Experimental contradiction of the conventional wisdom that continuous columnar pinning centers result in maximum $J_c$

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Abstract. Continuous columnar pinning centers result in maximum pinning potential, $U_{pin}$. Most scientists have assumed maximum $U_{pin}$ would maximize $J_c$. However, several clues pointed to high $J_c$ despite pinning discontinuities. An experiment was performed to directly compare continuous and discontinuous pinning, using high-energy ion damage to create the pinning centers. Results in YBCO show that $J_c$ for discontinuous pinning is much higher than for continuous pinning. At high pinning density (20 Tesla equivalent field), $J_c$ is 60 times higher for discontinuous pinning, and at 5 Tesla equivalent field, it is 4 times higher. Record $J_c \approx 300$ kA/cm$^2$ at 77 K was achieved in large grain textured HTS for pinning which was 67% discontinuous. This resulted without improving the texturing or purity. Despite reduced $U_{pin}$, $H_c$ for discontinuous pinning is as high as for continuous pinning. The superior $T_c$ and percolation, achieved by discontinuous pinning, far outweighs the decrease in $U_{pin}$.

1. Continuous columnar pinning centers (CCPCs)

In a type II superconductor, magnetic field within the superconductor is quantized into fluxoids of $\phi_0 \approx 2 \times 10^{-7}$ Gauss-cm$^2$. When current flows, a Lorentz force moves the fluxoids, which generates a dissipative electric field, and lowers the critical current density, $J_c$. In order to obtain high values of $J_c$, the fluxoids must be “pinned” in place. A region of non-superconducting material of diameter, $d_{pin}$, more than twice the coherence length, $\xi$, acts as a strong “pinning center.” The fluxoid potential energy is reduced by the condensation energy, resulting in an attractive potential well [1]

$$U_{pin} = \left( H_c^2 / 8\pi \right) \pi \xi^2 L \ln \left( 1 + \frac{d_{pin}}{2\sqrt{2}\xi} \right)$$

where $L$ is the length of the pinning center. If a pinning center is a continuous column of non-superconducting material, parallel to the applied field, then the pinning potential is maximum.

CCPCs, created by ion damage, were successfully used for a decade to investigate the behavior of “vortex matter” in high temperature superconductors (HTS) (e.g., [2]). Theoretical statements strongly encouraged the assumption that CCPCs would produce maximum $J_c$. For example [3], “The columnar morphology of such defects makes them the most effective pinning centers,” and “For effective localization of a vortex, the defect must extend along its entire length.” As a result, scores of experiments attempted to maximize $J_c$ using CCPC (e.g., [4]).

2. Disquieting observations concerning CCPCs

In HTS, as the number of CCPCs per unit area is increased, $J_c$ at first increases, as expected, then peaks and begins to decrease. The decrease in $J_c$ is usually attributed to a decrease in $T_c$, caused by the introduction of disorder to the HTS crystal. However, the decrease in $J_c$ is larger than expected for the change in $T_c$ [5]. A clue about an additional cause for the decrease in $J_c$ is obtained from a classical experiment on electrical conductivity [6]. Holes were drilled at random in a sheet of conducting metal. As the undamaged area decreased, the conductivity, $\sigma$, decreased. The conductivity approached zero when the undamaged area was still 35%. Although the experiment described was performed on a classical conductor, one is tempted to speculate [5] that a similar reduction of
percolation path is responsible for at least part of the decrease in $J_c$ when high densities of CCPC are used.

This leads us to a focus on the diameter and density of the CCPCs. The damage diameter, $d_{\text{pin}}$, of CCPCs is reasonably well known [7]. An analytical approximation was made [5] relating $d_{\text{pin}}$ to the energy loss of the ions per unit distance traveled, $S_e$. Using this, and the classical percolation experiment [6], one can estimate that CCPCs will reduce $J_c$ to zero (rather than improving $J_c$) for an ion fluence, $F_{\text{min}} = 7.3 \times 10^{11}$ ions/cm$^2$, in approximate agreement with experiments on HTS [5].

Another difficulty with the idea that CCPCs yield maximum $J_c$ is the fact that record $J_c$ in large grain YBCO was achieved using ions from nuclear fission [8]. Ions which produce CCPCs must have $S_e \approx 3.5$ keV/Å in YBCO [9]. Ions from fission have $S_e \approx 1.7$ keV/Å. The fission ions have gaps in their damage of over 80% of the ion path length. This is a very discontinuous column.

Another troubling aspect of the conventional wisdom concerning CCPC was the observation [10] that for ions with $S_e \approx 0.7$ keV/Å there is an increase in $\Delta J_c$ per ion by a factor of about 1000. $S_e \approx 0.7$ keV/Å is the threshold, in YBCO, for melting along portions of the ion track. $J_c$ appears to immediately improve when the threshold of melting is exceeded, even though for such low $S_e$ the strong pinning ion damage ($d_{\text{pin}} > 2\xi$) is highly discontinuous.

These observations all point to the possibility of achieving high $J_c$ by using pinning centers which are very discontinuous. As a result, an experiment was proposed [5] to directly compare $J_c$ achieved by CCPCs to that achieved by discontinuous multiple-in-line defects (MILD).

The question to be decided by experiment was whether the lower damage of MILD defects could result in sufficiently improved $T_c$ and percolation to overcome the expected decrease in $U_{\text{pin}}$.

3. Design of the experiment

Comparison of CCPC to MILD pinning, requires control of the morphology of ion damage. A large volume of literature exists on ion damage, and a fair amount even exists for HTS targets [7]. The dominant variable determining damage morphology is $S_e = \text{energy loss by the ion to the target, per unit length of ion path}$, i.e., $S_e = \text{dE}_{\text{ion}}/\text{dx}$. Given the ion species ($\text{U}^{238}$ in this experiment) the ion energy ($60.2$ GeV), the target chemistry ($\text{YBa}_2\text{Cu}_3\text{O}_7$) and the target density ($\sim 6$ gm/cc), one can determine $S_e$ precisely, by using an existing program [11]. $S_e$ determines both the diameter of the damage, $d_{\text{pin}}$, and the fraction of the ion path, $f$, which acts as a strong pinning center. Analytical approximations to $d_{\text{pin}}$ [5] and $f$ [12], in YBCO, for $0.7 \leq S_e \leq 3.5$ keV/Å are:

$$d_{\text{pin}} = (S_e-0.7) \times 48 \text{ Å} \quad (2)$$

$$f = [(S_e-0.7)/2.8]^{1.4} \quad (3)$$

where $S_e$ is given in keV/Angstrom. Figure 1 contains qualitative sketches of ion damage in YBCO.

In order to have well-defined damage morphology, we desired to use ions of well-defined $S_e$. We also wanted the YBCO targets to be thick enough to be self-supporting. Most values of $S_e$ can be achieved by either a high or a low ion energy. (See figure 2.) A high-energy ion can travel through a greater thickness of HTS for a given percent change in $S_e$. Hence, we chose to work with ions at high energy. Figure 2 shows $S_e$ for $\text{U}^{238}$ ions with an initial energy of 60.2 GeV. As the ion penetrates YBCO, the energy decreases, and $S_e$ increases. Near the end of the ion range, $S_e$ reaches a maximum, and then rapidly decreases to zero.

The ion targets used were sandwiches containing 6 YBCO slices. The thickness of each slice was chosen such that $S_e$ within a slice varied by $\pm 10\%$. Thus, the value of $S_e$ was well known. Five such sandwiches were made, each containing 6 slices of YBCO. These were exposed to ion fluences, $F_i = 0.25 \times 10^{12}, 0.50 \times 10^{12}, 1 \times 10^{12}, 2 \times 10^{12}$ and $4 \times 10^{12}$ ions/cm$^2$. One can alternatively express fluence, $F_i$, in terms of “equivalent field,” $B_{\phi} = \varphi F_i = 5, 10, 20, 40$ and 80 Tesla. The relative fluences were accurately controlled. The absolute values of fluence were later determined by TEM.
Figure 1. $S_e$ determines damage morphology along the ion’s path. Examples are given for $S_e = 2$, 2.5, and 3.5 keV/Å.

4. Experimental Results

$J_c$ was measured, before and after irradiation, by VSM. The improvement ratios of $J_c$, measured at 77 K in a field of 1 Tesla, are shown in figure 3. Continuous columnar pinning centers require $S_e \geq 3.5$ keV/Å [9]. Results indicate that, for $S_e \approx 2.1$, at a fluence of $B_\phi = 20$ Tesla, $J_c$ is about 60 times greater for MILD pinning than for CCPC [12]. At this $S_e$, pinning centers are ~ 67% discontinuous, and, $U_{\text{pin}} \sim 33\% U_{\text{pin,max}}$. We note that, despite this, $J_c$ is a world record value (~ 300 kA/cm$^2$) for large grain HTS. Also, $H_{\text{irr}} \approx 9$ Tesla is about equal to that obtained by CCPC. We conclude that MILD pinning results in much higher $J_c$ than CCPC, comparable $H_{\text{irr}}$, and much higher pinning center density [5].

We requested another research center to independently characterize the samples with fluence $B_\phi \approx 10$ Tesla, for these controversial results. Figure 4 shows results obtained at IFW, Dresden [13] for $F_0 = 10$ T, at 77 K. Note that the peak current density occurs for $S_e \approx 2.2$ keV/Å, and is $J_c \approx 275$ kA/cm$^2$, while the value of $J_c$ for CCPC (i.e., for $S_e \geq 3.5$ keV/Å) is only about 40 kA/cm$^2$.

5. Discussion and Conclusion

Conventional wisdom has maintained for over a decade that CCPCs result in the highest $J_c$ because $U_{\text{pin}}$ is maximized. As a consequence of this, scores of studies were made on the effects of CCPC on $J_c$, while the region in which MILD pinning is formed ($0.7 < S_e < 3.5$ keV/Å) remained neglected.
However, $J_c$ also depends on $T_c$ and percolation. The experimental results presented here indicate that superior $T_c$ and percolation, due to the reduced damage of MILD pinning centers, has far more effect on $J_c$ than does the reduction of $U_{uw}$. MILD pinning achieved record $J_c \approx 300 \text{kA/cm}^2$, in large grain YBCO, using pinning centers which are very nearly parallel. *We expect a further increase in $J_c$ for MILD centers which are splayed to encourage vortex entanglement.*

Our results show little if any decrease in $H_{irr}$ for MILD pinning compared to CCPC. This was unexpected since 65% of the ion track does not contain strong pinning. We believe that bundles of MILD pinning centers cooperate to pin a single fluxoid [12]. The fluxoid, encountering a gap in one ion track, crosses to another track which is continuous in that region. A bundle of 12 ion tracks, of separation \( \sim 20 \text{nm} \) at $B_\phi = 10 \text{T}$, is calculated to pin 99% of the entire length of the fluxoid [12].

We have considered the dependence of $J_c$ on $T_c$, $U_{uw}$ and percolation (using the results of Ref. [6] to estimate percolation losses). We emphasize that the improvement in $J_c$, by a factor of \( \sim 17 \), is accomplished by improved pinning only. *No improvement in texture, purity, or oxygenation was used.* This is in disagreement with literature stating that these are the causes of limited $J_c$ [14].

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