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S. Feher et al.

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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HTS Wire Irradiation Test With 8 GeV Protons

S.Feher, H.Glass, Y.Huang, P.J.Limon, D.F.Orris, J.Ozelis, P.Schlabach, M.A.Tartaglia, J.C.Tompkins
Fermilab, Batavia, Illinois, USA

***Abstract*—The radiation level at High Energy Particle Accelerators (HEPA) is relatively high. Any active component which should be close to the accelerator has to be radiation hard. Since High Temperature Superconductors (HTS) have a great potential to be used in HEPAs (e.g., in superconducting magnets, current leads, RF cavities), it is important to understand the radiation hardness of these materials. A radiation test of HTS wire (Bi-2223) was performed at Fermilab. The HTS sample was irradiated with 8 GeV protons and the relative I_c was measured during the irradiation. The total radiation dose was 10 Mrad, and no I_c degradation was observed.**

I. INTRODUCTION

In order to evaluate the long-term reliability of accelerator components made with new HTS materials, it is necessary to determine their performance characteristics in a radiation environment. A number of radiation hardness experiments have been conducted in the past [1]- [6]. Fermilab is evaluating the use of HTS power leads as a possible upgrade to the Tevatron, a superconducting proton accelerator. In this experiment we exposed an HTS current lead (as a source of the HTS material), manufactured from Ag-alloy sheathed Bi-2223 by the American Superconductor Corporation (Cryosaver; model number CS010030), to a high intensity 8 GeV (kinetic energy) proton beam using the Fermilab Booster. The wire we tested is a commercial product, and is made of the same HTS material that has been built into a pair of high-current leads which we separately power tested for use in the Tevatron.

II. TEST SETUP

A. Cryogenics and Beam

The radiation test was carried out in a section of the Fermilab Booster tunnel where beam could be extracted onto a target. Operational considerations limited access to the tunnel, so the apparatus was designed to minimize the need for access once it was assembled. Figure 1 shows a schematic view of the test setup. The liquid nitrogen (LN_2) cooling system was designed to operate for approximately a week without needing to refill the supply dewar.

The HTS power lead was immersed in LN_2 inside a test cryostat, whose elevation and horizontal position in the beam could be adjusted with a remotely operated table. The connection between cryostat and supply dewar was made with a flexible hose assembly to accomodate this motion. The cryostat was swept horizontally by several beam widths, and moved up and down the full wire length, continuously during the exposure to illuminate the entire HTS wire uniformly. These motions were made automatically in discrete steps (measured by a position encoder) between pulses whenever a preset number of beam counts was accumulated.

The beam position was continuously monitored using a fluorescent “flag” target viewed by a closed-circuit television camera. This flag was connected to the cryostat and its position was surveyed relative to the HTS wire; a coordinate system on the flag made it possible to determine the position of the beam spot. The beam spot size was of order 4 mm diameter – comparable to the 4 mm diameter power lead. The pulse-by-pulse beam intensity was monitored by the accelerator system using a beam toroid. The integrated radiation flux was also measured from the activation of two thin aluminum foils placed upstream of, and exposed with, the current lead.

B. DAQ and Power Systems

The data acquisition and power supply control systems are illustrated in Figure 2. The basic subsystems included 1) a scan system to monitor temperatures in the cryostat, 2) a scan system to measure the current and voltage across the power lead, and 3) the power supply control system. Existing coaxial cables, about 150 feet long from the tunnel to the readout electronics located in a remote service building, were utilized. Although not optimum, the cables provided quite low-noise performance.

Figure 3 shows a detail view of the power lead and sensors. The temperature and voltage measurements were made with multiplexer and digital multi-meters (DMM) connected via GPIB to a VXI crate, controlled by and logged to a SUN workstation that executed simple shell scripts. Temperatures were monitored continuously, every 30 seconds, using platinum resistor thermometers. A fixed-current source was used and a two-wire resistance measurement was made with a multiplexer/DMM combination. Two sensors monitored the LN_2 dewar temperature (and liquid level), and two others monitored the HTS

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wire temperature in the cryostat. The HTS wire temperature throughout the test was 78 K.

The lead voltage was measured with an HP3458 DMM configured to integrate over 1 line cycle, for 60 Hz noise rejection, and sample at 40 Hz. At each current, the system recorded 20 measurements with 3 nanoVolt resolution. The current was raised in 2 A steps, giving a ramp rate of 2 A/s. This DMM provided a digital display of the lead voltage for visual monitoring and quench detection.

A bi-polar supply was used to power the lead, and was controlled using an HP E1328A DAC module in the VXI crate. A unix shell script controlled the ramp up to a maximum current of 100 Amperes. The power supply polarity was alternated between ramps in order to determine and eliminate thermal emfs. The current measurement was made with a transductor whose output was digitized with an HP3458 DMM. The current was also visually monitored using a shunt resistor and displayed with a Keithley 2001 multi-meter. Due to the expected slow development of HTS quenches, the quench protection was performed manually by an operator watching that the lead voltage did not exceed a threshold of 1mV; if it did, the power supply was to be manually switched off.

C. Test Program and Data Sets

The primary purpose of the test was to measure the voltage vs current behavior as a function of radiation dose, in order to determine the critical current, I_c. Nearly 200 power supply ramps were measured during the 8-day test, in which 6.2e15 protons were delivered to the target. The radiation dose as a function of time was approximately linear.

Some special measurements were made in order to assess possible voltage growth due to resistance changes during the slow ramp. For this study, called the “step test”, the power supply was ramped very quickly to a current near I_c and the lead voltage was measured at that current for about 50 seconds (the same duration as the slow ramp). The stability of this voltage allows us to evaluate a systematic error in the measurement of I_c.

III. RESULTS

A. Radiation Dose

The integrated proton intensity on target can be used to estimate the total radiation dose to the HTS wire. The conversion to radiation dose requires the assumption of a quality factor, given by the Fermilab radiological survey group as 1 Mrad = 3.35e13 protons/cm^2 at 8 GeV. Folding in the exposed area (20 cm x 1.2 cm), we estimate the total radiation dose to be about 8 $Mrad/cm^2$.

The exposed aluminum foils were analyzed independently by the Fermilab radiological survey group [7], who calculated from the foil activities and mass that the total exposure of the two foils was 11.5 ± 1.5 $Mrad/cm^2$ and 10.2 ± 1.3 $Mrad/cm^2$, consistent with the rough estimate above. We take this more rigorous result as the actual exposure.

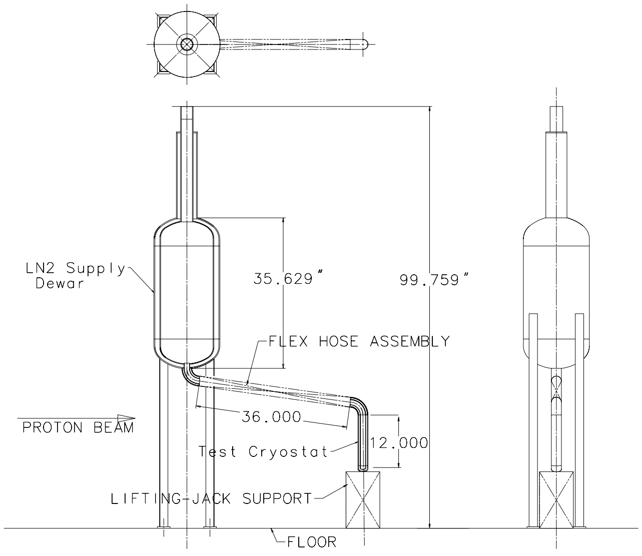

Fig. 1. Cryostat and motion table in the 8 GeV proton beam.

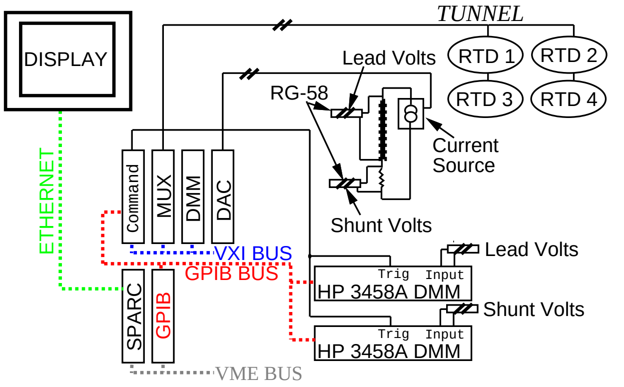

Fig. 2. Schematic diagram of data acquisition and power supply electronics.

B. Determination of I_c

The value of I_c is taken to be the current at which the voltage across the HTS wire corresponds to 1 mV/cm. Since the HTS wire was 18.5 cm long, this voltage is 18.5 mV. Therefore I_c can be read off the graph of voltage versus current. Figure 4 shows the voltage versus current for typical positive and negative ramps, plotted on the same graph. One can see there is an offset of about 100 μV, which is due to thermal emfs and was fairly stable. The uncertainty in this baseline, of about 5 μV, leads to an uncertainty in the critical current of about 2 Amperes. The scatter among the points at a given current is quite small, and has an RMS of about 100 $nanoVolts$. During the test the points with large scatter were found to occur in coincidence with the beam pulse.

Figure 5 shows the average current versus voltage, where the positive and negative polarity data have been averaged and the thermal emf eliminated. From this graph one can read off the critical current to be about 74 Amperes.

Figure 6 illustrates the behavior of the critical current as a function of the radiation dose. Each point represents

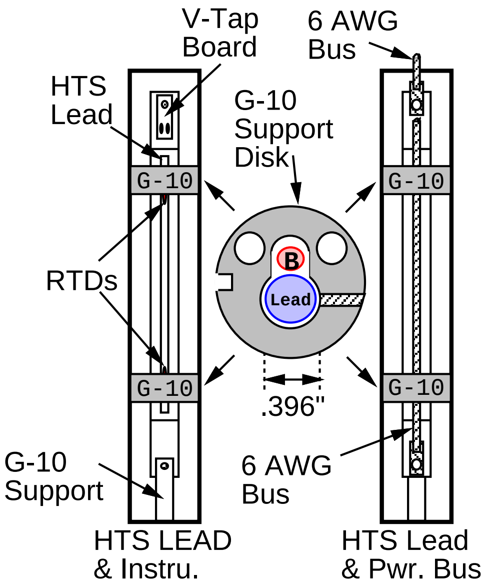

Fig. 3. Detail view of Power Lead Instrumentation.

the average of positive and negative ramp data taken in succession. A least squares fit is superimposed and indicates that, within errors, there is no dependence on the integrated radiation dose. The scatter in measurements is consistent with what is expected from observed variations in the baseline voltage. We therefore obtain the raw result, $I_c = 73.5 \pm 2$ Amperes.

C. Interpretation

This raw result may be subjected to some interpretation, first because of the possibility of voltage growth from resistance during the slow ramp; second, because the geometry of the test setup implies the HTS wire is influenced by a small magnetic field from the return current bus (see Figure 3).

From the study of voltage behavior during the step test, we find no systematic change with time, and variations are consistent with the baseline stability observed for slow ramps. We conclude there is negligible systematic shift of the critical current due to resistance growing with time.

The magnetic field from the return current bus next to the HTS wire is given by $B = \mu_0 I/(2\pi r)$, perpendicular to the wire. At a nominal current of 73.5 A and a distance of about 1 cm, $B = 15\ Gauss$. At this field and at 78K, the manufacturer's specification indicates the reduction in I_c is (very approximately) 10% relative to self field and 77K environment. Therefore our measurement of 73.5 A is consistent with the manufacturer-measured critical current of 80 A for this power lead (at self field and 77K).

Another consideration for interpreting the result may be the type of radiation to which the HTS material has been exposed. In this case, the primary beam is a strongly-interacting hadron beam. There will be some showering due to cryostat material upstream of the wire, leading to an electro-magnetic component of the radiation: The amount of material upstream corresponds to 0.03 interaction lengths, (.28 radiation lengths) of stainless steel. For this thickness of material, the probability of an inelastic hadron interaction leading to a shower is about 3 percent. On average about 3 secondary particles will be produced in such a shower (halfway through the material), of which 1/3 will be neutral pions that decay to a pair of photons. The photons will shower electromagnetically, and for this thickness about 1/8th of them will convert to a positron-electron pair. This rough order-of-magnitude estimate implies that 1 electron will traverse the HTS wire for every 70 protons.

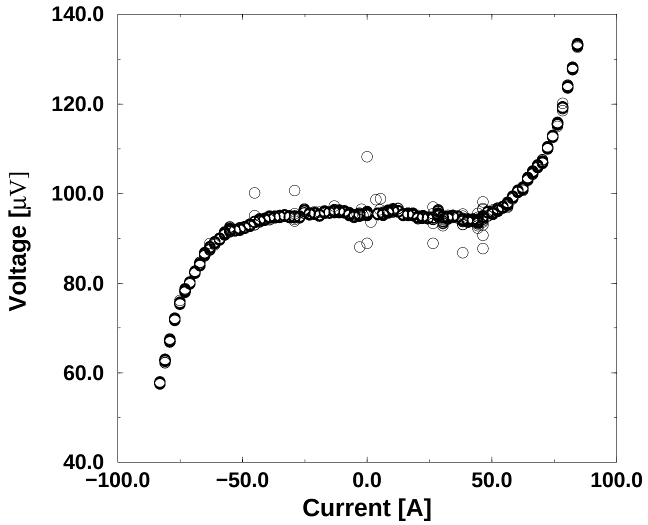

Fig. 4. Sample V vs I measurements for one positive- and one negative-polarity ramp.

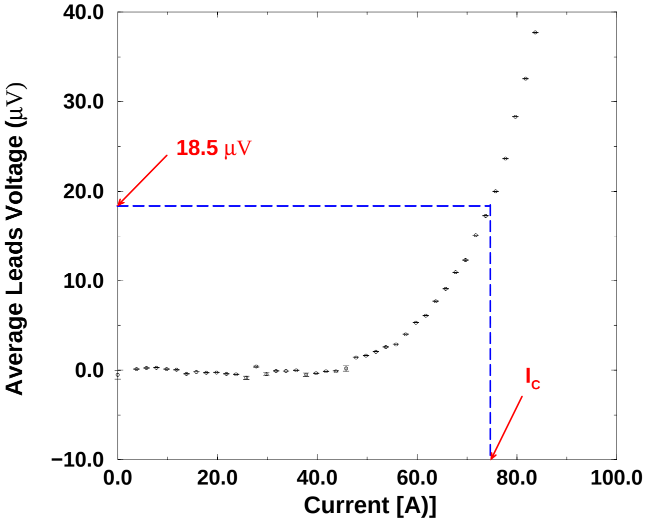

Fig. 5. V vs I curve, average of positive- and negative-polarity V data at each current.

IV. Conclusion

We exposed an HTS wire made of Bi-2223 to an 8 GeV proton beam, and measured the critical current of the wire to be $I_c = 73.5 \pm 2\ A$. This is consistent with the manufacturer's measurement of 80 A for this wire, when

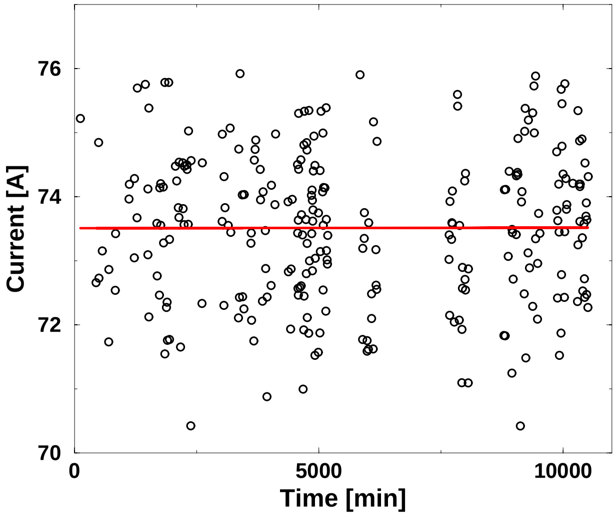

Fig. 6. Measured I_c as a function of time.

TABLE I

Comparison of analytical and numerical calculations with experiment.

the local magnetic field is taken into account. We saw no degradation of the critical current as a function of the radiation dose.

Acknowledgment

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