Irradiation response of commercial, high- T_c superconducting tapes: electromagnetic transport properties

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Abstract

Effects of low dose ion irradiation on the electrical transport current properties of commercially available high-temperature superconducting, coated-conductor tapes were investigated, in view of potential applications in irradiative environments. Three different tapes, each with unique and tailored as-grown flux-pinning structures, were irradiated with Au and Ni ions at energies that provide a range of damage effects, with accumulated damage levels near that expected for conductors in, for example, a fusion reactor environment. Measurements using transport current determined the pre- and post-irradiation resistivity, critical current density, and pinning force density, yielding critical temperatures, irreversibility lines, and inferred vortex creep rates. Results show that, at the irradiation damage levels tested, any detriment to as-grown pre-irradiation properties is modest; indeed in one case already-superior pinning forces are enhanced, leading to higher critical currents.

1. Introduction

Superconducting films of $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) deposited on flexible metal substrates – also known as YBCO-“coated conductors” [1] – have been commercially available for several years. The irradiation response of YBCO based conductors has been of interest both for pinning studies as well as for magnets in potential fusion applications. Until recently, the use of coated conductors in high magnetic field environments has been limited by inadequate current density due to their low irreversibility fields. While the present generation YBCO base tapes have demonstrated improved in-field properties [2, 3], which make them a potential option, the irradiation behavior is relatively unknown. In fusion applications, there is considerable cost and complexity associated with the superconducting cables presently in use [4, 5], and YBCO conductors have the potential of greatly reducing these costs due to their higher operating temperatures or higher current densities at low temperatures. Maximizing the critical current density, J_c , in YBCO has been achieved mainly through the combination of improved template-induced crystalline texture and the introduction of as-grown, tailored nanoscale defects designed to immobilize or “pin” supercurrent vortices that support magnetic flux quanta. It is in the form of these vortices that an applied magnetic field partially penetrates the otherwise superconducting bulk of type II superconductors, within the “mixed-state” range of applied magnetic fields and temperatures. The dissipative motion of vortices, when driven by the Lorentz force of an applied current, would make a nonzero J_c impossible without pinning of vortices. Several successful schemes for effective pinning by introducing as-grown, normal-state defects have been developed over the years (for example, see refs [6-11]), and three types of such films are the subject of this study. Another successful strategy for enhancing pinning is via the controlled irradiation by neutrons or ions of sufficient size and energy [1, 12, 13], which was actively investigated prior to the recent incorporation of effective as-grown defects in large-scale production processes. However, in the context of a radiation environment such as a fusion reactor, irradiation of the wire is already a *given consequence*: Radiation-induced damage will occur to the material producing electrical property changes, which could at low levels enhance performance, but eventually lead to degradation of the materials and a reduction in transport properties.

The three types of YBCO-coated conductors in this study contain already-superior pinning that has been proven to significantly enhance critical current density J_c [2, 14]. The radiation-induced changes to the pre-existing pinning structure is therefore of particular interest. This study focused specifically on electromagnetic transport measurements associated with vortex motion, before and after irradiation. A later paper will discuss in detail the correlating microstructural changes. In comparison to earlier generation tapes, the conductors of this study are found to demonstrate improved tolerance to comparable irradiation and damage levels without significant detriment to crucial superconducting properties such as critical temperature T_c , the field dependence of J_c , and magnetic irreversibility field. Indeed, for one type of film the irradiation was beneficial, resulting in even higher pinning force and a broadened non-dissipative phase space.

2. Experiment

The three types of superconducting tapes examined were produced by American Superconductor Corporation (AMSC) and Superpower Inc. (SPI). Two tapes purchased from SPI have approximately 0.8 μm thick superconducting film deposited via metal organic chemical vapor deposition on a 1-cm-wide MgO IBAD buffered metal strip. One of these tapes, designated as “Gd-BCO” ($\text{GdBa}_2\text{Cu}_3\text{O}_7$), in which excess rare-earth resulted in as-grown nano-precipitates of Gd_2O_3 aligned along *ab*-directions, is designed to provide isotropic pinning; the other, designated “Zr-BCO” – $(\text{Y}_{1-x}\text{Gd}_x)\text{Ba}_2\text{Cu}_3\text{O}_7$ – involves Zr doping (5 at%) which results in as-grown stacks of barium zirconate nano-disks designed to provide correlated pinning for fields aligned near the *c*-axis [14]. The third tape, provided by AMSC was fabricated through metal organic deposition (MOD) on a RABiTSTM template, and has a nominal superconducting layer thickness of 1.2 μm (excluding non-superconducting phases and porosity). This tape, designated “Dy-BCO” ($(\text{Y}_{1-x}\text{Dy}_x)\text{Ba}_2\text{Cu}_3\text{O}_7$), was Dy-doped (Y:Dy of 1:0.5), resulting in an as-grown random distribution of (Y,Dy)-oxide nanoparticles and a high density of *ab*-plane defects designed to provide an enhanced self-field I_c and strong pinning for fields parallel to the *ab*-planes at temperature $> 50\text{K}$. [2, 15, 16]. For all tapes, samples used in this study were cut from the same batch, in close proximity to one another along the tape. Before irradiation, electromagnetic properties of several

samples from different tape locations were evaluated, and have been found to be consistent. In this way, any sample-to-sample variations for each of the three tapes have been confirmed as negligible.

All three tape types were irradiated at the Ion Beam Materials Laboratory (IBML) at The University of Tennessee in Knoxville[17, 18]. The tapes were irradiated at room temperature under three conditions: 25 MeV Au ions, at fluences of $10^{11}/\text{cm}^2$ and $10^{12}/\text{cm}^2$, and 5 MeV Ni ions at a fluence of $5.5 \times 10^{11}/\text{cm}^2$. The ion energies and fluence were selected to avoid doping in the conductor layer, to produce damage levels for which the radiation effects of the conductor could be clearly examined, and which overlap with the levels of earlier ion irradiation studies of YBCO films (see [17] and references within). The ion fluences of both Au and Ni were chosen based on the assumption that the radiation effects would be measurable in the tapes for key properties of interest such as the critical current density and the critical temperature, but below estimated degradation levels. The higher Au fluence was estimated to be close to a level at which material degradation occurs. Electronic energy loss, S_e , of the Ni and Au ions was 2.5 and 6.5 keV/nm, respectively, staying below the threshold energy for columnar defect formation ($S_e \geq 20$ keV/nm). Nuclear energy loss, S_n , values were 0.29 and 1.4 keV/nm for the 5 MeV Ni and 25 MeV Au, respectively. The irradiation-induced damage for each particular type of tape is quantified in units of displacements per atom (dpa). The dpa levels of each type of tape were estimated from TRIM code [19] simulations using the available library of displacement energies for the atomic species and assuming a single phase YBCO structure. For the lower doses all three tapes showed between 0.003 and 0.005 dpa, and for the higher Au dose all three tapes showed 0.03 dpa. All the relevant parameters are listed in Table 1.

To our knowledge, calculations have not been attempted in correlating dpa to superconducting damage in these materials under neutron irradiation, nor does dpa correlate to specific microstructural changes resulting in predetermined electrical changes. The use of dpa here provides a first level of comparison to other ion irradiation data. Even so, there can be significant differences between the ions and energies used due to values of S_e and S_n . It is the intent of this paper to provide an initial assessment of changes to the material as a result of radiation damage and whether these materials should be considered for further testing.

Transport measurements, performed at the University of South Alabama, utilized short samples, each about 1.7 cm long. Before the irradiation, all the YBCO films were patterned into

a strip configuration (removing the silver “shunt” overlayer in the process) with silver contact pads and a 1-mm-long bridge with a width of either 1.00 mm or 0.200 mm, using a focused-electron-beam scribing system at Oak Ridge National Laboratory. For each current contact to the probe, a strip of indium was applied to the silver pads at pressed copper injection areas, which limited the electrical contact resistance to between $\sim 10^{-6}$ and $10^{-4} \Omega$. The probe was placed in a variable-temperature cryostat with the field of a 9-T superconducting magnet applied normal to the tape plane (approximately parallel to the crystal c -axis). Temperature- and field- dependence of resistivity, $\rho(T, B_o)$ was measured for each constant field B_o over a temperature T , scanned at a slow rate of change, never exceeding 0.2 K/min, such that there was negligible difference between the data acquired for cooling and for warming. The critical temperature for each field, $T_c(B_o)$, was determined using a resistivity criterion of $10^{-9} \Omega\text{cm}$, and the locus of all points $T_c(B_o)$ constituted the irreversibility line in the range of fields $B_o = 0$ to 9 T. For measurements of J_c , the system is designed to provide pulsed DC currents of up to 10 A, each with a duration of up to 50 ms, which, together with low contact resistance, effectively eliminates any significant joule heating[20]. Critical current was defined using the standard voltage criterion of 1 $\mu\text{V}/\text{cm}$.

3. Discussion of Results

In the following discussion, the plots all follow a consistent scheme for labeling the three different irradiations of Gd-BCO, Zr-BCO, and Dy-BCO, as described in Table 1. While the effect on transport properties varies with the different expected pinning microstructures, overall detrimental effects are very modest below the highest dpa of 0.03; for the case of Dy-BCO, there is actually enhancement of properties.

Figure 1 deals with the temperature dependent resistivity in self-field, with Figure 1(a) for Zr-BCO as an example set, where the main panel shows the common trend of the normal-state resistivity increasing, and the inset shows the expected decrease in critical temperature T_c with higher dpa, compared to non-irradiated (solid line). Also shown are thin, solid curves to illustrate how the residual resistivities were obtained from a fit to the $\rho \sim T^2$ portion of the curves, which extrapolate to residual resistivity ρ_i , as postulated in Mathiessen’s Rule, $\rho = \rho_i + \rho_n(T)$, where ρ_n is the temperature (T)-dependent normal-state resistivity and ρ_i is the

extrapolated intercept at zero temperature. This extrapolation was not possible for Gd-BCO as the curves had negative curvature, and so the resistivities at $T = 100 \text{ K}$ (ρ_{100}) were compared instead. The effects of irradiation on T_c , ρ_i , and ρ_{100} are summarized in Figure 1(b). For all three samples, the lower irradiation doses, 0.003 – 0.005 dpa, had modest effect on these quantities. The critical temperature reduction (triangles) below 0.03 dpa stayed within about 1% of T_{co} , the unirradiated T_c , with Dy-BCO (dashed line) having the smallest reduction at about -0.3% maximum and Gd-BCO having the largest at about -1%. In comparison, 1 MeV Ni and 2 MeV Ar irradiations ($S_e = 1.5$ to 2.3 keV/nm) of YBCO films on SrTiO_3 single crystals resulted in $-\Delta T_c/T_{co}$ values as high as 54 and 80%, respectively for dpa values near 0.026 [21]. Even for the highest dose of 0.030 dpa, where visible radiation-induced defect formations are observable through transmission electron microscopy (see reference [22], also to be further presented in a forthcoming paper), the critical temperature fall-off remained within 7% of the unirradiated T_c for all three samples, the smallest being less than -4% for Zr-BCO and the largest still less than -7% for Gd-BCO. Part of this limited reduction in T_c of the samples in this study may be due to the greater sensitivity of YBCO to electronic stopping and the lower S_e/S_n ratio, as compared to past work [23]. This is due to the sensitivity of ionic layers in the YBCO-structure to ionization events as compared to the more metallic like layered structures that are effected primarily by nuclear collision processes [24]

For residual resistivity ρ_i (squares), the increases are much more significant, indicative of further disordering in a microstructure that already had tailored as-grown impurity defects. The Zr-BCO (half-filled squares, thin line) experienced a smaller increase than Dy-BCO (open squares, dashed line) compared to the pre-irradiation level ρ_o , no more than about 50% for the lowest doses, and approximately doubling for the highest dose; meanwhile ρ_i for Dy-BCO experienced at least a threefold increment at the lowest dpa, a 15x jump for the Ni-irradiated sample, and finally a 60x jump for the highest dpa. These results would be consistent with Zr-BCO already having the highest level of impurities, in the form of extended stacks of BZO, compared to the localized impurity clusters in Dy-BCO. The trend for Gd-BCO (solid circles, thick line) could be speculated from changes in ρ_{100} : the trend for Dy-BCO is similar for both ρ_i and ρ_{100} (open circles, dashed line), although the latter has an initial jump that is about 30x smaller, as it is not as significantly affected by changes in sensitivity to temperature change (or the approximate slope of the normal-state resistivity). For Gd-BCO, the shift in resistivity is even

less sensitive, with little difference between the low-fluence Au and the Ni irradiations. Overall, then, aside from the initial jump for the Ni-irradiated Dy-BCO, the increase in residual resistivity and the reduction in T_c as a function of dpa appear to be very similar for all samples.

Figures 2 and 3 deal with results from the magnetic field dependence of critical current density J_c at temperature $T = 77$ K, where at self-field, most samples showed a J_c of at least 1 MA/cm², and stayed above this level for the lowest-damage irradiations, except for Dy-BCO as shown in the semi-logarithmic plot of Figure 2(a), where the curve for the unirradiated sample is shown as a solid line. A comparison for all fields is shown in Figure 2(b), which plots the normalized J_c relative to the unirradiated value $J_c^{unirrad}$. Overall, the greatest sensitivity for Gd-BCO (solid symbols) and Dy-BCO (open symbols) and a modest response for Zr-BCO are observed. The distribution is especially tight for the two lowest-dpa-irradiated Zr-BCO (half-filled) and Gd-BCO (solid). For all cases the reduction in self-field J_c is no more than five-fold, except for Gd-BCO at the highest dpa (triangles), with a drop of an order of magnitude. In field, this same type of tape shows the largest decrease in J_c , by almost three orders of magnitude at about 8.0 T. This and the 0.004-dpa Zr-BCO (half-filled circles), with a maximum decrease of a little over one order of magnitude, are the only cases where the J_c reduction increases with applied field. For all other cases, the reduction is the highest for self-field J_c and is alleviated with higher applied field. For both Zr-BCO (half-filled squares) and Gd-BCO (filled squares), all Ni-irradiated samples (squares) yielded a J_c that is *greater* after irradiation at sufficiently high fields – above 7 T. However, J_c enhancement under the Ni irradiation is unrivaled for Dy-BCO (open squares), with the lowest onset field at about 1.5 T and a maximum increase of more than two orders of magnitude at 8.5 T. This is particularly promising as the 5 MeV Ni irradiation effects could be considered closest to that expected for neutron irradiation in a fusion type of environment [25]. Above 7 T, the 0.003-dpa irradiation by Au ions (open circles) shows a comparable enhancement, with an onset field of above 4 T. Even the highest-dpa-irradiated film (open triangles) show enhancement, albeit above 6 T.

Presuming that changes in $J_c(B)$ are correlated with changes in the overall pinning force density, $F_p = J_c B$, F_p versus B was plotted for all cases, with an example shown for Dy-BCO in the inset of figure 2(a). In such plots there is an expected maximum pinning force F_p^{max} at a specific field B_{max} . Both these quantities are plotted versus dpa in figure 3. Dy-BCO (open symbols) and Zr-BCO (half-filled symbols) show significantly higher F_p^{max} overall compared to

Gd-BCO (solid symbols), specifically for all irradiations except with the lowest-dpa, lower-fluence Au, which show especially high degradation compared to others, yet only for Dy- and Zr-BCO. Otherwise, Zr-BCO and Gd-BCO show a similar decrease in F_p^{max} down from unirradiated (dpa = 0) values. Dy-BCO, on the other hand, showed an *increase* in F_p^{max} when comparing 0 dpa and 0.005 dpa, albeit a modest shift compared to the fall-off seen in other irradiations. As for the highest dpa, the significantly lower F_p^{max} for Gd-BCO is consistent with having significantly lowest $J_c(B)$. The field B_{max} is of interest as it is where the pinning landscape becomes optimal for a specific applied magnetic flux, and is plotted in figure 3(b). Once again Dy-BCO is set apart: For the two lowest doses below 0.03 dpa, Zr- and Gd-BCO show this field to stay within about 10% of 1.4 T, while for Dy-BCO there is a significant *increase*, under the same Ni irradiation condition that induced the enhancement in F_p^{max} ; interestingly, there is a significantly higher B_{max} for the lower-fluence Au irradiated sample that led to the largest *reduction* in F_p^{max} – i. e., the pinning that seems optimal for a specific field is not necessarily the strongest. As far as the highest dpa, Zr-BCO (half-filled diamonds) is the outlier, in that B_{max} is significantly higher than at 0 dpa, which would be consistent with its linear pinning structure which is generally expected to have a higher matching field than with isotropic pinning.

To summarize the $J_c(B)$ results: All samples show that irradiation causes modest reduction in J_c , *except* for two cases: significant enhancement for Dy-BCO consistent with improved pinning, and significant degradation for the highest-dpa Gd-BCO.

Such changes in the pinning landscape should be reflected in the magnetic phase diagram, $B(T)$, particularly in the irreversibility line (IL) between a state where vortices are pinned and a state where vortices are free to move under even slightest applied current. An example of the phase diagram is shown in the inset of Figure 4, again for Dy-BCO. As previously described, each point (B, T) on the IL consists of the applied field B and the corresponding critical temperature T for that field, determined from plots of resistivity versus temperature in constant field. Also shown is the approximate curve for the upper critical field, $B_{c2}(T)$, which at highest temperatures is expected to follow an approximate -1.5 T/K slope, up to the self-field T_c . As the IL appears well within the mixed or vortex state, it is essentially the depinning line: on the left side of the line (lower B and T) of each IL, vortices are pinned and J_c is nonzero, and on the right side of the line (higher B and T), the vortices are not pinned, and a

dissipative voltage due to vortex motion is present with even the slightest J , or in other words the J_c goes to zero [1].

In the main panel, the phase curves are re-plotted to include the post-irradiation shift in critical temperatures, by plotting the irreversibility field versus the irradiation-induced percent shift in T_c at each field. As such, the vertical, $\Delta T = 0$ line serves as the boundary between post-irradiation degradation ($\Delta T < 0$) or enhancement ($\Delta T > 0$). Overall, the results show good agreement with the $J_c(B)$ data (Figure 2). Once again, Dy-BCO (open symbols) and Gd-BCO (solid symbols) show the most sensitive response to irradiation: for Dy-BCO the pinned state has been enhanced to higher (B, T) for almost the entire range of fields for the two lower doses (dpa < 0.03) and above 7 T for the highest dose, while for the highest (0.03) dpa Gd-BCO (solid triangles) this pinned state is the most greatly reduced of all the samples. For the 0.004-dpa Zr-BCO (half-filled circles), the extent of the pinned state is reduced at higher fields (the curve has a negative slope), consistent with the decrease in J_c increasing with higher field; this is in contrast with the 0.03-dpa Gd-BCO (solid triangles) which had a similar trend in J_c , but here the extent of the pinned state is reduced at *lower* fields (the curve has a *positive* slope), which suggests that for Gd-BCO the reduction in J_c is less influenced by the reduced pinning but more sensitive with degradation of the superconducting phase. In contrast, for the 0.03-dpa Zr-BCO (half-filled triangles) and Dy-BCO (open triangles), the larger reduction in J_c at *lower* fields seems consistent with a more prevalent unpinned state at lower fields. For the Ni-irradiated Zr-BCO and Gd-BCO, a modest post-irradiation enhancement of the pinned phase at the highest fields is consistent with the modest J_c increase at highest fields.

To summarize the results from irreversibility lines: Post-irradiation reduction or enhancement in J_c are consistent with reduction or enhancement in the pinned state, respectively – with the exception of Gd-BCO, in which reduction in J_c is more sensitive with degradation of superconductivity in general.

The scaling of the IL's was also studied: IL's are expected to follow the approximate power law,

$$H \sim \left(1 - \frac{T}{T_c}\right)^m,$$

where T_c is the zero-field critical temperature while m is the scaling exponent – easily obtained as the slope of the logarithmic replotting of H versus $\left(1 - \frac{T}{T_c}\right)$ – typically between 1.5 and 2 for

YBCO. All three samples followed this power law, with the lower doses providing an m that averages to less than 1.3 and the highest dose providing an average m that is ~ 1.5 or higher. This consistent increase, as irradiation damage is increased, could be significant, and may warrant further study: It has been proposed that a higher m corresponds with a higher incidence of dissipative flux flow [26, 27] – which would be expected if isotropic pinning is made less effective by higher irradiation levels. This, as will be shown in a future paper, occurs with the development of small radiation-induced stacking fault like defects along with some disordered nano-sized regions appearing in the materials at high fluences. A particularly interesting result is the presence of two regimes in the Zr-BCO sample with the transition between the two at about 1.7 T: While the m values found for both regimes average out to match those of the other samples, below 1.7 T the IL is steeper, with m between 1.4 and 1.8, whereas above 1.7 T the curve is less steep: m between 1.1 to 1.2. The explanation behind this is unknown, as physical interpretations for the scaling component remain controversial; however it should be noted that Zr-BCO is the only set of films that exhibit *linear* pinning, as-grown, and may well be reason for two regimes for m .

The vortex creep rate, S , provides another probe into the effects of irradiation on the pinning landscape: it refers to how freely vortices can incrementally move (or creep) under the combination of a Lorentz driving force and random thermal excitation. S is found for temperature $T = 77$ K, by using the power law relationship between the voltage V associated with dissipative vortex motion and the applied current I : $V \propto I^n$, where n would be the slope of the same $\log V$ - $\log I$ curves used to determine critical currents at $T = 77$ K (Figure 2). The analysis is performed for only up to the lowest irreversibility field for dpa < 0.03 at this temperature, which is 7.5 T. The relationship between the $V(I)$ power law relationship and S is found in conjunction with the Maxwell Equation, $V \propto -\frac{d\Phi}{dt} \propto -\frac{dI}{dt}$, which leads to the expression for the vortex creep rate, $S = -\frac{d \ln I}{d \ln t} = \frac{1}{n-1}$ [28, 29]. This inverse relationship between S and n is consistent as follows: A lower creep rate would be desirable, as this means less dissipative vortex motion; a lower S also means a steeper V - I curve, which would make it possible to operate a device at lower dissipative voltages without reducing the current density significantly. The curves in Figure 5 show S in terms of a ratio between the irradiated and unirradiated values, for fields between 4.0 T and 7.5 T, scaled to the creep rate before irradiation,

S(unirrad), at $T = 77$ K. Overall, there is consistency with the IL's and $J_c(B)$ in that the most sensitive response to irradiation is for the highest-dose Gd-BCO and the lower-dose Dy-BCO: The $dpa < 0.03$ Dy-BCO (open symbols) showed the only significant improvement towards *lower* creep rates at higher fields, down by a factor of more than five at 7.5 T, in the case of the Ni-irradiated sample. While at these high field parameters at 77 K, the J_c levels and n values are too low to be practical for applications, the properties at $T = 77$ K could still serve as a benchmark for choosing which type of tape might be optimal for maintaining persistence at low dissipative voltages under more practical operating conditions, including lower temperatures where J_c 's are higher. Meanwhile, the $dpa = 0.03$ Gd-BCO (filled triangles) showed the most significant increase in creep rate – up to four times higher at 5 T, which is just below its irreversibility field. Also consistent with $J_c(B)$ data is the 0.003-dpa Zr-BCO (half-filled circles), which also showed an increase in creep rate, up to almost a factor of 2 at 7 T, in contrast to the other irradiated Zr-BCO, which showed practically no change in the creep rate. The same is true for the lower-dose Gd-BCO.

4. Conclusion

Ion irradiation study of three types of commercial YBCO coated conductor films produced by American Superconductor Inc. (designated “Dy-BCO”) and Superpower Inc. (designated “Gd-BCO” and “Zr-BCO,”), each with its own as-grown tailored pinning structures, has revealed different responses to doses of up to a threshold of 0.03 dpa, insofar as the transport properties – resistivity, critical current density J_c , and irreversibility line. Results from these measurements show that improvement in J_c – which occurred only for Dy-BCO – correlates with enhancement of pinning, while degradation of J_c – mainly in Gd-BCO – was attributed to degradation of the superconducting phase, while minimal effect was seen in Zr-BCO which likely had the most optimal pinning before irradiation. The behavior of the Gd-BCO conductor under ion irradiation suggests a less likely candidate for further experimental effort, while good performance was observed for Dy-BCO. The greater thickness of the Dy-BCO conductor may have influenced the comparative performance of the conductor, as it would create an increase in broadening of the defect cascade under ion irradiation. However, further analysis of the microstructural induced

changes needs to be completed. For the Zr-YBCO and Dy-BCO conductors, the comparable performance between the 5 MeV Ni and high fluence 25 MeV Au, despite the large difference in calculated displacement damage, may in part be due to the larger S_e/S_n ratio of the Ni irradiation (despite the lower overall S_e) suggesting a higher sensitivity to electronic stopping than that of nuclear.

At this time, microstructural examination is completing on the ion irradiated materials as well as the initial investigation into the neutron irradiation behavior of the Zr-BCO and Dy-BCO conductors.

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Table and Figure Captions:

Table 1. Brief description of the commercial superconducting YBCO tapes and irradiation conditions, plus labels and legends used in the Figures. Displacements per atom (dpa) were calculated using TRIM code. See text for details.

Figure 1. (a) Resistivity as a function of temperature with critical temperature (T_c) shown in the inset in comparison to unirradiated (solid line), for the “Zr-BCO” tape. Also included are curve fittings for residual resistivity determination. (b) Fractional shifts, relative to the unirradiated state, in residual resistivity ρ_i , resistivity ρ_{100} at $T = 100$ K, and critical temperature T_c .

Figure 2. (a) Critical current density as a function of the applied magnetic field with pinning force as a function of applied field. Inset is for “Dy-BCO” tape. (b) Normalized J_c relative to unirradiated, for all three tapes. Different irradiations are labeled as summarized in Table 1. Pre-irradiation curves are shown as a bold solid line in (a), for both the main panel and inset.

Figure 3. Effect of irradiation on (a) maximum pinning force and (b) the corresponding applied field B_{max} .

Figure 4. Shifting of irreversibility line (IL): field B versus percent shift in irreversibility temperature. Inset shows irreversibility lines for Dy-BCO, with pre-irradiation IL shown as a solid line.

Figure 5. Ratio of the flux creep rate of irradiated and virgin samples at $T = 77$ K as a function of applied fields, ranging from 4 to 7.5 T.

Table

<i>Samples</i>			<i>Irradiation: Displacements per atom (dpa), Line+symbol legend</i>		
<i>Label</i>	<i>Manufacturer</i>	<i>Expected pinning, as-grown</i>	25 MeV Au 10¹¹/cm²	5 MeV Ni 5.5x10¹¹/cm²	25 MeV Au 10¹²/cm²
Gd-BCO	<i>SPI</i>	isotropic pinning	0.0030 dpa —●—	0.0040 dpa —■—	0.030 dpa —▲—
Zr-BCO	<i>SPI</i>	correlated pinning	0.0030 dpa —◐—	0.0040 dpa —◑—	0.030 dpa —△—
Dy-BCO	<i>AMSC</i>	isotropic pinning	0.0033 dpa - -○- -	0.0050 dpa - -□- -	0.033 dpa - -△- -

Table 1 (Gapud *et al.*)

Figures

Figure 1 (Gapud *et al.*)

Figure 2 (Gapud *et al.*)

Figure 3 (Gapud *et al.*)

Figure 4 (Gapud *et al.*)

Figure 5 (Gapud *et al.*)