J.E. Evetts, Adv. Phys. **21**, 199 (1972)
5. M.R. Koblischka, A.J.J. van Dalen, T. Higuchi, S.I. Yoo, M. Murakami, Phys. Rev. B **58**, 2683 (1998)
6. M.R. Koblischka, Physica C **282-287**, 2197 (1997)
7. P. Fabbricatore, C. Priano, A. Sciutti, G. Gemme, R. Musenich, R. Parodi, F. Gömöry, J.R. Thompson, Phys. Rev. B **54**, 12543 (1996)
8. M.R. Koblischka, M. Murakami, Supercond. Sci. Technol. **13**, 738 (2000)
9. M.R. Koblischka, M. Murakami, Phys. Stat. Sol. (b) **218**, R3 (2000)
10. W.G. Wang, Z. Han, P. Skov-Hansen, J. Goul, M.D. Bentzon, P. Vase, Y.-L. Liu, IEEE Trans. Appl. Supercond. **9**, 2613 (1999)
11. M.R. Koblischka, W.G. Wang, B. Seifi, P. Skov-Hansen, P. Vase, N.H. Andersen, IEEE Trans. Appl. Supercond. **11**, 3242 (2001)
12. X.Y. Cai, A. Polyanskii, Q. Li, G.R. Riley Jr., D.C. Larbalestier, Nature **392**, 906 (1998)
13. G. Fuchs, E.S. Vlakhov, K.A. Nenkov, T. Staiger, A. Gladun, Physica C **247**, 240 (1995)
14. Quantum Design, San Diego CA 92121, model MPMS7 and model XL
15. M.R. Koblischka, M. Muralidhar, T. Higuchi, K. Waki, N. Chikumoto, M. Murakami, Supercond. Sci. Technol. **12**, 288 (1999)
16. J. Sosnowski, M. Rabara, K. Demachi, K. Miya, Supercond. Sci. Technol. **13**, 558 (2000)
17. O.F. de Lima, V.P.S. Awana, R.A. Ribeiro, M.A. Avila, Europhys. Lett. **51**, 174 (2000)
18. M.R. Koblischka, M. Murakami, T.H. Johansen, IOP Conf. Ser. **167**, 915 (2000)
19. M.R. Koblischka, Phys. Stat. Sol. (a) **189**, R1 (2002)
20. L. Gottschalk-Andersen, S. Bals, G. van Tendeloo, H.F. Poulsen, Y.-L. Liu, Physica C **353**, 251 (2001)
21. M.R. Koblischka, Tsinghua Sci. Technol. **8**, 280 (2003)
22. P. Kovac, L. Kopera, I. Husek, L. Cesnak, Supercond. Sci. Technol. **9**, 79 (1996)
23. D.T. Fuchs, E. Zeldov, T. Tamegai, S. Ooi, M. Rappaport, H. Shtrikman, Phys. Rev. Lett. **80**, 4971 (1998)
24. K. Christova, A. Manov, J. Nyhus, U. Thisted, O. Herstad, S.E. Foss, K.N. Haugen, K. Fossheim, J. Alloy Comp. **340**, 1 (2002)
25. B. Zhao, W.H. Song, X.C. Wu, J.J. Du, Y.P. Sun, H.H. Wen, Z.X. Zhao, Physica C **361**, 283 (2001)
26. T. Hu, H. Xiao, M.H. Pu, X.C. Wu, W.H. Song, B. Zhao, Y.P. Sun, J.J. Du, Phys. Stat. Sol. (a) **186**, 135 (2001)
27. M. Annabi, A. Mchirgui, F. Ben Azzouz, M. Zouaoui, M. Ben Salem, Physica C **405**, 25 (2004)
28. R.C. Ma, W.H. Song, X.B. Zhu, L. Zhang, S.M. Liu, J. Fang, J.J. Du, Y.P. Sun, C.S. Li, Z.M. Yu, Y. Feng, P.X. Zhang, Physica C **405**, 34 (2004)