Supercond. Sci. Technol. **10** (1997) 484–491. Printed in the UK PII: S0953-2048(97)78896-1

Relaxation and scaling of magnetization around the fishtail minimum in $DyBa_2Cu_3O_7$ single crystal with columnar tracks

M Jirsa†, M R Koblischka‡ and A J J van Dalen‡§

† Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ-18040 Praha 8, Czech Republic
‡ Superconductivity Research Laboratory, ISTEC, 1-16-25, Shibaura, Minato-ku, Tokyo 105, Japan

Received 24 October 1996, in final form 17 February 1997

Abstract. Conventional and dynamic relaxation processes and scaling properties of the magnetic hysteresis loops (MHL) were studied on a Pb-ion irradiated $DyBa_2Cu_3O_{7-\delta}$ single crystal by means of the torque magnetometry. The columnar pinning structure produced by irradiation enhanced considerably the induced critical current density and caused the high-field part of the MHL to be field-independent up to $B \geq 7$ T. The substantial change of the pinning structure shifted the appearance of the fishtail effect to higher temperatures and fields. The relaxation experiments confirm a correlation between the relaxation rate and the MHL shape and point to quite different relaxation regimes at high and low fields. Correspondingly, the scaling of the MHLs in both field ranges is different. This behaviour is modelled by two separable contributions to the MHL, one being active mainly at high fields and the other at low fields (central peak). Possible origins of these two contributions are discussed.

1. Introduction

A lively discussion on the origin of the fishtail effect (FE) and a deformation of the magnetic hysteresis loop (MHL) observed on many bulk samples [1–4] brought many controversial explanations including the granularity appearing in the sample at higher fields [5], oxygen vacancies changing the pinning efficiency at higher fields [6], creep effects in the vortex system [7–9] or a crossover of the pinning regimes [10]. Whereas the former two (static) approaches present the fishtail shape as a 'peak' effect caused by a pinning enhancement at high fields, the latter two approaches point to the dynamic character of the fishtail effect and attribute FE to the enhanced flux creep at low fields which results in the development of the (fishtail) minimum in the MHL.

However, the actual shape of the MHL is a result of an equilibrium between current-constituting (induction and pinning) and current-reducing (relaxation) processes [11, 12]. Therefore, any of the static or dynamic approaches, used separately, describe only one of the two sides of the same coin. A strong support for this follows from the model proposed in references [13, 14] which show that in the case of a $TmBa_2Cu_3O_{7-\delta}$ single crystal there is a close relation between the shape of the MHL and the normalized relaxation rate. This model was recently applied to measurements on twin-free $DyBa_2Cu_3O_{7-\delta}$ single crystals [15]. It was shown that, at least in $(RE)Ba_2Cu_3O_{7-\delta}$ ((RE)-123, (RE)=rare earth) samples with a random disorder, the MHL can be understood as a superposition of two independent pinning regimes, each of them having domain of its main activity at another field range. This approach explains practically all features of the fishtail effect in (RE)-123 twin-free single crystals.

It is well known that columnar tracks, produced by irradiation with heavy ions, are very effective pinning centres, especially for vortices aligned parallel to the tracks [16–20]. The pinning structure consisting of columnar defects can mask most of other contributions from the pre-existing natural pinning structures [19]. Introduction of columnar defects into a sample exhibiting a pronounced fishtail effect should have a drastic effect onto the shape of the MHL. However, preliminary results presented in reference [21] showed that FE did not disappear completely after the irradiation, it only changed its character. After irradiation with Pb ions, the fishtail maximum was masked by a plateau at high fields. The fishtail effect survived, being manifested at temperatures

§ Present address: Argonne National Laboratory, Argonne, Il 60439, USA.

above 30 K by a minimum in the MHL at fields below 2.4 T.

In this paper, we analyse the scaling and relaxation properties of the Dy-123 single crystal irradiated with Pb ions in more detail and test the model of Perkins *et al* [13, 14] on a sample with columnar defects.

2. Experimental procedure

2.1. Sample preparation and characteristics

The twin-free $DyBa_2Cu_3O_{7-\delta}$ single crystal was prepared by a self-flux method in SnO_2 crucibles [22] and had dimensions $(a \times b \times c)$ 800 ×800× 15 μm^3. After extensive magnetic measurements, analysed in references [7, 9], the sample was irradiated by Pb ions with energy $E = 0.9$ GeV and a fluence $\phi t = 1.15 \times 10^{11}$ ions cm^{-2} at GANIL, Caen. The incident beam was parallel to the c-axis, and produced a structure of columnar tracks propagating all over the thickness of the sample. The dose-equivalent field was $B_\Phi = 2.4$ T, i.e. the number of vortices just matched the number of columnar tracks at 2.4 T. To characterize the sample in both cases, magneto-optical observations of flux distributions at external fields up to 0.5 T were carried out before and after the irradiation, using the Faraday effect in thin EuSe layers [23].

It is interesting to note that after the irradiation the maximum remanent current density at 10 K yielded $j_s \simeq 1.2 \times 10^{11}$ A m^{-2} which corresponds to the estimations for Dy-123 and vortices confined to columnar tracks in the whole length [17], $j_s \approx j_d\ \xi(T)/R$, where ξ is the coherence length, R is the radius of the columnar defect, and j_d is the depairing current. For typical values $\xi \simeq 10$ μm, $R \simeq 30$ μm, and $j_d \simeq 4 \times 10^{12}$ A m^{-2} (see e.g. reference [24]), we get the theoretical value $j_s \simeq 1.3 \times 10^{12}$ A m^{-2}. This value is only ten times higher than the experimental one detected with a finite sweep rate. The difference is attributed to a strong relaxation effect which will be documented below.

2.2. Torque measurements

Magnetic properties were studied by means of torque hysteresis loops ($\boldsymbol{\tau} = \boldsymbol{M} \times \boldsymbol{B}_e$) measured using a capacitance torque magnetometer in external magnetic fields up to ±7 T, oriented at an angle Θ with respect to the c-axis of the crystal. The measured torque was translated into magnetic moment

$$M = \tau/(B_e \sin\Theta) \qquad (1)$$

and the associated current densities j_s were calculated using the extended Bean formalism

$$j_s = \Delta\tau/(\Omega B_e \sin\Theta) \qquad (2)$$

where $\Delta\tau$ denotes the difference between the torque amplitudes on the descending and ascending branches of the torque curve, and the geometrical factor Ω for the rectangular sample is given by $\Omega = a^2(b - a/3)c/2$.

In order to adjust the applied magnetic field as close as possible to the columnar tracks direction and still obtain reasonable torque values, most of the measurements were performed at $\Theta = 5°$. Some additional measurements at $\Theta = 59°$ manifest the orientation effect.

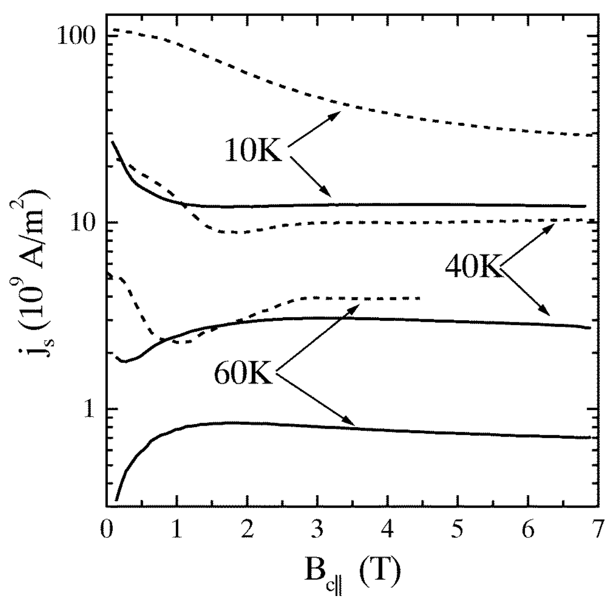

Figure 1. Comparison of the critical current densities before (full curves) and after (dashed curves) the irradiation with Pb ions for 10 K, 40 K and 60 K.

Conventional relaxation (CR) experiments were carried out sweeping the applied magnetic field to the target value with a rate of 40 mT s^{-1}, holding it constant there and measuring the decay of the torque and/or the associated current density j_s for t = 900 s. Dynamic relaxation (DR) measurements [11, 12] consisted of recording the torque curves with various sweep rates dB_e/dt ranging from 40 to 2.5 mT s^{-1}.

3. Experimental results

3.1. Specific shape of the MHL

After irradiation with Pb ions, the Dy-123 single crystal exhibited the MHL with a specific shape, very different from MHLs on other irradiated samples described in literature [16, 25]. Although persistent currents were enhanced by the Pb-ion irradiation several times in all the investigated field and temperature ranges (see figure 1), giving evidence that columnar tracks are dominant pinning structures, the MHL exhibited a plateau at fields above $\gtrsim B_\Phi$, in contrast to the theory that predicts a $1/B_e$ dependence for this field range [26].

As expected, pinning on columnar defects was most effective at low fields, and resulted in a broad central peak of the hysteresis loop, especially at low temperatures. With increasing temperature, size of this maximum rapidly decreased. Above $T \approx 30$ K the halfwidth was reduced to ≈ 2.4 T and a fishtail minimum appeared below the plateau. This minimum became deeper with increasing temperature and its position shifted to lower fields, similarly to the fishtail minimum in unirradiated samples.

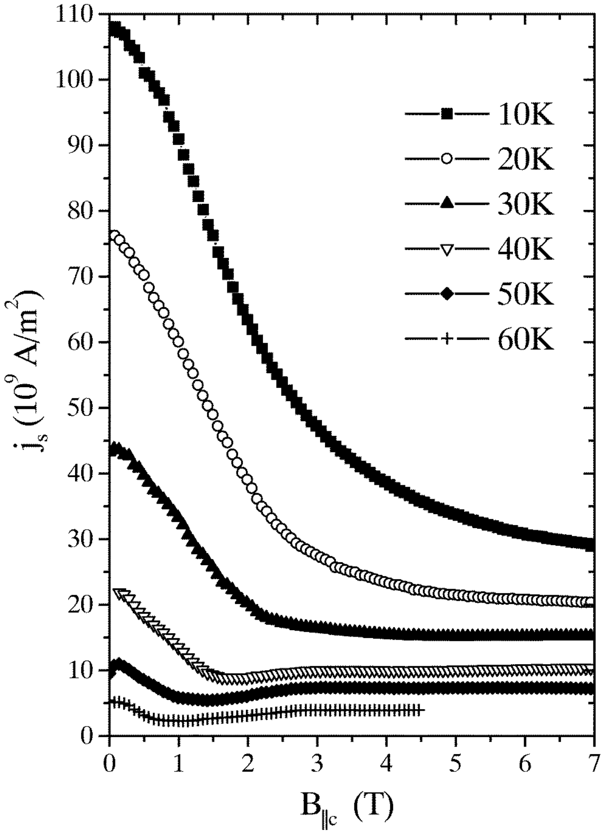

Figure 2. The induced critical current density, j_s, calculated using equation (2) for $\Theta = 5^\circ$ as a function of the effective magnetic field component $B_{||c} = B_e \cos\Theta$ for various temperatures.

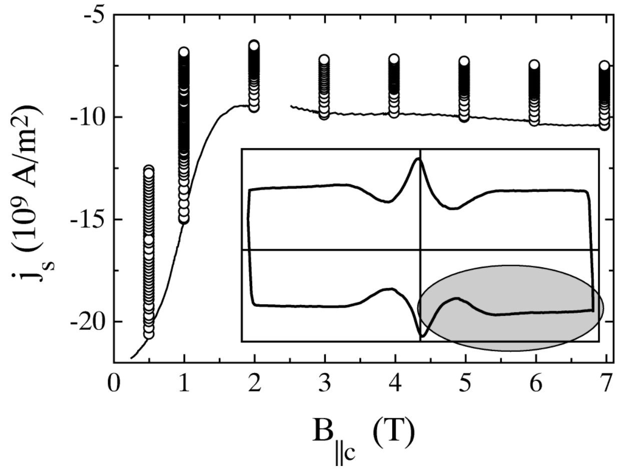

Figure 3. Conventional relaxation (CR) measurements in the ($j_s - B_e$) diagram, detected at various external fields B_e = 0.5 T to 7 T at T = 40 K; $\Theta = 5^\circ$. The CRs were recorded for t = 900 s.

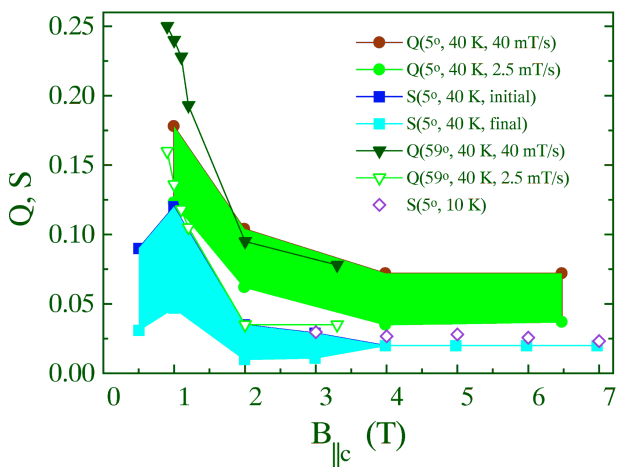

Figure 4. Summary of the logarithmic relaxation rates Q and S as a function of $B_{||c}$ for T = 40 K, $\Theta = 5^\circ$ and 59°. The dashed areas mark a dispersion of Q or S during each experiment. For comparison, Q data for T = 10 K and $\Theta = 5^\circ$ are added.

While the sample before irradiation exhibited a pronounced fishtail effect at temperatures above T = 10 K [7, 9] the irradiation shifted appearance of the minimum to temperatures above 30 K (figure 2). No fishtail maximum has been observed at high fields. It was evidently masked by a saturation effect on persistent currents at high fields.

3.2. Conventional relaxation processes

The unconventional shape of the MHL gave us the opportunity to test the validity of the relation between the relaxation rate and the shape of the MHL proposed by Perkins *et al* [13, 14]. We measured conventional relaxation rates (B_e = const) at T = 40 K where a well-developed fishtail minimum had been detected. In figure 3 the relaxation measurements are presented as the dependence $j_s(B_{||c})$ for comparison of the relaxation processes at different fields both with each other and with the size of the magnetic hysteresis loop preceding the relaxation. The strength of relaxation is expressed by the vertically aligned sets of symbols running from the starting to the final point ($\approx$ 900 s) of each relaxation in the (j_s, $B_{||c}$) plane. All the conventional relaxation processes were measured on the ascending field branch of the MHL as indicated in the inset in figure 3. Note the striking difference between the relatively slow flux creep at fields $B_{||c} \geq 2.4$ T and the much faster creep at lower fields.

In agreement with already published observations [27, 28] the relaxation was significantly non-logarithmic at most investigated fields. Consequently, the normalized logarithmic relaxation rate $S = -\mathrm{d}\ln j_s/\mathrm{d}\ln t$ (calculated as a tangent to the $\ln j_s$ versus $\ln t$ plot) decreased continuously with increasing relaxation time. The initial stage of the relaxation process was much faster at low external fields than at higher ones. At low fields, S dropped from the value of ≈ 0.1 at the beginning of relaxation to $S \approx 0.02$–0.03 at t = 900 s, while at high fields ($B_{||c} \geq B_\Phi$), S did not change so dramatically, and always was close to 0.02–0.03 (see figure 4).

Effect of irradiation upon the relaxation process is documented in figure 5. Columnar defects caused reduction of the relaxation rate at high fields, whereas in the intermediate field range, the relaxation was enhanced.

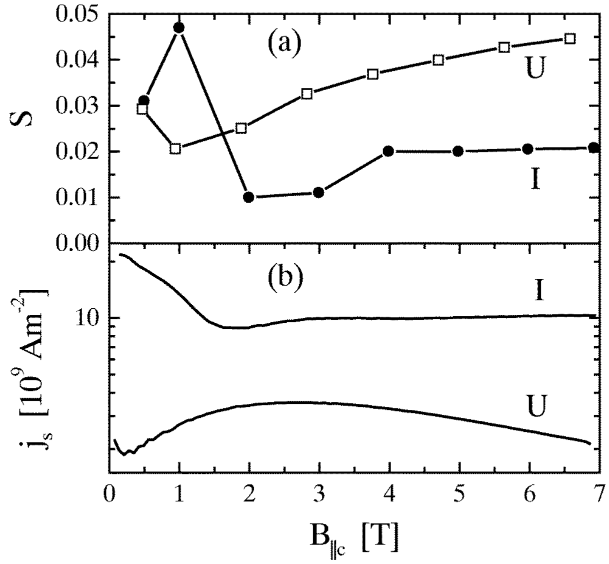

Figure 5. The logarithmic relaxation rate S at t = 900 s (a) and the critical current density j_s (b) as a function of $B_{||c}$ before (U) and after (I) irradiation. T = 40 K and Θ = 5°.

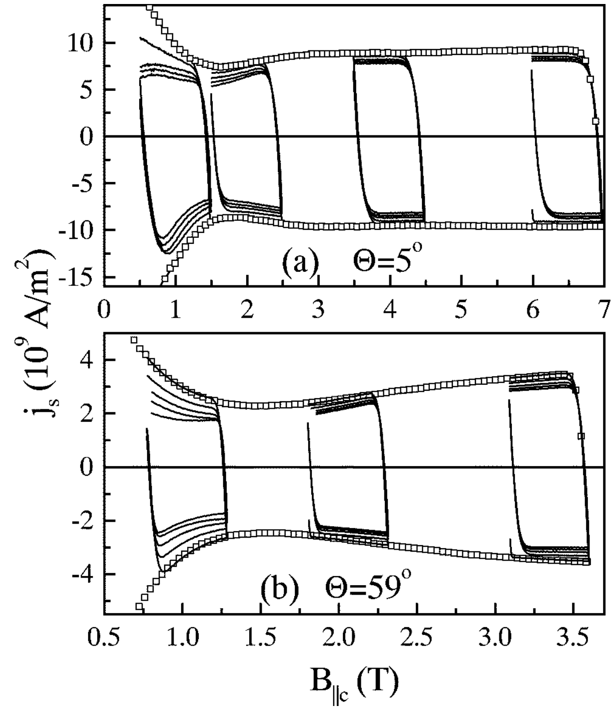

Figure 6. Dynamic relaxation measurements at T = 40 K. The full loops were recorded with the sweep rate dB_e/dt = 40 mT s^{-1}, minor loops with the sweep rates 20, 10, 5, and 2.5 mT s^{-1} (from outside to inside). Θ = 5° (a), Θ = 59° (b).

3.3. Dynamic relaxation processes

As the conventional relaxation processes were considerably non-logarithmic, especially at the beginning, we combined CR with dynamic relaxation measurements that cover a short-time range of relaxation [11]. Magnetic hysteresis loops measured with different sweep rates at $T = 40$ K at two different angles $\Theta = 5°$ and $\Theta = 59°$ are shown in figure 6. The full magnetization loop measured using a sweep rate of $dB_e/dt = 40$ mT s^{-1} encloses minor loops taken around fields $B_e = 1$, 2, 4 and 6.5 T with four lower sweep rates, $dB_e/dt =$ 20, 10, 5 and 2.5 mT s^{-1}.

Similarly to the conventional relaxation, the normalized dynamic relaxation rate [12] $Q = d\ln(M_{||c})/d\ln(dB_{||c}/dt)$ increased significantly at fields below 2.4 T. This is indicated by increased distance of the MHL curves measured with different sweep rates. This behaviour was consistently observed at different angles Θ (figures 6(a) and (b)).

The non-logarithmic $j_s(B_e)$ dependence, observed in the CR experiments, was even more pronounced in the dynamic relaxation measurements. The normalized relaxation rate Q decreased with decreasing sweep rate in the whole investigated field range. As a result, instead of $Q(B_{||c})$ curves, we obtained Q bands (figure 4) with limits given by the highest and the lowest sweep rate used. The Q bands lay consistently above the corresponding bands of the S values, in accordance with the fact that the dynamic relaxation describes an early (fast) stage of the relaxation process [11, 12]. Such a behaviour corresponds to the $U(j_s)$ dependence that is significantly stronger than linear.

The Q band for $\Theta = 59°$ lies at low $B_{||c}$ even above that for $\Theta = 5°$ which indicates that the relaxation increases anomalously with increasing tilt angle, especially at low fields [29] similar to unirradiated samples [7, 30].

4. Discussion

In unirradiated (RE)-123 single crystals, it has been experimentally well documented that the shape of the MHL at high fields reflects interaction of vortices with an active pinning structure [2,4–6,31]. Pinning on a random disorder (e.g. due to oxygen vacancies [5, 6]) is effective mainly at fields above the full flux penetration and is responsible for the *fishtail maximum*. This part of the MHL usually scales well with field and temperature, producing a universal curve with a shape that can be well described as [15]

$$j_{sc}(b) = b^m \exp\left[\frac{m}{n}(1 - b^n)\right] \quad (3)$$

where j_{sc} is the critical current density and b is the applied field normalized with respect to the current density and field of the fishtail peak, respectively. The coefficients m and n are consistent with those used in reference [14] and with the factors k_E and $(1 - \gamma_E)/[\gamma_E \ln(vB_e/E)]$, respectively, of reference [13]. Note that qualitatively the same relation as in equation (3) follows from the collective pinning theory for the high-field region [32]. Equation (3) indicates that the high-field pinning regime looses its efficiency at fields close to zero. According to this model, the *fishtail minimum* is a result of the loss of efficiency of the high-field pinning regime and of a contribution of an additional pinning regime, active mainly at low fields.

The critical current *proportional* to B_e in the low-field region looks rather striking. Perkins' model [13, 14] predicts such a behaviour for a general thermally activated relaxation process and explains that by an interplay of different field dependencies of the characteristic critical current j_0 and the characteristic energy barrier U_0 defined by the relation [33, 13]

$$U_{\mathrm{eff}}(j_s, B_e, T) = U_0(B_e, T)\ f[j_s/j_0(B_e, T)] \qquad (4)$$

j_0 being directly, and U_0 reciprocally proportional to a power of B_e. Note that the same relation was a starting point of the model of vortex accommodation to columnar defects [25].

The MHLs observed in our irradiated sample show that a strong pinning on columnar defects is able to mask the fishtail *maximum* at high fields. However, even in such a case, the critical current density corresponding to the high-field pinning regime tends towards zero at low fields. The central peak enables the fishtail minimum to appear by becoming at elevated temperatures sufficiently slender. Similar effect was also observed at 77 K in the Sn-irradiated Y-123 single crystal [16]. In this case, however, the magnetic moment exhibited a sharp maximum at intermediate fields. A narrow sharp minimum on the MHL at external fields around zero and temperatures above 60 K was also observed during our own, yet unpublished, experiments on Xe-irradiated Dy-123 single crystals.

The interpretation of the MHLs observed in the irradiated sample has several problems. First of them is the presence of a huge central peak extending at low temperatures above 7 T. Second is the saturation of persistent currents at high fields. And third is the appearance of a minimum on the MHL at high temperatures and intermediate fields.

The first problem should be solved using the theory of pinning on a columnar structure [26]. This theory introduces a term 'accommodation field', B^*, as a crossover between a strong pinning of individual vortices on columnar tracks and a regime when vortices are able to move among the columns. This regime corresponds to much weaker collective pinning with a $1/B_e$ dependence of critical currents. Krusin-Elbaum *et al* [25] recently showed that in the Y-123 single crystals irradiated with Xe ions, the accommodation field drops with increasing temperature from the value close to B_Φ to zero at $T \approx 0.5\ T_c$. This rapid reduction of the regime of a strong individual pinning can qualitatively explain the experimentally observed behaviour of the huge central peak. There are, however, some discrepancies between our experiments and the model:

(i) the slope of the central peak can be at high fields approximated by the $1/B_e$ dependence only at $T = 10$ K, at higher temperatures j_s drops with increasing field more rapidly. Figure 8 shows that this dependence is close to exponential;

(ii) j_s does not fall with increasing field to a constant value given by pre-existing point disorder. At all temperatures and at high fields j_s is well above the value of the unirradiated sample;

(iii) even above the decoupling temperature $\approx 0.5\ T_c$ a significant central peak was observed (see figure 2);

(iv) the model does not explain appearance of the fishtail minimum.

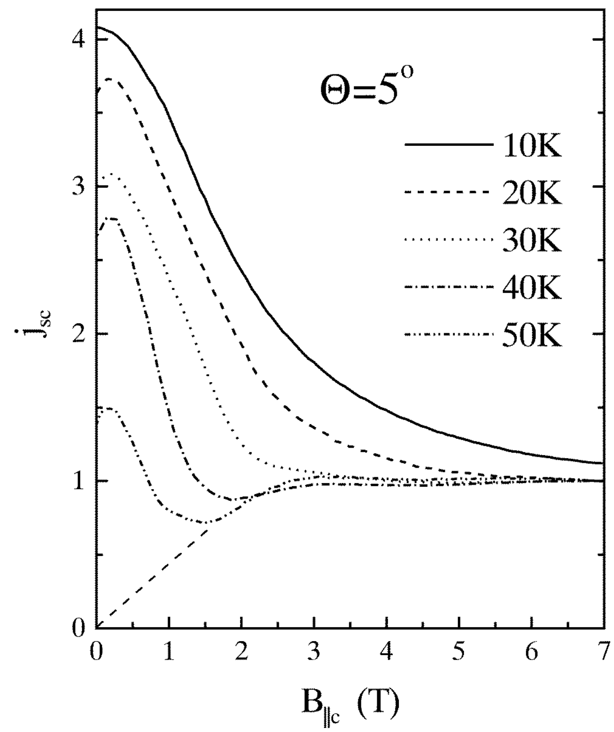

Figure 7. The $j_s(B_{||c})$ dependencies from figure 2 normalized with respect to the value of j_s at $B = 7$ T at the given temperature.

The observed discrepancies at low fields might be explained in the following way: the central peak is composed of a huge contribution from the individual vortex pinning on columnar tracks and an additional, much weaker, contribution due to stray fields. At high fields, another pinning regime exists making j_s high, field-independent and only slightly temperature-dependent.

As regards the fishtail effect, different temperature dependencies of j_s at low and high fields seem to be crucial. If the central peak drops with temperature faster than the high-field part of the MHL, a fishtail minimum appears at intermediate fields at sufficiently high temperature. Such a behaviour is apparent from figure 9 where the high-field curves cross the low-field ones at temperatures just above 30 K.

To investigate different temperature dependencies of critical currents at low and high fields in more detail, we normalized the critical current densities presented in figure 2 with respect to the level of the high-field plateau. At the lowest temperature, where the central peak extended above 7 T, we used a normalized value obtained as an extrapolation of the temperature dependence of $j_s(7\ \mathrm{T})$ from higher temperatures. The result is shown in figure 7. Below 30 K the central peak becomes slender enough to reveal the real shape of the high-field pinning contribution to the MHL. Figures 2 and 7 show that the high-field contribution tends towards zero at low external fields, similar to unirradiated samples [13, 15].

Under the assumption that the high-field part falls to a value close to zero at low fields [15], we approximated this pinning regime by a universal curve coinciding with

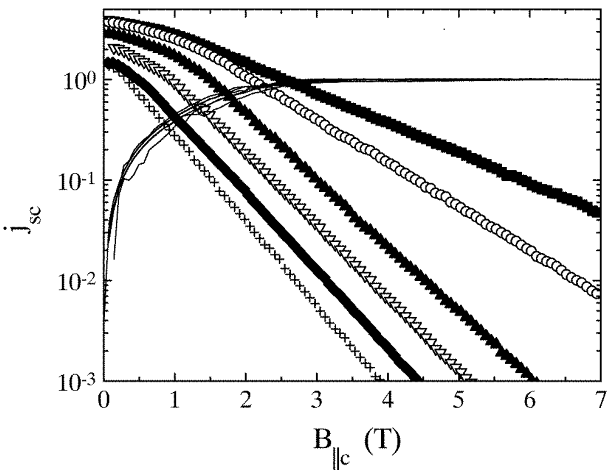

Figure 8. Decomposition of the normalized $j_s(B_{||c})$ curves from figure 7 into two additive contributions corresponding to the high-field pinning mechanism and the central peak pinning regime.

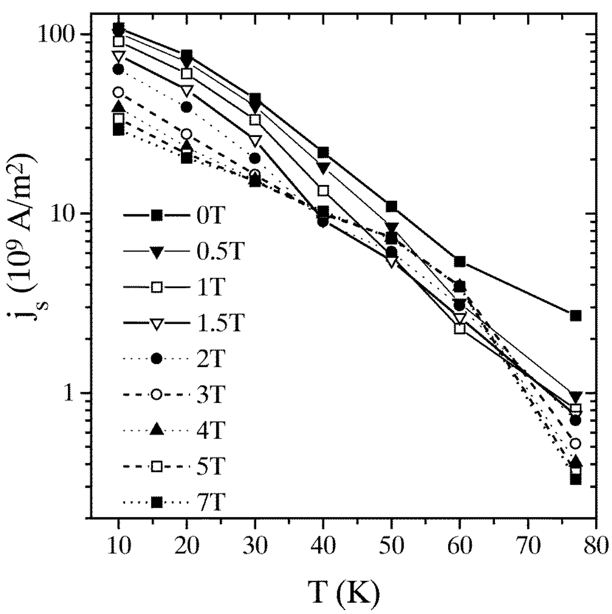

Figure 9. Temperature dependencies of j_s for different field values.

the normalized $j_{sc}(B_{||c})$ curve for 60 K. The central peak is sufficiently narrow at this temperature to be eliminated by an extrapolation of the positive slope of the high-field part of the curve towards zero. The universal curve was then subtracted from the experimental $j_{sc}(B_{||c})$ data shown in figure 7. The result is an approximate low-field contribution. As shown in figure 8, it decays nearly exponentially with $B_{||c}$.

Due to the absence of a well-defined fishtail maximum at a single field value, we could not establish field scales at different temperatures in the same way as in the reference [13]. However, in our decomposition procedure, the scaling factor would enter the exponential decay rate only and would not change the shape of the central peak.

Although it might seem speculative, the decomposition procedure presented in this paper gives surprisingly consistent results for all the investigated temperatures. It means that in our irradiated sample, the MHL also can be understood as a superposition of two (or more) critical current contributions with different temperature dependencies.

As regards the origin of the field-independent critical current at high fields, it is interesting to note that the regime of individually pinned vortices, extended up to 6.5 T, has been deduced from the slowly decreasing field dependence of j_s in the sample before the irradiation [9]. A high-field plateau on the MHL has also been found in twinned (unirradiated) Y-123 single crystals [31]. The authors have shown that twinning and detwinning reproducibly changed the character of the MHL and twins caused a plateau at high fields. It means that the plateau might be a result of pinning on some type of a correlated disorder. Twins are probably excluded in our case because

(i) the sample was twin-free before the irradiation and
(ii) the critical currents after irradiation are too high to be caused by twin boundaries.

Some arrangement of columns into a regular structure might be a possible explanation. The high plateau in the $j_s(B_e)$ dependence extended up to fields as high as 7 T, represents an interesting subject for applications. It is a pity that a detailed investigation of the relevant defects was not possible as the sample was damaged at the end of magnetic measurements.

Now we turn to the relaxation phenomena. Comparing the $S(B_{||c})$ dependencies before and after the irradiation (figure 5(a)) with the corresponding $j_s(B_{||c})$ functions (figure 5(b)), the relation between the shape of the MHL and S becomes evident. Extremes of the $S(B_{||c})$ curves lie in both cases close to the inflection points of the corresponding $j_s(B_{||c})$ functions which is a further supporting argument for the Perkins' model [13, 14].

Krusin-Elbaum *et al* [25] predicted the $S(T)$ dependence to have a pronounced maximum at intermediate temperatures. Unfortunately, our experiments overlap at only a few points of the (B_e, T) plane and there is not enough evidence for making unambiguous conclusions. At the points where data exist, our S values do not contradict the model.

We also tried to interpret the S values in terms of the collective pinning theory [32]. On the basis of the interpolation formula

$$j_s = \frac{j_0}{[1 + (\mu T/U_c)\ln(t/t_0)]^{1/\mu}} \tag{5}$$

we get the relation

$$S = \frac{1}{[U_c/kT + \mu \ln(t/t_0)]}. \tag{6}$$

At high fields $\mu \simeq 1$, the relaxation time t is 900 s, and the attempt time t_0 is typically of order of 10^{-10} s. For $S = 0.02$ at $T = 40$ K, equation (6) gives $U_c/k = 800$ K. For the minimum value of $S = 0.01$, we obtain $U_c/k = 2800$ K. Such pinning energy is an order of magnitude larger than that before the irradiation [9]. This result contradicts the magnetooptic studies of Schuster *et al* [17] performed on the Pb-irradiated Dy-123 samples from the same batch. The authors found U_c to be small and practically independent of the irradiation dose. Taking U_c in the range of 100–200 K for our irradiated sample would lead on the other hand to the unrealistic values of $\mu \simeq 4$ or t_0 of order of 10^{-17} s. The explanation of the low values of S observed in the irradiated sample on the basis of a simple collective pinning regime without taking into account the effect of columnar defects is difficult and inconsistent with some experimental results. These values, however, do not collide with the phenomenological models of Perkins *et al* [13, 14] and Krusin-Elbaum *et al* [25] even though each of the models interprets the minimum relaxation rate in different way.

5. Conclusions

The irradiation by Pb ions introduced into the Dy-123 sample a pinning structure of columnar tracks that is dominant in the whole investigated range of fields and temperatures. The irradiation led in our sample to a specific shape of the MHL with a huge central peak and a plateau at fields between $B_\Phi \approx 2.4$ and 7 T.

The central peak is strongly temperature dependent. It leads to the reduction of the central peak width under 2.4 T at about 30 K, and to the appearance of the fishtail minimum at higher temperatures. The fact that a weak central peak is seen even at temperatures well above [25] $T_{dp} \approx 0.5\,T_c$ might indicate that the peak consists of two contributions, a strong one from the pinning on columnar tracks and a much weaker one due to stray fields.

The high-field plateau in the $j_s(B_e)$ dependence is very similar to that observed in the twinned (unirradiated) samples [31]. It might be that this feature is due to some specific arrangement of columnar tracks into a regular correlated structure.

The separation procedure proposed recently for unirradiated samples [15] and based on different temperature scaling of the low- and high-field contributions to the MHL is shown to work quite well for the present, very different pinning structure, too. Irrespective of the evident domination of the columnar pinning structure in the whole investigated field range, relaxation and scaling properties of the present sample resemble, surprisingly, more the behaviour of unirradiated samples than that of the irradiated ones.

The relaxation experiments support the relation between the relaxation rate and shape of the MHL proposed by Perkins *et al* [13, 14]. The available $S(T)$ data also conform to the model of vortex accommodation to columnar defects [25] but do not allow us to make unambiguous conclusions. Interpretation of the low S values on the basis of collective pinning, without taking into account the effect of columnar tracks, is rather controversial.

We suppose that for the appearance of the fishtail minimum, a different temperature dependence of the low- and high-field pinning regime is crucial. Only when j_s at low fields drops with increasing temperature more rapidly than at high fields, the decay of the high-field pinning regime at low fields (the fishtail minimum) can appear at a sufficiently high temperature. In the irradiated samples such a temperature is expected to be close to T_c. In some cases, however, no such dip was observed at all [27].

In spite of great amount of studies dealing with irradiated samples, we consider the available experimental material not to be sufficient for making reliable conclusions. Irradiation with a proper dose of heavy ions usually leads to a significant enhancement of pinning, however different conditions of the irradiation and specific properties of the superconducting samples may result in different relaxation and scaling properties. A further study of the pinning structures leading to high, field-independent critical currents (plateau) in a wide range of high fields is certainly of great interest also from the application point of view.

Acknowledgment

The authors thank Th Schuster (Max-Planck Institut für Metallforschung, Institut für Physik, Stuttgart) for the magnetooptical investigations, M Leghissa (University Erlangen–Nürnberg) and S Bouffard (Caen) for the irradiation of the sample, and Prof R Griessen (Vrie Universiteit Amsterdam) for the hospitality enabling to perform the torque measurements in his laboratory. This work was partly supported by the GA of the Czech Republic (grant 202/93/0669) and by GA of ASCR (grant A 1010512).

References

[1] Yeshurun Y, Bontemps N, Burlachkov L and Kapitulnik A 1994 *Phys. Rev.* B **49** 1548
[2] K A Delin, Orlando T P, McNiff E J Jr, Foner S, van Dover R B, Schneemeyer L F and Waszczak J V 1992 *Phys. Rev.* B **46** 11092
[3] Cohen L F, Laverty J R, Caplin A D and Assmus W 1993 *Cryogenics* **33** 352
[4] Werner M, Sauerzopf F M, Weber H W, Veal B D, Licci F, Winzer K and Koblischka M R 1994 *Physica* C **235–40** 2833
[5] Däumling M, Seuntjens J M and Larbalestier D C 1992 *Nature* **346** 332 Osofsky M S, Cohn J L, Skelton E F, Miller M M, Soulen R J Jr, Wolf S A and Vanderah T A 1992 *Phys. Rev.* B **45** 4916
[6] Vargas J L and Larbalestier D C 1992 *Appl. Phys. Lett.* **60** 1741
[7] Jirsa M, van Dalen A J J, Koblischka M R, Ravi Kumar G and Griessen R 1994 *Critical Currents in Superconductors* ed H W Weber (Singapore: World Scientific) p 221
[8] Hiergeist R, Hergt R, Erb A and Müller-Vogt G 1994 in *Critical Currents in Superconductors* ed H W Weber (Singapore: World Scientific) p 225
[9] van Dalen A J J, Koblischka M R, Griessen R, Jirsa M and Ravi Kumar G 1995 *Physica* C **250** 265
[10] Krusin-Elbaum L, Civale L, Vinokur V M and Holtzberg F 1992 *Phys. Rev. Lett.* **69** 2280
[11] Půst L, J. Kadlecová, Jirsa M and Durčok S 1990 *J. Low Temp. Phys.* **78** 179
[12] Jirsa M, Půst L, Schnack H G and Griessen R 1993 *Physica* C **207** 85
[13] Perkins G K, Cohen L F, Zhukov A A and Caplin A D 1995 *Phys. Rev.* B **51** 8513
[14] Perkins G K and Caplin D 1996 *Phys. Rev.* B **54** 12551
[15] Jirsa M, Půst L, Dlouhy D and Koblischka M R 1997 *Phys. Rev.* B **55** 3276

[16] Civale L, Marwick A D, Wortington T K, Kirk M A, Thompson J R, Krusin-Elbaum L, Sun Y, Clem J R and Holtzberg F H 1991 *Phys. Rev. Lett.* **67** 648

[17] Schuster Th, Leghissa M, Koblischka M R, Kuhn H, Kraus M, Kronmüller H and Saemann-Ischenko G 1992 *Physica* C **203** 203

[18] Holtzapfel B, Kreiselmeyer G, Kraus M, Saemann-Ischenko G, Bouffard S, Klaumünzer S and Schultz L 1993 *Phys. Rev.* B **48** 600

[19] Schuster Th, Indenbom M V, Kuhn H, Kronmüller H, Legissa M and Kreiselmeyer G 1994 *Phys. Rev.* B **50** 9499

[20] Prozorov R, Tsameret A, Yeshurun Y, Koren G, Konczykowski M and Bouffard S 1994 *Physica* C **234** 311

[21] Koblischka M R, van Dalen A J J, Schuster Th, Leghissa M and Jirsa M 1994 *Physica* C **235–40** 2899

[22] Hadjiev V G, Thomsen C, Erb A, Müller-Vogt G, Koblischka M R and Cardona M 1991 *Solid State Commun.* **80** 643

[23] Koblischka M R and Wijngaarden R J 1995 *Supercond. Sci. Technol.* **8** 199

[24] Clem J R *Proc. NATO Advanced Study Institute (Cargese, Corsica, 1993)* ed N Bontemps (Dordrecht: Kluwer)

[25] Krusin-Elbaum L, Civale L, Thompson J R and Feild C 1996 *Phys. Rev.* B **53** 11744

[26] Nelson D R and Vinokur V M 1993 *Phys. Rev.* B **48** 13060

[27] Konczykowski M, Vinokur V M, Rullier-Albenque F, Yeshurun Y and Holtzberg F 1993 *Phys. Rev.* B **47** 5531

[28] Hardy V, Groult D, Provost J and Raveau B 1992 *Physica* C **190** 289

[29] Jirsa M, Koblischka M R and van Dalen A J J 1997 *Superlatt. and Microstruct.* **21** 3 at press

[30] Solovjov V, Pan V M and Freihardt H C 1994 *Phys. Rev.* B **50** 13724

[31] Zhukov A A, Küpfer H, Claus H, Wühl H, Kläser M and Müller-Vogt G 1995 *Phys. Rev.* B **52** R9871

[32] M V Feigel'man and Vinokur V M 1990 *Phys. Rev.* B **41** 8986

[33] Schnack H G, Griessen R, Lensink J G and Wen Hai-Hu 1993 *Phys. Rev.* B **48** 13178