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Superconductor Critical Currents Densities**

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Pinning Vortices and Enhancing High Temperature Superconductor Critical Current

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). Our work focused on developing an understanding of the mechanisms that limit resistance-free current flow in high-temperature superconductors. Because vortex motion is known to constitute the major source of dissipation, we concentrated on the effects of strong pinning columnar defects on vortex dynamics and structure. We demonstrated impressive enhancements of critical currents in commercial BSCCO/Ag conductors by irradiating with 0.8-GeV and 0.5-GeV protons, which fission bismuth nuclei and create fission tracks. We showed that lower energy protons are more effective in producing strong pinning without damaging intergrain connections; and we irradiated a BSCCO coil, achieving impressive performance enhancement in a macroscopic device. We also developed the theoretical framework for using the Josephson plasma resonance as a new tool to determine vortex structures. We conducted transport measurements on both Bi-2212 and YBaCuO single crystals containing columnar defects and discovered dramatic changes in vortex mobility related to filling the columnar defects with vortices.

Background and Research Objectives

High-temperature superconducting (HTS) materials present challenging scientific and technical problems for efforts aimed at developing conductors that sustain high current densities at liquid nitrogen temperature in magnetic fields of several tesla. As in low-temperature superconductors (LTS) when subjected to magnetic fields, HTS are penetrated by vortices that move and dissipate energy when acted upon by Lorentz forces imposed by transport currents. Generally, a high density of microscopic defects must be introduced to "pin" the vortices and stabilize dissipationless currents. In the HTS, several unique physical properties conspire to defeat the usual strategies that proved successful in the LTS.

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These include:

1. The small size of the normal core of the vortex ($\sim 20 \text{ \AA}$), which reduces the energy scale for pinning;
2. Large anisotropy coming from the layered structure that entails extreme flexibility for vortex lines, allowing wandering and entanglement much like a polymeric liquid; and
3. Elevated operating temperatures, made possible by the high critical temperature (T_c), enhances the importance of thermal fluctuations, introducing vortex melting transitions and other phenomena never seen in the LTS.

Even when strong pinning and high current densities are achieved at low temperatures, thermal activation of vortex lines out of pinning sites creates activated vortex motion and dissipation as the temperature is elevated above a characteristic T_{irr} . It is this thermally activated flux motion, TAFM, that limits the performance of HTS conductors. To stabilize currents with low dissipation at higher temperatures will require defect structures with much higher pinning strength. Recent success with amorphous columnar defects produced by heavy ion irradiation at high energy has shown that linear tracks with well defined radii of 5-7 nm are the most effective in pinning flux lines and that T_{irr} can be raised substantially in both the BiSrCaCuO (BSCCO) and YBaCuO (YBCO) compounds. The unique efficacy of this defect comes both from its radius, which matches the size of the vortex core, and from its linear geometry, allowing coherent pinning over a significant length of the vortex line.

The practicality of heavy ion irradiation for enhancing the operating temperatures of HTS conductors is limited by the short range of the ions (5-20 μm), making penetration of thick conductors impossible. It has recently been demonstrated that such columnar defects can be also created in BSCCO by irradiation with 0.8-GeV protons, which fission Bi nuclei and produce high-energy heavy fragments. These energetic heavy fragments create columnar tracks throughout the bulk of the superconductor. The beauty of the high energy proton technique is that the projectiles have a range of $\sim 0.5 \text{ m}$ in dense matter and create the columnar tracks *in situ* and uniformly distributed throughout the bulk of the superconductor. These properties make feasible the introduction of defects into a macroscopic HTS device, e.g. a magnet, as a final step in the manufacture. In 1995 we demonstrated a proof-of-principal for this technique, achieving a record-high critical current density of 5000 A/cm^2 at 75K in a magnetic field of 1.0 Tesla in a commercial BSCCO tape conductor. Optimization of this technique and understanding the physics behind its efficacy was a major goal of this LDRD project.

The BSCCO conductors are presently the only commercially viable HTS long wires and tapes because of ease of manufacture into long lengths with good connectivity between HTS grains. Unfortunately, they are the most anisotropic of the HTS compounds, resulting in the decomposition of vortex lines into two-dimensional "pancake" vortices that are weakly pinned by even ideal defects. Recent experiments indicate that columnar defects may lead to enhanced coupling between pancakes in adjacent planes, improving the pinning energy. By contrast, the more isotropic YBCO compound has well-coupled vortex lines with greatly enhanced pinning and maintains high current densities in high magnetic fields at liquid nitrogen temperature. Recently our group developed a new process that enables production of long, well-coupled conductors of YBCO on flexible substrates with $J_C > 10^6$ A/cm² at 75K and maintaining above 10^5 A/cm² in fields above 4.0 Tesla. Investigations of the dependence of J_C on the orientation of the magnetic field indicates the presence of strong pinning defects that extend through the entire thickness of the films. Further enhancements may be achieved with additional columnar defects either by heavy ion irradiation or by high-energy proton irradiation. We contrast the effects of these extended defects with effects of point defects introduced by atomic substitutions on the Yttrium site.

The HTS compounds present entirely new physical problems in the area of vortex behavior and its influence on transport properties. The layered structures in which superconductivity is present in CuO₂ sheets separated by insulating layers creates two-dimensional structure and dynamics for the vortices. This, coupled with unprecedented high operating temperatures where fluctuations often play a dominant role, creates a great variety of new vortex phases including liquids, lattices and two varieties of glass phases, depending on the disorder present in the underlying atomic crystal lattice. The columnar tracks that can be introduced in a controlled manner by heavy-ion or high-energy proton irradiation offer an ideal opportunity for studying these vortex phases in the presence of a well-defined, tailored defect structure. The proton-fission tracks are random in orientation in contrast to the heavy-ion-induced tracks, which are all parallel to the ion beam. By studying the effects of these two track morphologies on two HTS systems, YBCO and BSCCO, with greatly differing anisotropies, we have been able to shed light on the connection between vortex dimensionality and orientation with respect to linear defects and pinning and melting transitions.

Importance to LANL's Science and Technology Base and National R&D Needs

Since their discovery in 1987 the high temperature superconductors have offered the promise of more efficient and powerful motors, generators, transmission lines and

other electrical devices that can operate at liquid nitrogen temperatures where refrigeration efficiency and simplicity of design will enable superconducting technology to be economically competitive. Since 1988, LANL has been engaged in a major DOE-funded program to develop high-current HTS conductors with performance levels adequate for electric utility applications. This requires the development of HTS conductors that carry current densities in the MA/cm² range. A recent dramatic advance by a LANL team has resulted in the development of a high-current flexible HTS conductor with superior properties at liquid nitrogen temperatures. The emphasis of the DOE program has shifted to process scale-up to long conductor lengths.

The purpose of this LDRD project has been to supply the underlying scientific base for the effort to understand the mechanisms that limit current flow in these materials and to explore new means of improving critical current densities. The HTS compounds present an array of entirely new physical problems in the area of vortex behavior and its influence on transport properties. This array of interesting new physics has engendered a new sub-field of condensed matter physics, known as “vortex matter”, in which LANL has played a major role. This area of investigation provides a basis of understanding the mechanisms of current flow in HTS materials. It also addresses the major impediment to application of HTS technology, which is resistive dissipation associated with vortex motion at elevated temperatures. By understanding how to create and control defect structures that will inhibit vortex melting and depinning, we hope to greatly enhance the operating performance of HTS conductors.

Scientific Approach and Accomplishments

We have applied a variety of experimental and theoretical approaches to investigate the nature of vortex dynamics and interactions with microstructural defects in three HTS compounds, Bi₂Sr₂Ca₂Cu₃O_{8+x} (Bi2223), Bi₂Sr₂CaCu₂O_{8+x} (Bi-2212) and YBa₂Cu₃O_{7-x} (Y123). Bi-2223 and Bi-2212 represent the most anisotropic HTS compounds, while Y-123 is the least anisotropic. We have focused our attention on investigating the effects on critical current behavior of well-characterized “columnar” defects produced by heavy-ion irradiation and by 0.8-GeV proton irradiation. The theoretical effort has concentrated on the analysis of the Josephson plasma resonance (JPR) technique and c-axis transport to determine the structure of the vortex system in Bi-2212. These efforts will be separately described below.

Enhancement of Critical Currents in Bi-2223 Tape Conductors and Coils

We have previously developed the technique of introducing strong-pinning columnar defects into Bi-2223/Ag commercial tape conductors by means of 0.8-GeV proton irradiation[1, 2]. The incident protons induce fission reactions in the heavy Bi nuclei and the resultant energetic heavy fission fragments produce amorphous linear tracks of length $\sim 6\mu\text{m}$ and diameter $\sim 0.5\text{nm}$. The amorphous track is insulating and roughly the same diameter as the normal core of a superconducting vortex. It represents an approximately ideal pinning center for the vortex. As we have reported, high energy proton irradiation has led to a substantial increase of the magnetization critical current density J_c and of the irreversibility line in Bi-2212 single crystals. For Bi-2223/Ag tapes, proton irradiation leads to an improvement in the magnetic field dependence of J_c at 75 K, amounting to an improvement by ~ 100 for a 1-T magnetic field oriented along the tape normal (roughly parallel to the c axes of the Bi-2223 grains in the tape).

When a proton with energy greater than ~ 100 MeV (0.1 GeV) bombards a Bi-2223/Ag tape, most protons pass through the tape with no interaction; in fact, the mean free path in matter for 0.8-GeV protons is ~ 50 cm. This allows deep penetration of thick conductors and devices, and the columnar tracks are created throughout the bulk of the conductor. The tracks are random in orientation with respect to the incident proton beam and are called splayed columnar defects. These have been predicted theoretically to be more efficient in pinning magnetic flux (and thus enhancing J_c) in two-dimensional HTS systems, such as Bi-2212 or Bi-2223, than are the parallel columnar defects produced by heavy ion irradiation. Because of the short penetration depth of the heavy ions, heavy-ion irradiation is typically limited to samples less than $10\mu\text{m}$ thick and therefore is not useful for irradiating HTS materials in Ag sheaths, which typically have a total thickness of 60-200 μm or more.

We pursued proton irradiation studies to higher dose levels to find the optimum density of defects for maximizing the critical current density (J_c) at high fields and temperatures. We also investigated the possibility of irradiating at lower energies to improve economic feasibility; to reduce radioactivity and damage to the intergranular connectivity in the conductor; and we irradiated a thick “pancake” coil of Bi-2223/Ag tape to demonstrate the feasibility of using proton irradiation to improve the performance of macroscopic HTS devices.

Multi (85)-filament Bi-2223/Ag tape samples were manufactured by American Superconductor Corporation as one of their commercial products employing a standard OPIT process. Tapes were prepared by packing the powder into cylindrical silver billets,

which were deformed into tape using standard deformation techniques, including wire drawing to a hexagonal shape; repacking an 85-filament bundle into a silver tube; wire drawing; and rolling. The samples were given multiple heat treatments at temperatures between 800 and 830°C in 7.5% oxygen with intermediate deformations consisting of pressing for the monofilament tapes and rolling for the multifilament tapes. The 85-filament tapes have final dimensions of 0.25 x 2.5 mm with filament dimensions of 15- μ m thick and 120- μ m wide and a 28% fill factor. The critical current I_c of the tape stock is about 30 A at 77 K, 0 T; the J_c and J_e are 20 and ~ 4.5 kA/cm², respectively, under the same conditions.

The irradiations took place at the Weapons Neutron Research (WNR) facility of the Los Alamos Neutron Science Center (LANSCE). The tapes were irradiated at several fluences, which are characterized by a "matching field" $B\phi$, at which the number of quantized magnetic flux lines equals the nominal defect density, from 1 T to 4 T. To investigate the effect of incident proton energy on the nature of the defects produced and the amount of induced radioactivity, we selected energies of 500 and 800 MeV. Finally, to look at scale-up issues, we irradiated from 2 to 9 tapes at a time, in various configurations, to determine the effect of the beam on a multiple layers of tape.

In our previous work we achieved significant enhancements in J_c at dose equivalent levels ~ 1.3 T. Attempts to gain further improvements at higher doses failed due to extensive damage to intergranular boundaries [3, 4]. We believe that this was caused by "spallation" products that are generated by collision of the protons with nuclei in the material. This collateral damage is in the form of point and cascade defects that are far more numerous than the columnar tracks, but do not result in strong pinning of vortices. At sufficient densities they break down the intergranular connectivity and decrease J_c [4]. We confirmed this suspicion by annealing the tapes at 400° C for 1-h and observed substantial recovery of J_c . This temperature was sufficient to heal some of the grain boundary damage without annealing out the columnar tracks. We then carried out irradiations at the lower proton energy of 0.5 GeV, where fewer spallation products are generated.

The results are shown in Figure 1, where J_c versus B at 75K is plotted for an unirradiated tape and for two tapes irradiated to dose levels ~ 1.0 T at 0.5 GeV and at 0.8 GeV, respectively. The large enhancement at high fields is evident for both irradiated tapes. It is also clear that the 0.5-GeV irradiation is more effective over the entire field range than the 0.8-GeV irradiation. The low field drop in J_c is associated with the effect of the field on weakened grain boundaries. Thus the improvement in this region can be attributed to decrease of spallation damage at the lower proton energy. The higher field

dependence of $J_c(B)$ is related to the effectiveness of the defects in pinning vortices. The enhanced performance here for 0.5-GeV irradiation indicates that the lower energy is just as effective in producing columnar tracks from Bi fission products. This is a very important result because it indicates that further improvements in performance may be realized at even lower energies, where higher doses can be applied before grain boundary degradation becomes a limitation. If this result can be extended to the range 0.2 GeV, lower cost cyclotrons could be employed for this purpose. An added benefit that was obtained from the lower energy was reduced radioactivity of the samples.

The primary demonstration of this technique was the irradiation of a macroscopic superconducting device. Prior to this attempt, we irradiated stacks of tapes to determine whether the proton induced tracks would be uniformly distributed through thick layers. For 9-layer stacks we observed nearly identical $J_c(B)$ curves for all of the tapes. For the demonstration we obtained a pancake coil manufactured by ASC from their standard Bi-2223/Ag tape. The coil was wound in a flat spiral from ~10 m of tape, and the winding thickness was ~1.0 cm. It generated a magnetic field at its center of 0.038 T at 75 K. The coil was situated in the proton beam on a rotating platform and rotated at a rate of ~1.0 rpm. It was irradiated for a period of 24 h at the LANL WNR facility with 0.8-GeV protons to an estimated dose of ~0.4 T. It was possible to handle it for measurement after a radioactive decay of 4 months.

We did not observe a change in the measured critical current after the irradiation, but this is expected from the results of Figure 1, where it is seen that the major enhancements produced by the irradiation occur for fields $> 0.2T$ applied perpendicular to the tape. We mounted the coil in a large bore superconducting solenoid with its axis orthogonal to that of the solenoid to produce a field orientation as shown in Figure 2. Figure 2 shows the major result of this project. It is clear that substantial improvement in the performance of the coil ($> \times 10$ for fields above 0.5T) have been achieved by this rather low irradiation dose. This may have important technological applications, because superconducting devices based on Bi-2223 conductors are presently limited to operation below 30K in fields above 1.0T, and increasing the operating temperature would have major benefits. Further work in this area should be concentrated on lower energy proton irradiation.

C-Axis Current Transport in Bi-2212 Single Crystals

The Bi-based compounds are the most anisotropic of the HTS and can best be understood as comprised of stacks of two-dimensional superconducting sheets (CuO_2) separated by insulating layers. In such a system current transport between layers (along the c-axis) takes place by tunneling and in the superconducting state takes the form of

Josephson tunneling of paired carriers. When a magnetic field is applied along the c -axis, point vortices appear in the planes that are weakly coupled to their neighbors in adjacent planes. It is this weak interplanar coupling that is responsible for the poor performance at high temperatures of the Bi-based HTS conductors described above. We have chosen to study the dynamics and pinning of these point (pancake) vortices by investigating the properties of current transport along the c -axis.

Our theoretical effort has focused on the properties of c -axis transport at microwave frequencies where the tunneling nature of current transport reduces the plasma resonance (usually in the optical range for isotropic metals) into the high microwave region. The principal result of our work has been to discover that the Josephson plasma resonance (JPR) frequency is highly sensitive to the arrangement of pancake vortices and that it can be used to probe the changes in the vortex structure as a function of temperature and magnetic field. If the pancake vortices are perfectly aligned in straight columns along the c -axis, then the c -axis microwave current flow that occurs when the JPR is excited is unaffected. However, when the pancake positions are displaced between layers, a local phase shift is induced between layers that strongly affects the Josephson tunnel currents that can flow coherently. If the pancake positions are completely random between layers, then the Josephson current and the JPR are reduced to zero. However in the presence of finite correlations between pancake positions, the JPR and Josephson critical current reflect the degree of correlation.

Over the past few years the theoretical and experimental work in this field have developed into a powerful tool for studying the dependence of vortex correlations on temperature, magnetic field and defect structures. The accomplishments of our project [5-11] over the last three years include:

1. Theoretical prediction of the temperature and magnetic field dependence of the JPR in the vortex liquid state that agrees with the experimental results;
2. Development of a theory that correctly describes the dependence of the JPR on the orientation of the magnetic field;
3. Description of the field and temperature dependence of linewidth of the JPR as caused by inhomogeneity in the interlayer Josephson interaction in the presence of randomly positioned vortices (inhomogeneous broadening); and the effect of parallel columnar defects on producing large enhancements in the JPR, due to forcing alignment of pancake vortices; and
4. Discovery of a recoupling effect of pancake vortices in the liquid state that is driven by filling of columnar defects. This explains the appearance of a second

high-magnetic-field JPR that is a signature of increased correlations in the pancake vortex liquid brought on by partial filling of the defects.

This last discovery suggested a c-axis transport experiment that we carried out to test the validity of our description of the origin of the JPR results [12]. We prepared several single crystals of Bi-2212 and irradiated them to various dose levels with 1.0-GeV U^{238} to produce parallel arrays of columnar defects (CDs). Current and voltage contacts were applied to drive current along the c-axis and to measure ρ_c as a function of applied magnetic field along the c-axis at various temperatures. We chose the temperature range to be close to the vortex melting transition in the field range corresponding to the equivalent density of CDs. In this range of fields and temperatures, we expect that even in the liquid state, the vortices are predominantly located on the CDs even though the mobility between CDs is high.

In Figure 3 we show the central result. Here $\rho_c(B)$ at $T=69K$ is plotted for three crystals, one pristine and the others with CD densities of 1.0 T and 2.0 T. As shown $\rho_c(B)$ for the pristine crystal shows a smooth concave rise with field as the melting field is exceeded and the pancake vortices become mobile. In this configuration, with field and current parallel, the c-axis current interacts with the segments of Josephson currents (strings) that connect pieces of misaligned pancake vortices. Thus, as in the JPR experiments, ρ_c is sensitive to the degree of alignment of the pancake vortices between adjacent layers. Perfect alignment results in the vanishing of ρ_c , while random pancake positions maximize it. In the irradiated crystals $\rho_c(B)$ shows more complex non-monotonic behavior. This is most evident for the crystal with the 2 T dose, where $\rho_c(B)$ shows reentrant behavior, reaching a minimum near 0.6 T and then approaching the normal state resistivity at higher fields.

We have developed a model for this behavior that is consistent with the double peak structure seen in the JPR measurements. In this model, at low fields, vortices outnumber CDs and move freely between them by variable range hopping, similar to what is observed in doped semiconductors. Thus the vortex system can enter a mobile dissipative state while still largely confined to the CD sites. Upon increasing the magnetic field, the CDs begin to fill and the mobility begins to be reduced. In addition, aligned stacks of pancake vortices begin to form as the fraction of available empty sites begins to diminish and the c-axis current has fewer positions of misalignment with which to interact. We have recently developed a quantitative theory based on the Kubo formalism that describes the dependence

of c-axis resistivity on pancake vortex correlations and that provides a basis for understanding these effects of improving correlation by filling of CD sites [13]. This experimental result, coupled with the JPR results presents a new picture of vortex dynamics in the liquid state in the presence of strong pinning correlated defects.

Effects of Columnar Defects on Vortex Pinning in Y-123 Films

The Y123 compound presents an entirely different physical system as far as the vortex dynamics and phase diagram are concerned. Vortices in the more anisotropic Y-123 form continuous lines with finite bending modulus that adds additional restoring force against thermally induced distortions from linearity. Coherent pinning along finite segments of vortex line are effective in suppressing thermal fluctuations and melting up to much higher temperatures than is the case in the more two-dimensional Bi-based compounds. Even in the liquid state the vortex lines maintain their integrity and a liquid of lines forms. Upon freezing into the solid state, the vortex structure depends upon the nature of the underlying crystal disorder. If the defects are random in all three dimensions, then the resulting solid phase is a “glass” of lines with no long-range order. On the other hand correlated defects, such as columnar defects produced by heavy-ion irradiation, suppress line wandering transverse to the field direction and result in a “Bose-glass” phase in which the vortices are localized on the defects. The theory of the Bose-glass phase transition from the liquid has been worked out by Nelson and Vinokur [14] and has been verified by numerous experimental studies done on irradiated single crystals of Y-123.

One of the practical benefits of columnar defects is that they have a much larger effect on enhancing critical currents and on shifting the melting line to higher temperatures than any other type of defect. One of the great mysteries has been that films of Y-123 grown on single crystal substrates exhibit critical current densities and high melting lines comparable to those achieved by optimum doses of heavy ion irradiation of single crystals. It appears that some unidentified defect of great pinning strength grows naturally in these films. We attempted to identify the nature of the pinning by measuring the dependence of the critical current on the orientation of the field and observed the presence of a prominent peak in J_c when the field is oriented along the crystal c-axis. This suggests that the operative defects are coherent and aligned with the c-axis much like the parallel columnar defects. We then carried out an investigation to test whether the scaling laws predicted for I-V curves near a Bose-glass transition by the Nelson-Vinokur (NV) theory were obeyed for these films [15].

We found complete agreement between the scaling of the I-V curves for our as-prepared films, that observed in heavy-ion irradiated crystals, and the Bose-glass theory

[15]. This was an important discovery since it relates the superior performance of Y-123 films to the presence of a correlated defect aligned with the c-axis. One of the by-products of the I-V scaling procedure is that the fitted scaling parameter that allows all I-V curves at different temperatures to coalesce is the glass temperature, T_G (H), that separates the liquid and solid vortex phases. It also separates the region of finite critical currents from that where $J_c = 0$.

The next question that we addressed was whether these high performance films could be further enhanced by the introduction of columnar defects [16]. The Y-123 films were deposited onto single-crystal, yttria-stabilized-zirconia substrates by pulsed laser deposition and were about 1.0 μm in thickness. All of the films used in the study exhibited J_c of order 1.0 MA/cm² at 75 K in zero field. The critical currents were determined from the I-V curves using a 1.0 $\mu\text{V}/\text{cm}^2$ criterion. Results of I_c ($B \parallel c$) for one film after irradiation to a dose equivalent of 3.9 T are shown for three temperatures in Figure 4 [16]. Also shown is data for I_c versus B for the same sample rotated by 55° away from c-axis alignment with the field. This data is representative of the field dependence for the unirradiated samples. It is clear that a large enhancement of I_c has been obtained at fields near 4.0 T and that this enhancement is absent when the field is not oriented parallel to the defects. What is more striking is the appearance of a peak in $I_c(B)$ at a field that closely corresponds to the “matching field” at which the density of vortices equals the density of columnar defects.

One of the predictions of the NV theory is that, at intermediate temperatures where vortices are still localized on the columns, critical currents are limited by a form of variable range hopping between columns driven by the Lorentz force. As the matching field approaches, there are few empty columns available and the vortex mobility drops. This form of “Mott insulator” state would be reflected in an increase of the critical current as seen. We were also interested in seeing whether the columnar defects also affected the glass line transition to the unpinning liquid state. We measured the I-V curves and applied the Bose-glass scaling analysis described above to derive values for T_G (B). The results are shown for two different dose levels in Figure 5. As is apparent from the figure, the introduction of columnar defects does indeed enhance the glass line monotonically with dose. It is also seen that there is a distinct kink in $T_G(B)$ for both doses at a field near the matching field. This is clear evidence that vortices are still largely localized on the columns near the melting (glass) line and that the character of the melting transition changes when there are more vortices than defects. Future work in this field will explore the nature of the

glass transition in very high magnetic fields. This work is important in establishing the mechanism of strong pinning and how it effects the vortex dynamics.

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Figure 1. Critical current versus magnetic field at 75K for an unirradiated tape, a tape irradiated with 800-MeV protons, and one irradiated with the same dose of 500-MeV protons. Both irradiated tapes show enhancement at high fields. However, there is less weak-link behavior for the lower proton energy, and the field enhancement is substantially better.

Figure 2. Critical current versus magnetic field applied, as shown in the insert, orthogonal to the coil axis at three temperatures, after proton irradiation at a dose equivalent of 0.4 T. The critical current of the coil will be determined by the sections of the coil that are normal to the applied field. For comparison we show I_c versus B at 75K for an unirradiated section of the same tape that was used to wind the coil.

Figure 3. Resistance along the c-axis as a function of applied field along the c-axis for an unirradiated Bi-2212 crystal and for two Bi-2212 crystals irradiated to produce columnar defects with equivalent densities of 1.0 T and 2.0 T respectively. The measuring current was 20 mA and the temperature was 68K. Inset: Blowup in linear scale showing the region of the anomaly in R_c (B) for the crystal with the 2 T dose.

Figure 4. Full symbols: magnetic field dependence of the critical current density of a film irradiated with a dose equivalent of 3.9 T at $T=67\text{K}$ and 70K and $H//c$ -axis. Open triangles: $2 \times I_c$ vs H for the same sample and $T=70\text{K}$, with the magnetic field applied 55° off the c -axis. Inset: I_c vs H at 76K and $H//c$ -axis.

Figure 5. Irreversibility (or Bose-glass) lines for unirradiated and irradiated samples at different doses as indicated.