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On the pinning performance analysis in bulk RE-123 twin-free superconductors

M. Jirsa [a,*], P. Petrenko [a], X. Yao [b], M. Muralidhar [c]

[a] Institute of Physics ASCR, Na Slovance 2, CZ-182 21 Praha 8, Czech Republic
[b] Shanghai Jiao Tong University, 1954 Hua Shan Road, Shanghai 200030, China
[c] SRL/ISTEC, 1-10-13, Shinonome, Koto-Ku, Tokyo 135-0062, Japan

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Abstract

We show that the replacement of B_{c2} by the irreversibility field in the classical scaling law for the sake of high-T_c superconductors (HTSCs) magnetic data interpretation is not an ideal solution. Field normalization to the peak position is more exact but it also gives rise to parameter values that are too high to be in any correlation with the original theory. Model of the thermally activated vortex dynamics, based on the super-current scaling and on the logarithmic pinning potential, works equally well but with only one reasonably ranging parameter, directly accessible from experiment. This parameter can thus serve as a classification factor for the pinning efficiency of bulk twin-free HTSCs.

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Keywords: Peak effect; Bulk RE-123 superconductors; Pinning force scaling; Pinning classification

1. Introduction

Scaling of the volume pinning force density, $F(B)$, with temperature in conventional superconductors was described by the phenomenological scaling law [1–3]

$$F(B) \propto B_{c2}^{r}\left(\frac{B}{B_{c2}}\right)^{p}\left(1-\frac{B}{B_{c2}}\right)^{q}. \tag{1}$$

For various vortex-pin configurations a set of characteristic discrete values of p and q was inferred [2–4], and the relative position of the curve maximum, B_{maxF}/B_{c2} [$= p/(p+q)$], was adopted as a parameter identifying the principal pinning mechanism involved. In high-T_c compounds $F(B)$ and $J(B)$ (critical current) curves scale with temperature, too, at least in some temperature range. However, the field range of detectable critical currents terminates at the irreversibility field, $B_{irr} \ll B_{c2}$ [5]. A frequent practice is to modify Eq. (1) by replacing B_{c2} with B_{irr} and to deduce the pinning mechanism from the value of B_{maxF}/B_{irr}. In the present work, we show the drawbacks of this approach for bulk twin-free $REBa_2Cu_3O_y$ compounds (RE-123, RE = rare earth). The modified classical scaling scheme is compared with the model of thermally activated flux dynamics [6–9].

2. Classical model and its modifications

While B_{c2} in Eq. (1) is a thermodynamic quantity, B_{irr} results from equilibrium between Lorentz and pinning forces, frequently under a strong thermal activation. B_{irr} is a sample-specific quantity. For high-T_c compounds the modified scaling law

$$\frac{F(B)}{F_{max}} = \frac{(p'+q')^{p'+q'}}{p'^{p'}q'^{q'}}\left(\frac{B}{B_{irr}}\right)^{p'}\left(1-\frac{B}{B_{irr}}\right)^{q'} \tag{2}$$

* Corresponding author. Tel.: +420 266052718; fax: +420 286890527.
E-mail address: jirsa@fzu.cz (M. Jirsa).

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can be used only as a purely empirical analytical formula. For the first glance, the only difference between Eqs. (2) and (1) is the different effective field scale. However, there is a principal physical difference: due to a substantially smaller coherence length in HTSCs, vortex core size and, consequently, the typical size of "point-like" pins are by orders of magnitude smaller than those in conventional superconductors. This, together with a high vortex elasticity and thermal activation, completely changes the physical problem.

As regards p' and q' values, the peak effect occurring on $J(B)$ in bulk HTSCs requires that $p' > 1$:

$$J(B) \propto F(B)/B \propto \left(\frac{B}{B_{\rm irr}}\right)^{p'-1}\left(1-\frac{B}{B_{\rm irr}}\right)^{q'}. \qquad (3)$$

Further, the magnetic hysteresis loops (MHLs), $J(B)$, and $F(B)$ dependences approach zero at $B_{\rm irr}$ *asymptotically*, which means that for the determination of $B_{\rm irr}$ from experiment one needs to set a precision criterion on magnetic moment, J or F. The relaxation state of the sample at the moment of measurement is principal for the determination of $B_{\rm irr}$ [6–8]. Fig. 1 shows the irreversible magnetic moment measured with different field sweep rates. The inset indicates the size difference of the lower branches of the MHLs detected by SQUID (with each point measured after the magnetic field was stabilized for 3 min) and by extraction magnetometer with the magnetic field ramping at 0.51 T/min. The $B_{\rm irr}$ values obtained by the two different experimental techniques can differ by several teslas [7]. Thus, the sometimes-reported shifts in the $J(B)$ and/or $F(B)$ peak positions with temperature with magnetic field normalized to $B_{\rm irr}$ might be only due to an uncertainty in the $B_{\rm irr}$ determination. In general, the use of $B_{\rm irr}$ as a field scale makes any quantitative analysis and results comparison rather vague. More appropriate would be the relation of the magnetic field to a more exactly detectable feature of the $J(B)$ or $F(B)$ dependences, like the second peak position on the $J(B)$ curve, $B_{\rm max}$, or the peak position on the $F(B)$ curve, $B_{\rm maxF}$. Following this idea, Eq. (2) can be translated into the form

$$\frac{F(B)}{F_{\rm max}} = \left(1+\frac{p'}{q'}\right)^{q'}\left(\frac{B}{B_{\rm maxF}}\right)^{p'}\left(1-\frac{p'}{p'+q'}\frac{B}{B_{\rm maxF}}\right)^{q'}. \qquad (4)$$

Fig. 2 shows how this formula works for various values of q' and for fixed values: $p' = 1.5$ (Fig. 2a) and $p' = 4$ (Fig. 2b). One limiting case, corresponding to the $F(B)$ symmetrical around $B_{\rm maxF}$, so that the peak lies just in the middle between zero and the irreversibility field, is $p' = q'$. The higher the p' value is, the slimmer is the curve. Parameter q', when departing from p' upwards, makes the curve asymmetrical, with the peak shifting to lower fields with respect to $B_{\rm irr}/2$. However, for very high q' values F drops to a negligibly low value already at a field significantly lower than $B_{\rm maxF}(1+q'/p')$ $(= B_{\rm irr})$! Fitting of experimental curves by Eq. (4), as well as by Eqs. (2) and (3), becomes insensitive to parameter q' at high q' values. Even the relatively "low" values of p' and q' in the range

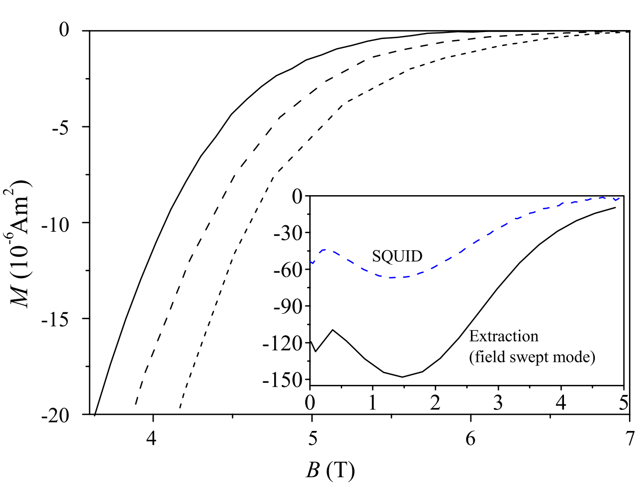

Fig. 1. High-field ends of lower branches of MHLs measured at 77 K by an extraction magnetometer on a slightly under-doped $SmBa_2Cu_3O_y$ single crystal ($T_c = 92.5$ K), with the field sweep rates (from above) 0.12 T/min, 0.39 T/min, and 1.2 T/min. In the inset lower branches of MHLs, measured by the SQUID and extraction magnetometer with the field sweep rate 0.51 T/min, are compared.

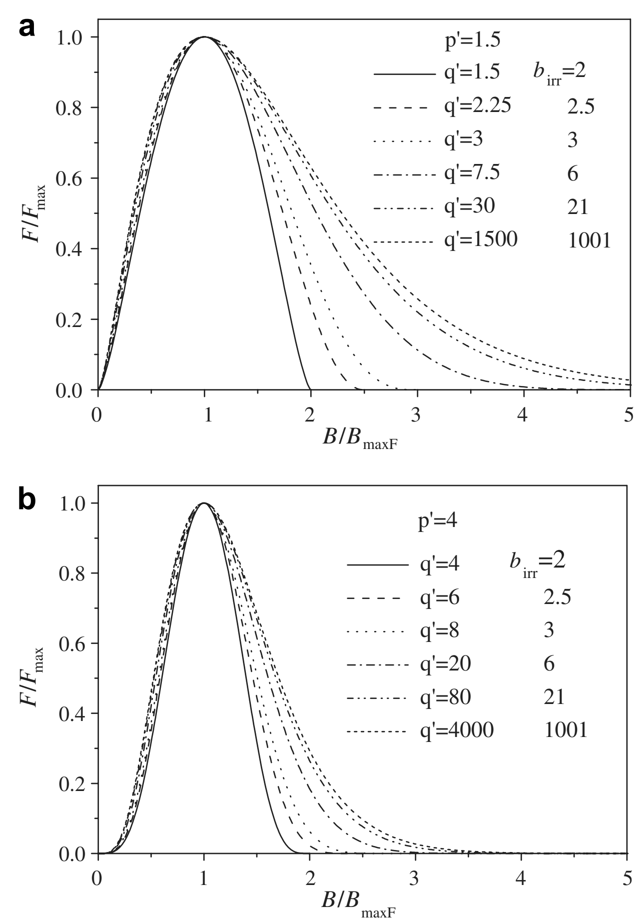

Fig. 2. Theoretical $F(B)$ curves according to Eq. (4) for $p' = 1.5$ (a) and for $p' = 4$ (b) and a wide range of q' values. For $q' \gg p'$ the curve shape becomes insensitive to q' at all values.