Transition from columnar to point pinning in coated conductors: critical currents that are independent of magnetic field direction

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Abstract
We identify a sharp crossover in the vortex pinning of a high-temperature superconductor with nanocolumnar stacks of precipitates as strong vortex pinning centers. Above a particular, temperature-dependent field $B_X(T)$ the vortex response is no longer determined by the nanocolumns, and is instead determined by point-like pinning. This crossover is evident as a change in the dependence of the critical current density on the angle between the applied magnetic field and the nanocolumns. It also leads to the field-orientation-independent power law index $n$ of the $E–J$ curves. Below the transition, there is a strong maximum in $J_C$ when the field is aligned parallel to the columns and $n$ depends on field direction. Above the transition, $n$ is independent of the field direction and there is a $J_C$ minimum for $H$ parallel to the columns. We discuss a possible mechanism for such behavior change, as well as testing and confirming a prediction that the crossover must become very broad at high temperatures and low fields.

The use of high-temperature superconducting (HTSC) wires and cables in electric power industry hinges upon our ability to engineer defect structures that effectively immobilize magnetic flux lines (Abrikosov vortices) in the presence of large magnetic fields and transport current densities. Significant recent progress in this direction has been made with the discovery of nanocolumnar stacks of second-phase precipitates (columnar defects, CDs), which form along high-temperature superconductors’ crystallographic $c$-axis under certain synthesis conditions [1–3]. Such CDs are clearly advantageous because the vortices bind strongly to them along the entire length of the column, rather than at a few points. As a result, the critical current density $J_C$ increases several-fold [4]. The original discovery was of the columns of barium zirconate BaZrO$_3$ (BZO), and other materials have been shown since to form similar extended structures [5–9]. In a medium-strength magnetic field (often 1 T is used) such CDs usually manifest themselves through a prominent maximum in angle-dependent $J_C$ when the field aligns parallel to them.

In addition to columnar pinning centers, point-like pinning is also present in real superconductors. The competition between columnar and point-like pinning was studied theoretically in detail some years ago [10–14]. These studies seem to agree that at least in 2 + 1 dimensions (vortices in crystals or films, as opposed to 1 + 1 dimensions, i.e. vortices in a plane) vortices unbind from the columns for sufficiently strong point disorder, whereas in a plane a vortex appears always bound to the column, whatever the strength of point pins. Crossover between columnar and point-like pinning has been recently addressed by, for instance, Horide et al [15]. For HTSC materials without $c$-axis oriented columns, the $J_C$ typically has a shallow minimum when magnetic field points along the $c$-axis, owing to the layered crystal structure of cuprates, captured by the Ginzburg–Landau mass anisotropy $\epsilon = (m_{ab}/m_c)^{1/2} = \dots$
with prominent 4c. Such compensation occurs in every sample and the extrinsic anisotropy, induced by the BZO stacks, standard four-probe transport technique, maintaining the sample preparation and characterization can be found in [6]. Details of the sample preparation and characterization can be found in [6]. The critical current density has been measured by a standard four-probe transport technique, maintaining \( J \perp B \) throughout. The criterion of 1 \( \mu \)V cm\(^{-1} \) of dissipation has been used for \( J_c \) determination.

As a further example of such behavior, figure 1 shows the \( J_c \) versus magnetic field \( B \) data from a 0.8 \( \mu \)m thick YBCO sample deposited on an ion-beam assisted deposition (IBAD) template with CDs comprised of cubic double perovskite \( Ba_2YNbO_6 \) (BYN) nanodots/rods. Details of the sample preparation and characterization can be found in [6]. The critical current density has been measured by a standard four-probe transport technique, maintaining \( J \perp B \) throughout. The criterion of 1 \( \mu \)V cm\(^{-1} \) of dissipation has been used for \( J_c \) determination.

In a recent paper [16] we reported the observation of an isotropic response to the applied magnetic field orientation in intrinsically anisotropic high-\( T_c \) superconductor (NdBa\(_2\)Cu\(_3\)O\(_7\) in that case) with CDs, comprised of self-assembled BZO stacks. Specifically, the basal-plane critical current density \( J_c \) becomes independent of the field orientation \( \theta \) with respect to the superconductor \( c \)-axis over a large range of angle \( \theta \). This phenomenon occurs at a particular, temperature-dependent field \( B_X(T) \), where the intrinsic anisotropy of the layered high-\( T_c \) superconductor and the extrinsic anisotropy, induced by the BZO stacks, effectively compensate. We emphasize that this phenomenon is quite universal: such compensation occurs in every sample with prominent \( c \)-axis peak that we have studied over several years.

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the field direction: it decreases as the field is tilted away from the $c$-axis. This is to be expected, since essentially $n = S^{-1}$, the inverse of the flux creep rate (see, for example, [17]). The creep occurs faster as the magnetic field is tilted away from the columns.

As the field magnitude increases further and $n$ resumes its decline, this orientation dependence becomes significantly weaker or disappears completely, suggesting that the underlying pinning mechanism becomes isotropic. It is interesting to note, however, that the magnetic field above which $n$ becomes orientation independent is somewhat lower than $B_X$. It also increases on cooling from 1 T at 77 K to about 2.5 T at 65 K and therefore cannot be identified with the matching field.

The sharp crossover (or possibly a phase transition) at the $B_X$ in figure 1 suggests that below the $B_X$ the columns dominate the point-like pinning and the vortices like to run parallel to them. Above the crossover the situation is reversed: the vortices meander around and between the columns, sampling mostly the point-like pins present in the superconducting matrix. As a possible driving force for this change in behavior, we first consider the gain in the vortex configurational entropy

$$\Delta S = k_B \ln(\Phi_0/\pi B_{ab}^2) \xi_{ab}^{d/\ell_c} = k_B \frac{d}{\ell_c} \ln \frac{B_{ab}^2}{B}$$

(1)

where the factor under the logarithm is the number of different ways to position the vortex core (of the cross-section area $\pi \xi_{ab}^2$) in an area per single vortex $\Phi_0/B$. The power $d/\ell_c$ is the number of independently pinned vortex segments of the length $\ell_c$ (the collective pinning, or Larkin, length) in a film of thickness $d$. From the critical current density we can obtain the Larkin length $[18] \ell_c = \epsilon \xi_{ab} (J_{ab}/J_C(0))^{1/2} \approx 1$ nm, where $\epsilon \approx 0.2$ is the YBCO mass anisotropy and the depairing current density $J_{ab}$ is about ten times larger than the measured zero-field critical current density $J_C(0)$. We obtain $\Delta S \approx k_B$ per vortex per CuO$_2$ layer. This is comparable to $\approx 0.4$–0.5 $k_B$ per vortex per layer, measured in the first-order vortex freezing transition in clean YBCO single crystals [19]. However, this entropy gain must be weighed against the extra energy cost of forming vortex half-loops. The appropriate energy is of the order of

$$\Delta U = \epsilon_1 (\Phi_0/B)^{1/2}$$

(2)

where $\epsilon_1 = \epsilon (\Phi_0/4\pi \lambda_{ab})^2 \ln \lambda_{ab}/\xi_{ab}$ is the vortex line energy for a vortex parallel to the $ab$ planes. The energy $\Delta U$ is of the order of $10^3$ K, about an order of magnitude greater than the latent heat $T_X \Delta S$ (where $T_X(B)$ is the temperature corresponding to the field $B_X$), therefore the small extra entropy cannot be responsible for the discussed change in the vortex configuration.

A natural question to ask is whether the vortices at the crossover outnumber the columns or are outnumbered by the columns. We can evaluate the matching field $B_\Phi$ in this sample from the $J_C(H)$ data of figure 1. We fit the empiric equation

$$J_C(H) = J_C(0) \left(1 - \frac{H/H_{irr}}{1 + H/H_{0}}\right)^\alpha$$

(3)

to the data, where $H_{irr}$ is the irreversibility field, $H_0$ is the ‘accommodation field’ below which the $J_C$ is field independent, and $\alpha$ is the power law exponent, describing the decrease of $J_C$ at intermediate fields. We have used this type of analysis in our previous publication [16], where more details can be found. Here, however, rather than fitting the entire $J_C(H)$ curve, we fit only the data at low fields of the order of $H_0$ and the data near the irreversibility line, and exclude the data at the intermediate fields from the fit. At 65 K the model fit agrees essentially perfectly with the actual measurement at all fields, but at 70 and 77 K the model prediction for $J_C$ at the intermediate field is lower than that actually measured. The normalized difference between the data and the model prediction is plotted in figure 4 for $T = 77$ K (red) and 70 K (black) for $H \parallel c$. The important point here is that at both temperatures the ‘excess’ $J_C$ is centered at the same field, which we identify as matching field $B_\Phi = 2$ T. We defer further analysis of matching effects in $J_C$ to a subsequent publication [20]. The so-obtained $B_\Phi$ agrees very well with the CD areal density, observed directly by scanning electron microscopy.

We note that the $B_X$ stays above $B_\Phi$. This means that at the crossover some vortices cannot be accommodated by a column. Nevertheless, the $J_C$ does not decrease abruptly above $B_\Phi$. Rather it shows a broad, $T$-independent hump, especially noticeable in the $\theta = 0$ data of figure 1.
example of a distinct decrease in $J_c$ columnar defects, but apparently not universal, and an
This behavior is common in superconducting coatings with
effort is centered at 2 T at both temperatures, which we identify
magnetic penetration depth $\lambda$
the effective range of the vortex–vortex interaction is given by the
pins to that characteristic of isotropic random pinning. The
vortex–column interaction. When flux density reaches
become screened. At this point the angular dependence
of the areal density of the columns, producing a characteristic
delocalized above approximately 40 K, regardless
From the columns no longer dominate the pinning and effectively
several columns [18], even below matching. A similar
phenomenon of vortex caging has been discussed in the
at liquid nitrogen temperatures, which is apparent in figure 2, suggests that the distance $(\Phi_0/B_X)^{1/2}$, below which the nanocolumns become
When the temperature rises so that $B_X$ decreases to
where there are insufficient interstitial vortices to screen the
columns, the sharp crossing must become smeared. This
means that there must be a lower field limit for the crossover,
and it is a few times $B_x$. Therefore, the $B_X(T)$ line in
figure 2 terminates at $a_B$ with $a$ of the order of a few,
rather than extending all the way to $B = 0$. Figure 5 presents
evidence in favor of this idea. Since the original sample
with Ba$_2$YNbO$_6$ nanocolumns was no longer available, a
similar YBCO sample with Ba$_2$YZrO$_6$ nanocolumns was used
to examine the common crossing phenomenon at high
temperature and low field. The areal density of columnar
defects in this sample corresponds to the matching field of
about 1 T and the critical temperature is 86.2 K.
At 70 and 77 K (black and red respectively) there
are well defined $B_X = 5.8$ and 3.6 T respectively. As the
temperature increases, the $B_X$ cannot be clearly identified
above approximately 80 K (orange, $B_X \approx 3$ T). Above this
temperature (below this field), the individual $J_C(B)$ lines still
cross, but not at a common field. This supports the argument
presented above, where $a \approx 3$ in this case. The matching field,
i.e. the columnar defect density, may be the main parameter
that controls the magnitude of $B_X$.

As a final topic, we would like to discuss the evolution of
the columnar pinning and its effect on $J_C$ as the temperature
decreases. The $B_X$ quickly exceeds the maximum magnetic
field available to us, and the critical current density becomes
too large, so that data are hard to obtain below 65 K.
Nevertheless, we can say that at low temperatures, just as at
high temperatures, the crossover no longer occurs, and there

Figure 4. The $J_C$ enhancement compared to the model prediction
for $H \parallel c$ at $T = 70$ and 77 K (black and red respectively). The
excess is centered at 2 T at both temperatures, which we identify
with the matching field.

Figure 5. Series of $J_C(B)$ data for a sample with Ba$_2$YZrO$_6$
nanocolumns in the temperature interval between 70 and 85.8 K, as
indicated. Symbols of different shape in each family represent
different field orientations: ▲, $\theta = 60^\circ$, to •, $\theta = 2^\circ$, similar to
figure 1. Above $T = 80$ K (orange) it is difficult to identify
unambiguously the common crossing field $B_X$. 
is always a $J_C$ minimum for $H \parallel c$. For example, there is
mounting evidence that the $c$-axis peak in $J_C$, prominent at
high temperatures and low to intermediate fields, disappears
at low temperatures ($4$ K) [25, 26] for fields up to at least
30 $T$. Likewise, the relative contribution of the correlated
pinning to the irreversibility field has been found to decrease
on cooling [27, 29]. Clearly, this is counter to the present
results as well as findings of references [21, 22]. This suggests
that the $B_X$ line must terminate or become re-entrant, such that
$B_X = 0$ at some low temperature. In [28] the very prominent
columnar pinning contribution was found by contactless
measurements of $J_C(\theta)$ on IBAD coated conductors at as low
as 30 $K$ and up to at least 3 $T$. If anything, the $c$-axis peak at
30 $K$ was even more prominent than that at 77 $K$ in the same
samples. Therefore, 30 $K$ may be viewed as an upper limit
for any such re-entrance. We note that at low temperatures we
are either in single vortex pinning regime ($B < B_\Phi$), where
each vortex is bound to a particular column along its entire
length, or in the plastic regime ($B > B_\Phi$), where some vortices
are bound to the columns and the rest are collectively pinned
by a point-like background [18]. The analysis outlined above
will not apply in either regime because a column cannot be
screened by a single vortex.

In conclusion, we have proposed an explanation for the field-orientation-independent in-plane critical current at
a particular, $T$-dependent field $B_X$. The crossover from the
columnar pinned vortices at low field and/or temperature to
point pinned vortices at high field and/or temperature occurs
in the vortex system when mean intervortex spacing becomes
shorter than about one-tenth of the in-plane penetration depth.
This phenomenon may be usefully employed in rotating
machinery (motors, generators) utilizing second generation
superconductive technology.

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