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Critical currents in high T_c superconductors

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In honor of Martin Peter's 60th birthday.

Abstract. Critical currents in the high T_c superconductors often are low, strongly T-dependent even at low temperature, and show logarithmic decay in time. These features may perhaps be accounted for in the general framework of the Anderson–Kim flux-creep critical-state model by an expected intrinsic weakness of pinning. We also propose a novel pinning mechanism due to fluctuations in oxygen concentration.

The critical current and magnetic properties of most bulk samples of the new high T_c superconductors studied to date appear to be dominated by their gross granular structure on the scale of ~ 1 micron. This can lead to low and magnetic-field-dependent critical currents because of weak 'Josephson-like' coupling between grains, because of magnetic-flux-induced 'frustration' or 'spin-glass' behavior, or because of anisotropy (with associated limitation of J_c to that set by the weakest direction). Presumably, these limitations can be alleviated by development of more compact and oriented materials (*cf.* Jin, et al. [1]). In anticipation of better samples, here we consider the critical current if limited only by pinning of flux lines by point-like defects in otherwise ideal material. We do this in terms of concepts concerning flux creep in superconductors, as developed by Anderson [2] and Kim in 1962.

Although the detailed relation between defect structure and pinning force is quite complex, the basic idea is that the energy per unit length of a vortex line carrying one quantum of flux depends on the local electronic environment. The relevant energy scale is the superconducting condensation energy per unit volume $H_c^2/8\pi$, and the length scale is set by the coherence length ξ, which gives the radius of the vortex core. More precisely, taking account of the energy of circulating vortex currents outside the core in addition to the core energy itself, the fluxon energy is $\sim(H_c^2/8\pi)(\pi\xi^2)(4 \ln \kappa)$ per unit length. This suggests using an effective radius of $2(\ln \kappa)^{1/2}\xi$ ($\sim 4\xi$ for a typical $\kappa \sim 100$) for numerical estimates. [Here $\kappa = \lambda/\xi$ is the Ginzburg–Landau parameter.] Pinning arises because this energy can be avoided if the fluxon can find a void or normal inclusion to run through. The most efficient pinning sites (per unit volume of defect material) are equiaxed, so that they are fully effective regardless of flux line direction. Thus, we can define a characteristic point pinning energy

$$F_0 = (H_c^2/8\pi)(4\pi\xi^3/3)(4\ln\kappa)^{3/2} \tag{1}$$

with the expectation that the actual pinning energy will be some $F_p = pF_0$, with $p < 1$ for fractional modification of the energy density, or $p > 1$ if the pinning geometry requires correlated activated motion of more than one vortex or of a length of vortex greater than $\sim 4\xi$, or some combination of these effects. This F_0 depends on temperature, vanishing at T_c, and reaching a saturation value at $T \ll T_c$; for order of magnitude estimates, we will use this low temperature limit. In thermally activated flux creep, this pinning energy appears in a Boltzmann factor, $\exp -F_p/kT$. Obviously, at the higher temperatures made accessible with higher T_c materials, pinning is less effective against thermal activation, for a given value of F_0. In fact, we now show that F_0 may be expected to be *smaller* in the new materials than in conventional superconducting materials. Thus we argue, on these two grounds, that the high T_c materials may be expected to have lower J_c because of weaker intrinsic pinning.

First, let us compare estimated values of F_0 for Nb_3Sn and YBCO. For this purpose it is convenient to eliminate ξ in favor of the directly measureable H_{c2} by using the relation $H_{c2} = \varphi_0/2\pi\xi^2 = \sqrt{2}\kappa H_c$. Then expressing F_0 in terms of an equivalent temperature $T_0 = F_0/k$, we obtain

$$T_0 = 2.9 \times 10^6 H_{c2}^{1/2}(\ln\kappa)^{3/2}/\kappa^2 \tag{2}$$

where T_0 is in Kelvin and H_{c2} in Tesla. Taking representative values $H_{c2} = 25T$ and $160T$, and $\kappa = 30$ and 140, respectively, for Nb_3Sn and YBCO[3], we find $T_0 \approx 100{,}000$ K for Nb_3Sn and $T_0 \approx 20{,}000$ K for YBCO. When compared with their respective values of T_c, 18 and 95 K, the difference is even more decisive: T_0/T_c is ~ 25 times smaller in YBCO than in Nb_3Sn.

A second approach is to relate T_0 to normal metal parameters. Independent of the detailed model (BCS or other), the condensation energy is expected to be of the order $\gamma T_c^2/4$, where γ is the coefficient of the electronic specific heat, proportional to the density of states at the Fermi energy $N(0)$. Similarly, the most favorable (largest) value of ξ is that in the clean limit, where $\xi(0) \sim \xi_0 = a\hbar v_F/kT_c$, with $a \sim 0.2$, as shown originally by Pippard, and confirmed by BCS. (This should not be far from the actual regime in the YBCO-type materials because ξ_0 is so small.) Combining these two estimates, we have

$$T_0 = (\gamma T_c^2/4)4\pi(a\hbar v_F/kT_c)^3(4\ln\kappa)^{3/2}/3k \propto \gamma v_F^3/T_c \tag{3}$$

if we neglect the weak logarithmic dependence on κ. Using standard interrelations of parameters (in the spherical Fermi surface approximation), we can generate many alternative proportionalities, such as:

$$T_0 \propto N(0)v_F^3/T_c \propto nv_F/m^*T_c \propto \omega_p^2 v_F/T_c \propto n^{4/3}/m^{*2}T_c \tag{3a}$$

Although reliable quantitative data are limited, and these relations are approximate, it is clear that the characteristics: high T_c, low carrier density n, and high m^* which mark high temperature superconductors all tend to reduce the potential pinning strength. Taken together with the higher operating temperatures, this suggests that thermally activated creep, as a limit to useable J_c values, should in general be more important in high-T_c materials than in conventional superconductors.

The essential physics behind this result is this: T_c is a measure of the effect of the superconducting transition in lowering the energy of a single electron at the Fermi surface, whereas F_0 is a measure of this energy summed over the electrons in the core of the a flux line. As T_c is increased, the shrinking of the size of the vortex core outweighs the increasing energy shift per electron, causing weaker pinning. When this lower F_0 is compared to higher thermal energies, this effect is accentuated. [The related effect of the small characteristic volume ξ^3 in enhancing fluctuation effects near T_c has been noted by Lobb [4].]

We now estimate $F_p = pF_0$ for a pinning mechanism that is specific to the oxide superconductors, and would exist even in the absence of gross defects such as grain boundaries, twin boundaries, or voids, which were clearly shown by Ourmazd, et al. [5] to dominate the pinning. It is based on the local fluctuation in oxygen concentration, which is inevitable if the number of oxygen atoms per unit cell is non-integral (e.g., something like 6.8 on average). [We presume that oxygen atoms diffuse between coherence volumes more slowly than do flux lines, so they may be considered fixed in position.] One knows that a variation of this number from 6.5 to 7.0 is enough to go from semiconducting to maximally superconducting material. Moreover, this variation seems thermodynamically constrained to occur primarily in the single favored 'chain' site per orthorhombic unit cell. Applying a $\sqrt{N}$ approximation (*i.e.*, assuming no correlations between unit cells) to the fluctuating number of oxygen atoms on these sites in a coherence volume of radius $\sim 4\xi$ containing roughly 4,000 unit cells, one might expect a fluctuation of ~ 0.01 in the average number per unit cell, and a corresponding change of order 2% in condensation energy. This corresponds to a value of $p = 0.02$ in the estimate of $F_p = pF_0$. Combined with the estimate above for F_0, this leads to $F_p \approx 400$ K. However, this estimate is very rough numerically, and neglects the effects of correlated vortex motions. Thus it is not clear *a priori* whether this novel pinning mechanism is actually strong enough to play a significant role in these materials, and further investigation might be worthwhile.

A possible experimental manifestation of a creep-limited J_c is a strong temperature dependence of J_c at low temperatures. It is a consequence of the Anderson–Kim model[2] that the creep-limited J_c should vary as

$$J_c \sim 1 - \alpha t - \beta t^2 \tag{4}$$

for $t = T/T_c \ll 1$. Here the quadratic term is the usual one based largely on the temperature dependence of thermodynamic quantities, while the linear term is determined by the kinetics of flux creep. In this model,

$$\alpha \approx [kT_c/F_p(0)] \ln (v_0/v_{\min}) \tag{5}$$

where $v_{\min}$ is the minimum creep velocity detectable with the sensitivity of the voltage measurement. In conventional superconductors, $\alpha \approx 0.1$ was found to be a typical experimental value. The discussion above suggests that a 10 times larger value of α would not be unreasonable in YBCO. This would lead to a drop of J_c at low temperatures roughly as fast as $1 - t$. In fact, the recent data of Ogale, et al [6] on thin films of YBCO shows a temperature dependence close to that form from $t = 0.6$ down to $t = 0.1$, the lowest temperature at which data were reported. This resemblence may be entirely fortuitous, but the I–V curves of their data do show a gradual onset of voltage with increasing current (as might result from creep behavior), rather than a sharp jump at a well-defined critical current value. Of course, an inhomogeneous film could provide a simpler explanation of these data, as the authors suggest.

A second observation consistent with a creep type of model[2] is the quasi-logarithmic decay of 'persistent' currents. This has been reported by several authors, most recently by Tjukanov, et al [7]. [Their data also show $J_c \sim (1 - t)$ at low temperature, the behaviour discussed in the previous paragraph.] Although they point out that their regime differs from that described by Anderson and Kim in that H is well below H_{c1}, the observed decay phenomena are very similar. Presumably their sample is sufficiently granular that the spin-glass picture is more appropriate for it than the model of point defects in otherwise ideal compact material, but the basic physics of the spin-glass state and of the classic critical state should be quite similar, apart from this change in size scale of the relevant inhomogeneity with respect to which fluxons are moving.

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REFERENCES

[1] S. Jin, T. Tiefel and B. van Dover, MRS meeting, Boston, Nov., 1987.

[2] P. W. Anderson, Phys. Rev. Lett. *9*, 309 (1962); P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. *36*, 39 (1964); see also a tutorial discussion in M. Tinkham, *Introduction to Superconductivity,* R. E. Krieger Publishing Co., Melbourne, FL (1975) pp. 175–181.

[3] R. J. Cava, et al, Phys. Rev. Lett. *58*, 1676 (1987); A. J. Panson, et al, Phys. Rev. *B35,* 8774 (1987).

[4] C. J. Lobb, Phys. Rev. *B36,* 3930 (1987).

[5] A. Ourmazd, J. A. Rentschler, W. J. Skocpol and D. W. Johnson, Jr., Phys. Rev. *B36,* 8914 (1987).

[6] S. B. Ogale, D. Dijkkamp, T. Venkatesan, X. D. Wu and A. Inam, Phys. Rev. *B36,* 7210 (1987).

[7] E. Tjukanov, et al. Phys. Rev. *B36,* 7244 (1987).