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Comparison of the history effects in magnetization in weakly pinned crystals of high T_c and low T_c superconductors

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Abstract
A comparison of the history effects in weakly pinned single crystals of a high T_c $YBa_2Cu_3O_{7-\delta}$ (for H ∥ c) and a low T_c $Ca_3Rh_4Sn_{13}$, which show anomalous variations in critical current density $J_c(H)$, is presented via the tracings of the minor magnetization hysteresis loops using a vibrating sample magnetometer. The sample histories focussed are: (i) the field cooled (FC), (ii) the zero field cooled (ZFC) and (iii) an isothermal reversal of field from the normal state. An understanding of the results in terms of the modulation in the plastic deformation of the elastic vortex solid and supercooling across the order–disorder transitions is sought.

The critical current density $J_c(H)$ of a hard superconductor does not display any path dependence in field (H) and it decays monotonically with increase in H. Its magnetic response is well described by the prescriptions of the celebrated critical state model. An isothermal magnetization hysteresis (M–H) loop of a strongly pinned superconductor defines an envelope within which lie the magnetization values measured along all paths. However, an anomalous magnetization maximum in $J_c(H)$, which relates either to the second magnetization peak (SMP) and/or to the peak effect (PE) phenomenon, occurs ubiquitously in weakly pinned samples of low T_c and high T_c superconductors. Ever since the $J_c(H)$ data were looked at carefully in a clean single crystal of Nb [1], it became evident that $J_c(H)$ depends on the history of a given H. Early transport data of Steingart *et al* [1] in Nb revealed that

$$J_c^{FC}(H) \geqslant J_c^{rev}(H) \geqslant J_c^{ZFC}(H) \qquad H \leqslant H_m \qquad (1)$$

where H_m is the field at which the $J_c(H)$ peaks and the rest of the symbols have their usual meaning. No exceptions have so far been reported as regards the above inequality in the context of low T_c superconductors which display either the SMP or the PE phenomenon. The collective pinning description due to Larkin and Ovchinnikov (LO) [2], which relates J_c inversely to the volume of the collectively pinned Larkin domain V_c $\left(J_c \propto V_c^{-1/2}\right)$, suffices to rationalize the observed behaviour via the possibility of supercooling the disorder existing at H_m during the field cooled (FC) mode. On the other hand, in the ZFC mode, bundles of vortices invade the superconductor at high velocity and they manage to explore the more ordered configurations (as compared to that in the FC mode). However, this appealing scenario undergoes a phase reversal in samples of high T_c cuprates, where the FC configurations are found to be more ordered than those obtained in the ZFC manner [3]. The inequality statement of equation (1) therefore no longer remains fruitful to comprehend the experimental observations. Another circumstance, where this inequality experiences limitations even in the low T_c superconductors is where the SMP and the PE are present in the same isothermal scan [4]. In such a case, the path dependence in $J_c(H)$ could be evident beyond the peak position of the SMP, up to the peak position of the PE.

A convenient way to explore the path dependence in $J_c(H)$ is the study of characteristic features of the minor

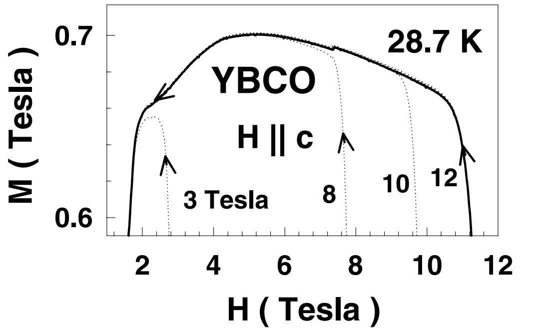

Figure 1. Portions of the minor hysteresis loop (dotted curves) initiated from the FC magnetization values along with the envelope loop at 28.7 K. Each minor hysteresis loop is labelled by the field in which the sample was initially cooled down.

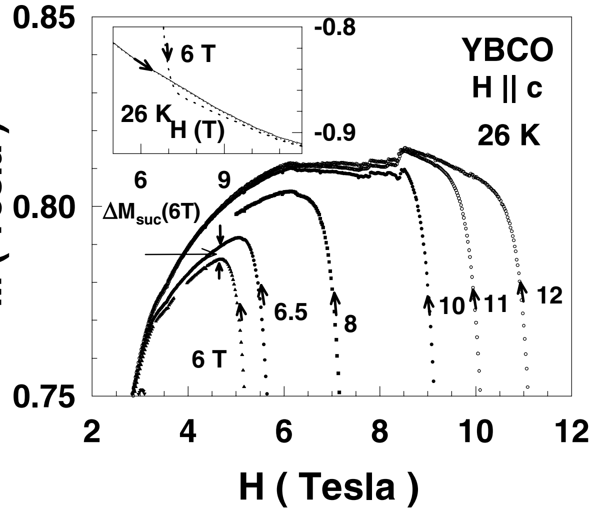

Figure 2. Portions of the minor hysteresis loop initiated from the fields lying on the forward leg (see main panel) and on the reverse leg (see the inset panel) of the envelope loop at 26 K. Each minor hysteresis loop is labelled by the initial field value.

hysteresis loops (MHLs). Existence of a linear relationship between $J_c(H)$ and $\Delta M(H)$ $[= M(H^{rev}) - M(H^{for})]$ facilitates this task. We provide here a glimpse into the results of a detailed study of the three types of MHLs in a weakly pinned crystal [3] of $YBa_2Cu_3O_{7-\delta}$ (YBCO) for H ∥ c. We shall highlight the differences in the observed behaviour with those reported earlier in the low T_c systems [5–7]. Equation (1) is exemplified via the study of MHLs in samples of 2H-$NbSe_2$ [5], $CeRu_2$ [6] and $Ca_3Rh_4Sn_{13}$ [7], where only the PE is visible. Here we will also present newer results in a single crystal of $Ca_3Rh_4Sn_{13}$ (CaRhSn) at a temperature where both the SMP and the PE are present [4].

In YBCO, MHLs were initiated from (i) the FC magnetization values (type I), (ii) the ZFC magnetization values, i.e., $M(H^{for})$ (type II) and (iii) the magnetization values on the return leg of the *M*–*H* loop, i.e. $M(H^{rev})$ (type III). The inset and the main panels of figures 1 and 2 show representative behaviour at temperature(s) where anomaly in $J_c(H)$ is broad. In figure 1, note that the FC minor curves (type I) in YBCO remain confined inside the envelope loop. This is in contrast to the behaviour in low T_c systems, where the analogous MHLs overshoot and cut across the envelope loop

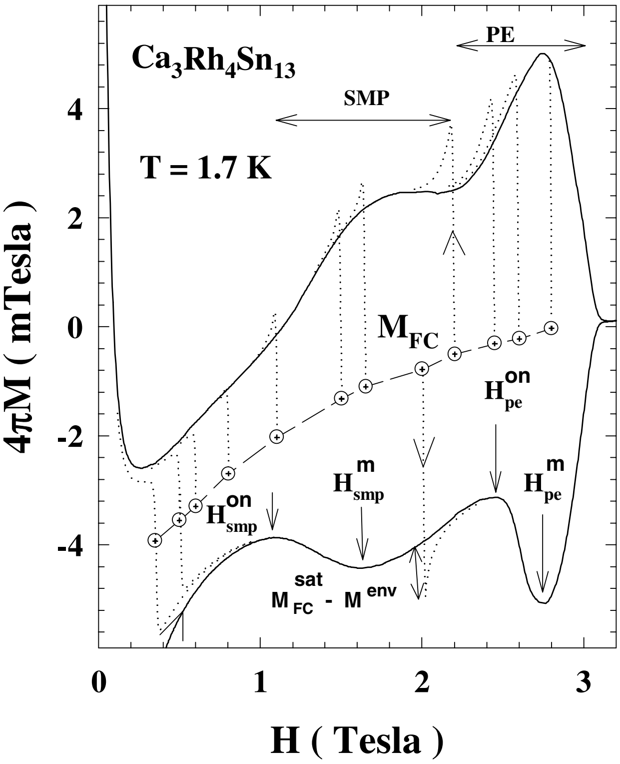

Figure 3. Minor hysteresis loops initiated from the FC magnetization values in a CaRhSn crystal at 1.7 K. For the MHL of 2.0 T, we also show the difference, $M^{sat}_{FC} - M^{env}$.

exemplifying the inequality, $J_c^{FC}(H) \geqslant J_c^{ZFC}(H)$. In the main panel of figure 2, the MHLs initiated from the forward leg (type II) remain well inside the reverse leg of the envelope loop. On the other hand, the inset panel of figure 2 shows that a MHL initiated from the reverse leg (type III) overshoots the forward envelope loop, thereby exemplifying the inequality, $J_c(H^{rev}) \geqslant J_c(H^{for})$, which is not different from the behaviour well documented in the low T_c systems. Two significant points to be noted, however, are as follows: (1) While the MHL of the type I (figure 1) initiated from 2 T and 10 T readily merge into the reverse envelope loop, those initiated from fields in between 3 T and 9 T merge into the envelope loop after a field change of about 2 T. This implies that not only the FC configurations have J_c values lower than their counterparts along the reverse envelope loop, but, also that the metastability effects in $J_c(H)$ persist up to 9 T, a field value greater than the notional peak field of the broad SMP at 28.7 K. (2) While the minor loop of the type II initiated from a field of 11 T (see figure 2) readily merges into the reverse envelope loop, those initiated from 2 T $\leqslant H \leqslant$ 10 T undershoot the envelope loop, thereby confirming the presence of the metastability effect in $J_c(H)$ up to 10 T.

In a crystal of CaRhSn [$T_c(0) \approx 8.2$ K], a SMP can be seen distinctly from the peak effect at $T \leqslant 4$ K. Figure 3 shows a plot of the *M*–*H* loop in this sample at 1.7 K along with the FC minor loops initiated from fields ranging from far below the onset field of the SMP $\left(H^{on}_{smp}\right)$ to above the maximum of the peak effect $\left(H^{m}_{pe}\right)$. The minor curves initiated from 1.0 T $\leqslant$ H $\leqslant$ 2.6 T overshoot the reverse envelope loop, thereby implying that $J_c^{FC}(H) \geqslant J_c^{rev}(H)$. Minor curves initiated from $H \geqslant H_{pe}^m$ at 1.7 K readily merge into the envelope loop, whereas those initiated from $H \leqslant 0.6$ T undershoot the envelope loop. The former indicates that path dependence in $J_c(H)$ presumably ceases at H_{pe}^m. The latter observation could imply that $J_c^{FC}(H) \leqslant J_c^{ZFC}(H)$ at $H \leqslant 0.6$ T, a behaviour analogous to that seen in YBCO for all fields. Considering that a FC configuration attempts to freeze in the disorder persisting at the peak temperature (at a given H), it is pertinent to recall here that in an earlier study [5] CaRhSn showed that the peak effect surfaces in a robust manner in temperature-dependent ac susceptibility runs only for vortex states prepared in $H \geqslant 0.5$ T. For $0.35\ \text{T} \leqslant H \leqslant 0.5$ T, the peak effect is so nascent that the shrinkage in the correlation volume V_c across the peak effect is miniscule and for $H < 0.35$ T, no signature of the peak effect is evident in $\chi'_{ac}(T)$ data. This in turn implies that while cooling the given CaRhSn crystal across the superconducting transition in $H \leqslant 0.5$ T, one would not encounter the pinned amorphous state, which could get supercooled on further lowering of the temperature.

Following Kokkaliaris *et al* [8], we now examine in YBCO and CaRhSn the progressive change in the plastic deformation of the elastic vortex solid by comparing the saturated value at an appropriate field of a given MHL (of type II) with the magnetization value corresponding to the same field but lying on a neighbouring (i.e. successive) minor hysteresis loop. In figure 2, we have identified one such difference, namely ΔM_{suc} for $H = 6$ T. The non-zero value of ΔM_{suc} implies a progressive enhancement in the plasticity. In figure 4, we show the plots of ΔM_{suc} versus H in YBCO at 26 K and in CaRhSn at 1.7 K. In YBCO, the dislocations causing the plastic deformation start to proliferate near the onset position of the anomalous increase in $J_c(H)$ and the plasticity reaches the saturation limit near 9 T (see figure 4(*a*)), above which the metastability effects in the $J_c(H)$ cease.

In CaRhSn, the ΔM_{suc} versus H (see figure 4(*b*)) shows an interesting modulation with two maxima, the first one lying in between the onset and peak positions of the SMP and the second one near the onset position of the peak effect, respectively. The ΔM_{suc} vanishes just above H_{pe}^m, where the metastability effects in $J_c(H)$ also cease. The relative heights of the two maxima imply that the vortex matter, after the occurrence of the SMP and near the onset of the peak effect, is sufficiently well ordered. It is to be noted that $J_c(H)$ monotonically decreases between H_{smp}^m and H_{pe}^{on}, thereby indicating that the topologically defective vortex solid existing at H_{smp}^m could heal to some extent while approaching H_{pe}^{on}. In this context it could be instructive to view the plot (see figure 5) of the difference between the saturated value of an FC minor curve $\left(M_{FC}^{sat}\right)$ and the corresponding magnetization value (M^{env}) on the usual envelope curve as a function of H. One such difference at a field of 2 T has been identified in figure 3. Figures display the plot of the parameter $R_{FC}\left[= \left(M_{fc}^{sat} - M^{env}\right)/\Delta M(H)\right]$ versus H [8]. Since $J_c^{FC}(H)$ has a correlation with the current density of the pinned amorphous state existing at the maximum position of the PE, the relative values of this parameter signify how far a given ZFC vortex state is from its FC counterpart. From figure 5, it is apparent that the ZFC vortex state at the onset field $\left(H_{pe}^{on}\right)$ of the PE is relatively more ordered than that at the maximum field $\left(H_{smp}^m\right)$ of the SMP. The equivalence in the values of the parameter R_{FC} near H_{smp}^{on} and H_{pe}^{on} reflects similarity in the state of spatial order in the vortex solid state before the commencement of two anomalous variations in J_c. The modulation in R_{FC} versus H reflects the modulation in the plasticity of the vortex solid. Note that the deformed vortex solid is not only in far from fully amorphous state *at* H_{smp}^m but it also heals further in between the field interval, H_{smp}^m and H_{pe}^{on}. In addition, the negative values of R_{FC} for $H \leqslant 0.6$ T could imply that $J_c^{FC} \leqslant J_c^{ZFC}$ for these fields.

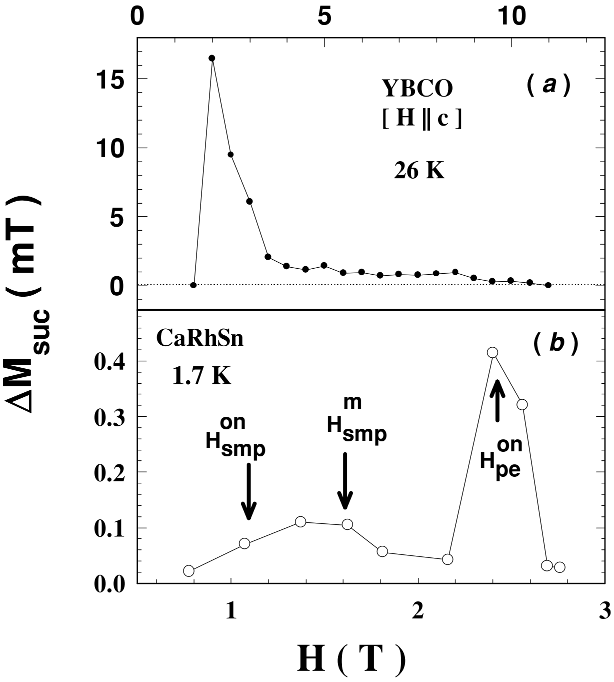

Figure 4. Plots of ΔM_{suc} versus field corresponding to MHL of type II in (*a*) YBCO and (*b*) CaRhSn.

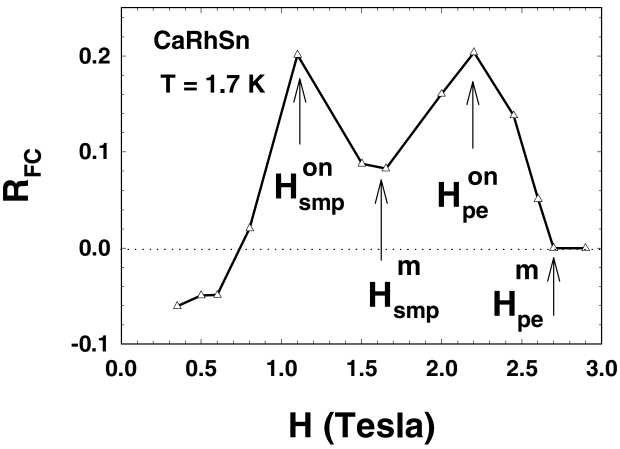

Figure 5. The parameter R_{FC} versus field values in which the CaRhSn sample was field cooled down to 1.7 K.

As yet it is not completely obvious why the FC states in YBCO show different behaviour from their counterparts in the low T_c superconductors. One plausible reason could be a clear distinction and a large separation between the vortex melting and the irreversibility line in the high T_c samples. In the high T_c cuprates, the vortices encounter the vortex liquid line first and they enter into a pinned configuration only on crossing the irreversibility line. On the other hand, in the low T_c systems, the vortex state at H_{pe}^m is termed as pinned amorphous and this amorphous state loses its pinning characteristic at the irreversibility field, which lies infinitesimally close to the H_{c2} line, where the vortices get nucleated. An understanding of the history effects evident via tracings of MHLs in low T_c superconductors was provided by G Ravikumar *et al* [5] through a phenomenological model incorporating the path dependence in $J_c(H)$ via the relationship, $J_c(B + \Delta B) = J_c(B) + (|\Delta B|/B_r)\left(J_c^{st} - J_c\right)$. In the limit that the parameter B_r measuring the extent of metastability vanishes, the above model reduces to the usual critical state model. A key assumption of this model is the postulation of the stable vortex state with current density J_c^{st}, which can be reached by repeated cyclings of the field by an amount ΔB. Prior to the peak effect the ZFC vortex states are the stable ones, whereas in between the H_{pe}^{on} and H_{pe}^m, the inequality $J_c^{ZFC} < J_c^{st} < J_c^{rev}$ should hold. An elucidation of this fact via the tracing of stable hysteresis loop above the PE region in weakly pinned crystals of 2H-$NbSe_2$ and $CeRu_2$ has been recently demonstrated [6, 9].

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