The Effect of Proton Irradiation on the Critical Current of Commercially Produced YBCO Conductors

G. A. Greene, R. C. Gupta, W. B. Sampson and C. L. Snead, Jr.

Abstract— **Samples of YBCO superconductor from two manufacturers were irradiated with protons at the BLIP facility at BNL. Two specimens of each type of conductor were irradiated to five fluences covering the range from 10^{16} to $4x10^{17}$ protons/cm^2. The beam parameters for the irradiations were 42 µA and 142 MeV. The critical current (zero field, 1µV/cm) for all twenty samples was measured in liquid nitrogen before and after irradiation to quantify the effects of high-dose proton-induced radiation damage on the performance of the conductor, and thus evaluate its suitability for service in high-radiation environments. All of the specimens had a pre-irradiation current of about 100 A. This current decreased linearly with fluence, with a slope of about 20% per 10^{17} protons/cm^2. The agreement between the two samples of each brand of conductor was exceptional.**

Index Terms— **Critical current, Radiation damage, YBCO conductor**

I. INTRODUCTION

In some accelerator applications certain magnets may be subject to very high levels of ionizing radiation. An extreme case would be the first elements in a machine such as the proposed Facility for Rare Isotope Beams (FRIB) [1]. Magnets made from High Temperature Superconductor (HTS) are ideal for this application since they could be operated near 40 K where the heat load due to the radiation can be removed more efficiently. Such magnets must be able to withstand the cumulative effect of the radiation over the lifetime of the project. The results presented in this paper are a first-order measurement of the radiation sensitivity of YBCO, a candidate HTS conductor for these magnets. The current at 1 µV/cm and zero applied field was measured before and after irradiation at 77 K for a series of conductor specimens.

Since it is difficult to irradiate a long length of superconductor uniformly with a proton beam, measurements must be made on very short segments. The profile of the beam used in this experiment is such that a region 1-cm long will see a proton flux varying by less than ±5% (see Fig. 4). A consequence of this short gauge length is that the voltages used for V-I curves must have a random noise level less than 0.1 µV. In the first section of this report the mounting and measuring of the samples is described. The second section gives the details of the irradiation and the third section the results.

Manuscript received on August 19, 2008. This manuscript has been authored by Brookhaven Science Associates, LLC under US DOE contract DE-AC02-98CH1-886. G. A. Greene, R. C. Gupta, W. B. Sampson and C. L. Snead, Jr. are with Brookhaven National Laboratory, Upton, NY 11973 USA (corresponding author: G. A. Greene; phone: 631-344-2296; fax: 631-344-2190; e-mail: greene@bnl.gov).

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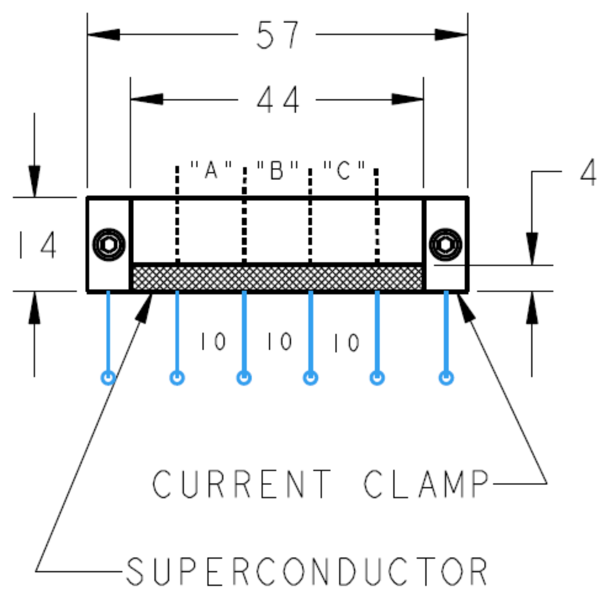

Fig. 1. Schematic diagram of the current measuring sample holder. The dimensions are in mm. Section "B" is at the center of the beam during irradiation.

II. CURRENT MEASUREMENTS

The fixture used for holding the conductor is shown schematically in Fig. 1. Samples are connected to the main current bus by mechanical clamps so that they can be easily removed and reinstalled. Thin (25 µm) copper foils which serve as voltage taps are permanently mounted on the micarta block separating the main current leads. During a test run, five sections of the conductor are monitored; the three 1-cm regions "A", "B" & "C", and the two joints. The section labeled B is positioned to be at the center of the beam for the irradiation, and the adjacent sections A and C are used to verify the accuracy of the centering. Voltages are averaged over 100 line cycles for each current point with steps of approximately ½ A over the transition up to 3 µV. A typical V vs. I curve for a 1-cm section is shown in

Fig. 2a with the companion log V vs. log I curve in Fig. 2b. The current at 1 μV and an estimate of the local "n" value (the slope of the curve) can be determined from these curves and results for all 20 samples are shown in Tables I and II in the RESULTS section.

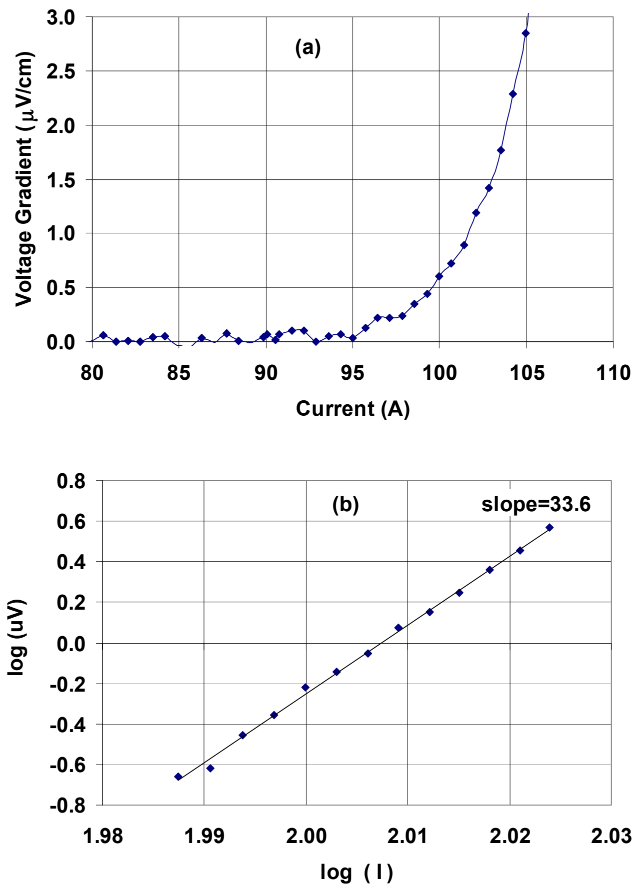

Fig. 2 (a) A typical voltage-current plot for section "B". The currents quoted in Tables I and II are at a voltage of 1 μV. (b) The log V – log I plot of the data in (a) near 1 μV/cm. I_1 is the x-axis intercept and "n" is given by the slope of the line.

III. PROTON IRRADIATION

Ten samples of YBCO conductor from each of two sources, American Superconductor Corporation (ASC) [3] and SuperPower (SP) [4] were used in this experiment. All 10 pieces came from the same length of conductor and both types had a current of approximately 100 A before irradiation. Two 7-cm lengths of each type were mounted on five aluminum frames and inserted into the water-filled target tank of the Brookhaven Linac Isotope Producer (BLIP). The irradiation was done at 142 MeV with a beam current of 42 μA, and different levels of proton fluence were achieved by progressively removing the aluminum frames after specific times to give 2.5, 25, 50, 75, and 100 μA hrs of irradiation. Two samples of each conductor at five fluence levels allow direct comparison as a check on the reproducibility of the results.

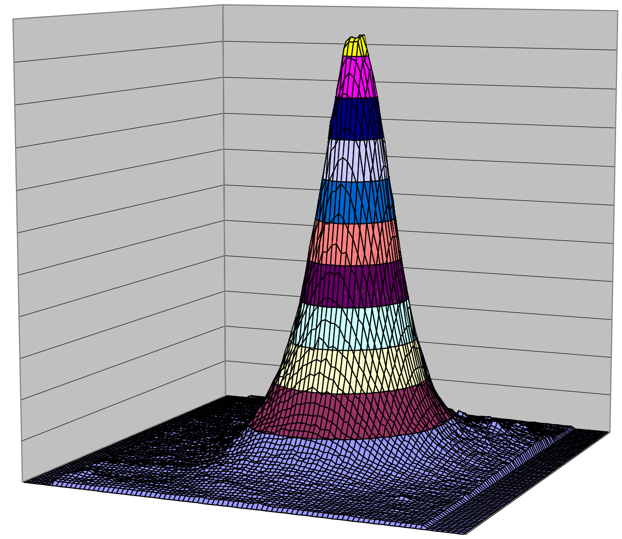

Fig. 3. The BLIP proton beam profile (in arbitrary units) deduced from a gamma scan of the activation foil irradiated with the superconductor samples.

The shape of the beam is shown in Fig. 3 which was plotted from a gamma scan of an activation foil irradiated during the experiment. This scan consists of a 90 x 90 grid with a resolution of 1 mm x 1 mm.

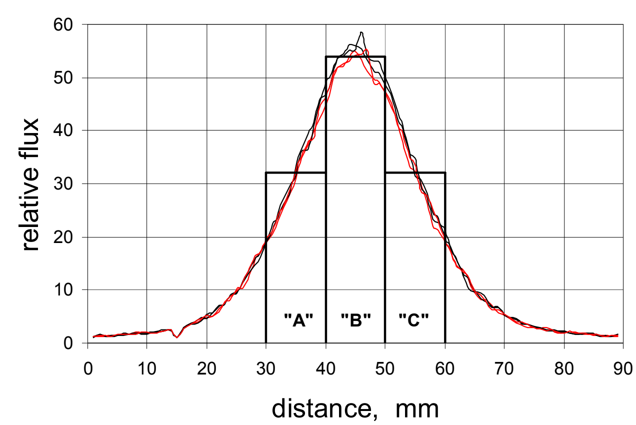

Fig. 4. The position of the three 1-cm segments in the beam cross section. The four curves cover the 4-mm width of the conductor.

Figure 4 shows the relative positions of the regions "A", "B" & "C" in the beam cross section. The four curves shown cover the 4-mm width of the conductor and indicate the uniformity of the irradiation of section "B". By adding the total counts over the whole grid and comparing it to the number of counts in the 40 mm^2 area of region B, the fluence can be converted to $protons/cm^2$ (100 μA-hr is equivalent to $3.4 \pm 0.5 \times 10^{17}$ $protons/cm^2$).

IV. RESULTS

Table I lists the 1-μV/cm current measured before and after irradiation for the ASC samples ("n" values are shown in brackets). The pre-radiation values are very uniform and all fall within the range 104-107 A with a typical n- value of about 35. The smallest proton flux level, 2.5 μA-hr ($8x10^{15}$ protons/cm^2), has no measurable effect on the properties of the conductor whereas the largest dose, 100μA-hr ($3.4x10^{17}$ protons/cm^2), has reduced the 77 K current to 32% of its original value. In general the results for two samples given the same fluence are in good agreement with the notable exception of the highest fluence, although in this case the average value is consistent with the other data (see Fig. 5). Currents measured for the “A” and “C” sections are higher since they are subject to a lower average flux. The fact that the reduction in current is less on either side of the central section indicates that the samples are well centered in the beam.

TABLE I ASC-YBCO Samples

rel.dose	section	$I_1(n)$ pre-rad	$I_1(n)$ post-rad	ratio
	A	107.1 (38)	107.0 (54)	
2.5	B	105.1 (35)	105.3 (38)	1.002
	C	104.5 (31)	103.4 (35)	
	A	106.8 (35)	103.5 (30)	
2.5	B	105.4 (37)	104.7 (36)	0.993
	C	104.8 (32)	99.5 (36)	
	A	104.8 (33)	99.5 (34)	
25	B	105.1 (36)	88.7 (30)	0.844
	C	106.8 (36)	93.6 (24)	
	A	104.7 (32)	95.6 (30)	
25	B	107.0 (37)	85.3 (29)	0.797
	C	105.0 (35)	99.7 (34)	
	A	104.6 (32)	96.3 (39)	
50	B	106.2 (39)	69.9 (26)	0.658
	C	105.1 (36)	75.6 (29)	
	A	107.2 (39)	77.0 (32)	
50	B	105.3 (37)	66.4 (28)	0.631
	C	104.4 (31)	83.8 (33)	
	A	106.5 (38)	68.0 (21)	
75	B	105.2 (36)	54.7 (24)	0.520
	C	104.8 (33)	78.7 (14)	
	A	104.6 (32)	79.2 (26)	
75	B	105.2 (36)	54.7 (25)	0.520
	C	106.1 (38)	67.7 (24)	
	A	106.5 (39)	51.6 (20)	
100	B	105.0 (34)	27.0 (20)	0.257
	C	104.8 (33)	46.1 (6)	
	A	105.8 (37)	63.3 (26)	
100	B	105.3 (38)	40.9 (24)	0.388
	C	104.5 (32)	59.7 (17)	

TABLE II SuperPower-YBCO Samples

rel.dose	section	$I_1(n)$ pre-rad	$I_1(n)$ post-rad	ratio
	A	101.9 (41)	101.1 (32)	
2.5	B	101.9 (43)	102.4 (35)	1.005
	C	99.8 (33)	103.1 (37)	
	A	106.0 (42)	109.8 (40)	
2.5	B	107.0 (42)	107.5 (36)	1.005
	C	107.4 (38)	107.5 (37)	
	A	107.6 (42)	104.0 (34)	
25	B	108.3 (42)	93.9 (27)	0.867
	C	108.0 (41)	104.2 (33)	
	A	109.4 (34)	102.0 (34)	
25	B	110.1 (39)	94.8 (29)	0.861
	C	109.6 (37)	103.3 (29)	
	A	100.8 (42)	84.1 (33)	
50	B	100.1 (40)	68.9 (27)	0.688
	C	100.3 (33)	87.5 (39)	
	A	99.6 (46)	58.5 (32)	
50	B	100.8 (37)	68.7 (27)	0.682
	C	102.2 (39)	79.8 (30)	
	A	106.3 (40)	74.9 (32)	
75	B	106.7 (42)	53.8 (26)	0.504
	C	107.0 (40)	73.2 (26)	
	A	104.3 (36)	69.6 (34)	
75	B	105.6 (42)	51.0 (26)	0.483
	C	105.5 (39)	69.1 (25)	
	A	102.5 (41)	54.5 (31)	
100	B	101.8 (39)	33.4 (24)	0.328
	C	101.6 (41)	49.1 (24)	
	A	100.5 (38)	50.4 (24)	
100	B	100.6 (39)	32.6 (23)	0.324
	C	100.2 (39)	52.1 (11)	

Table II is a similar compilation of the data obtained from the SuperPower specimens. In the case of the SuperPower specimens, the variation between the pre-irradiated conductors is somewhat larger (100-110 A) but the agreement between the ratios of pre- to post-irradiation of each pair is excellent. There is one unusual result in the table. Section “A” of the second conductor, at 50 μA-hr has a lower than expected current, less than the corresponding “B” section. Since all the samples were irradiated at the same time there is no obvious explanation for this except the possibility that this sample was mechanically damaged (i.e., bent) during the decontamination process.

The results for section B are plotted in Fig. 5 as the ratio of post to pre-irradiation currents vs. the fluence in µA-hrs. A least-square fit of the data gives a slope of 0.7%/µA-hr for both ASC and SuperPower. This is equivalent to a reduction of 20% in the 77 K current for each 10^{17} protons/cm^2.

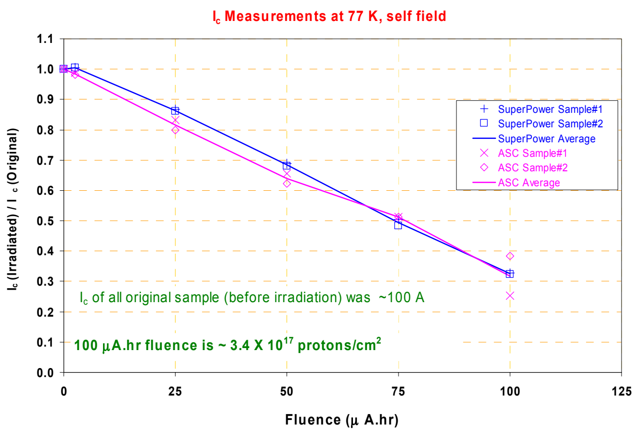

Fig. 5. The ratio of the irradiated conductor currents to their original values, plotted against the proton flux. The maximum (100 µA-hr) is equivalent to 3.4x10^{17} protons/cm^2**.** The two equations are a least square fit to the ten data points for each conductor type.

Measurements are currently underway to determine the temperature and magnetic field dependence of these samples. Preliminary data indicate a reduction in the critical temperature of the ASC conductor of approximately 3 K (see Fig. 6) while the SuperPower conductor showed an even larger change in T_c. Radiation effects in YBCO have been the subject of many experiments since this material was first discovered 20 years ago. Most of these studies used thin films which showed much bigger changes in J_c and T_c, for example, see [5-6].

V. CONCLUSIONS

High-energy proton irradiation of ribbon type YBCO conductor will reduce the current measured at 77 K significantly. However, the maximum radiation doses used in these experiments are well over an order of magnitude equivalent of what would be present in FRIB [7] (> 10^6 Gray per year). Both types (ASC and SuperPower) tested showed almost identical behavior. The radiation sensitivity of YBCO appears to be comparable to that of Nb_3Sn [2]. If both the temperature and magnetic field dependences scale with the 77 K data, the adverse effect of radiation on a magnet could be mitigated by slightly reducing the operating temperature. Thus, a magnet designated to operate at say 40K could be restored to its original current after accumulating some radiation damage by reducing the temperature to say 35 K, an option not really practical for LTS magnets.

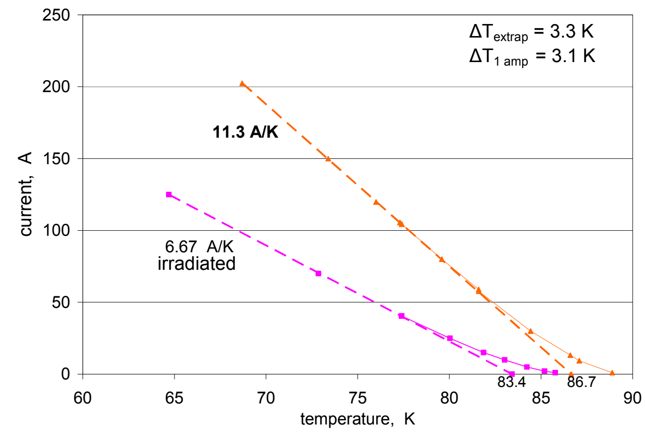

Fig. 6. The temperature dependence of ASC conductor before and after irradiation. The change in T_c obtained by extrapolating to zero current is the same as the change at 1A.

ACKNOWLEDGMENT

The authors would like to thank L.F. Mausner and his associates at the BLIP facility for the sample irradiation, E. Korach for the measurement of the activation foil, A. Zeller for feedback on irradiation, and M. Garber for analysis of the V–I data.

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