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TRANSIENT X-RAY IRRADIATION OF HIGH TRANSITION TEMPERATURE SUPERCONDUCTING MATERIAL

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July 1990

Final Report

Approved for public release; distribution unlimited.

Weapons Laboratory
Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008

WL-TR-90-47

This final report was prepared by the Weapons Laboratory, Kirtland Air Force Base, New Mexico, Job Order ILIR8805. Robert M. Pelzl (NTCET) was the Laboratory Project Officer-in-Charge.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE July 1990

3. REPORT TYPE AND DATES COVERED Final Report; Feb 88 - Mar 90

4. TITLE AND SUBTITLE
TRANSIENT X-RAY IRRADIATION OF HIGH TRANSITION TEMPERATURE SUPERCONDUCTING MATERIAL

5. FUNDING NUMBERS
PE: 61101F
PR: ILIR
TA: 88
WU: 05

6. AUTHOR(S)
Robert M. Pelzl and David C. Koller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Weapons Laboratory
Kirtland AFB, NM 87117-6008

8. PERFORMING ORGANIZATION REPORT NUMBER
WL-TR-90-47

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes transient radiation studies performed on high critical temperature (T_C) superconductors by Weapons Laboratory (WL) personnel in the WL Flash X-ray Facility. The objective was to detect any transient effects on the superconductivity of high T_C material during irradiation by an X-ray pulse. Each sample of high T_C material was cooled to a temperature below its T_C and then irradiated with a 20-ns pulse from a Febetron 705 flash X-ray machine. Each pulse delivered 85 rad(Si) to the sample. The samples were current biased and their conductivity measured during irradiation. Within instrumentation limits, measurements made on thin film high T_C material revealed no changes in conductivity during or after irradiation.

14. SUBJECT TERMS High T_C Superconductors, Superconductor Electronics, Radiation Effects, Transient X-Ray Effects.

15. NUMBER OF PAGES 34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

PREFACE

The authors wish to acknowledge the invaluable support of the Los Alamos National Laboratory (LANL) in providing high critical temperature (T_C) thin film superconducting samples. Our experiment could not have been completed without them. We would like to give special thanks to Jerry Beery of LANL for his guidance and support throughout the project.

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INTRODUCTION

Soon after the discovery of high critical temperature (T_C) superconducting materials, experimenters exposed samples of the material to high total doses (above a megarad) of gamma rays from cobalt 60 sources. Critical temperature and critical current measurements were made before and after exposure, but exposures were typically passive (no biasing or measurements during exposure) and at room temperature. No significant effect upon the superconductivity of the materials was observed as a result of those experiments.* The experiment reported here differed in that it was designed to look for effects while the material was in the superconducting state, i.e. for transient effects. This was accomplished by cooling each sample below its transition temperature, establishing a fixed current bias through the sample and then monitoring the current flow during irradiation of the sample by an X-ray pulse. During the pulse, a four point resistance measurement was made. Figure 1 is a simplified schematic of the test setup. A more detailed description of the test setup can be found in the Appendix.

Looking for transient effects was considered important because electronic devices (e.g., Josephson Junction devices) that will ultimately be fabricated from high T_C materials will certainly find applications in a space environment. Consequently, exposure to X-ray pulses generated by high altitude nuclear bursts are a possibility. Any transient effects upon the superconductivity of the material could result in circuit upset of electronics employing high T_C devices.

The results of this experiment revealed no measurable transient effects upon high T_C thin films as a result of exposure to X-ray pulses generated by a Febetron 705 flash X-ray (FXR) machine.

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* Bohandy, J., et al., "Gamma Radiation Resistance of the High T_C Superconductor $YBa_2Cu_3O_{7-x}$," Phys. Lett., vol. 51, p. 2161-2163, 1987.

Attempts to make similar measurements on samples of plasma sprayed high T_c material were inconclusive because of instrumentation limitations. The resistivity of the plasma sprayed samples at temperatures above T_c was very low. Consequently, any increase in resistance above the zero resistance of the superconducting state would not likely have been detected with the instrumentation available for this experiment.

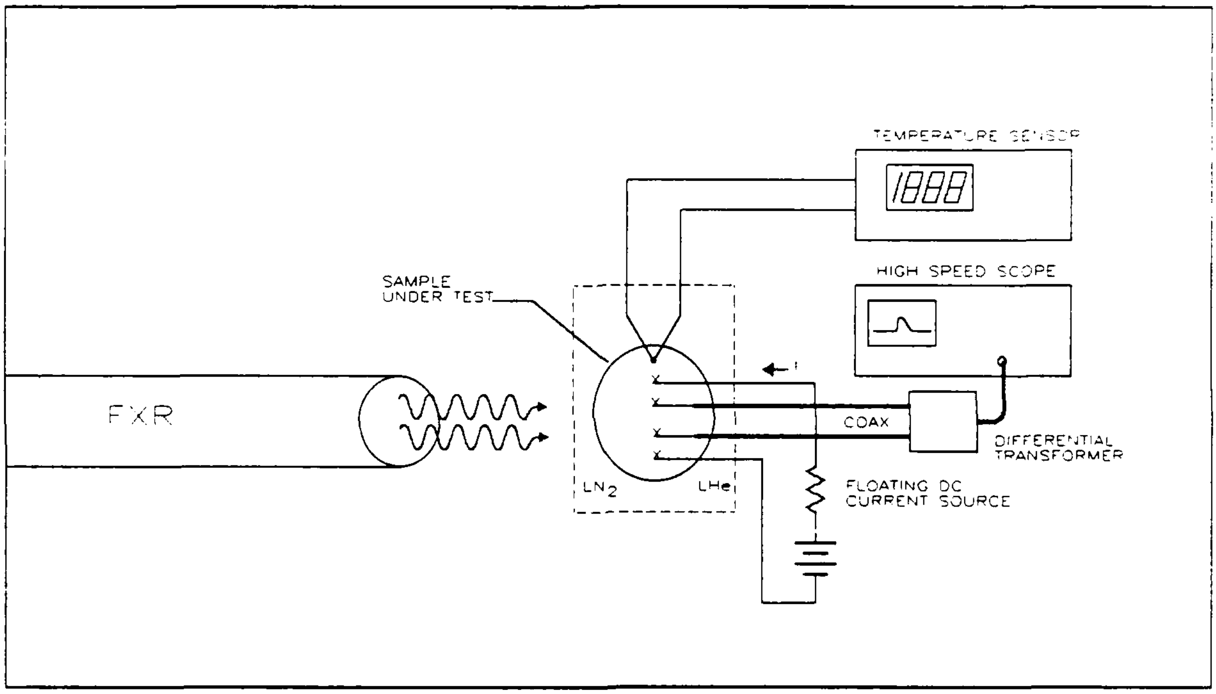

Figure 1. Test configuration for a transient measurement.

EXPERIMENT PROCEDURES

The objective of this experiment was to determine whether high temperature superconductors would experience any transient changes in superconductivity when exposed to an X-ray pulse. To accomplish this task, several sample types of high temperature superconducting material were chosen for irradiation in the Weapons Laboratory (WL) Febetron 705 Flash X-ray Facility. The first sample type chosen was prepared from a powdered mix of yttrium-barium-copper-oxygen in the standard 1-2-3 ratio. The powder was plasma sprayed to form a thick film on an Inconel 718 (nickle alloy) substrate. These samples were fabricated at the State University of New York (SUNY) at Stony Brook and were procured through the Naval Research Laboratory (NRL), Washington, D.C. The second sample type was essentially the same ratio of elements applied by vapor deposition to a substrate to form a thin film array of four bridges. Figure 2 shows the configuration of the superconducting bridges for this sample type. These samples were fabricated by the Los Alamos National Laboratory (LANL), Los Alamos, New Mexico.

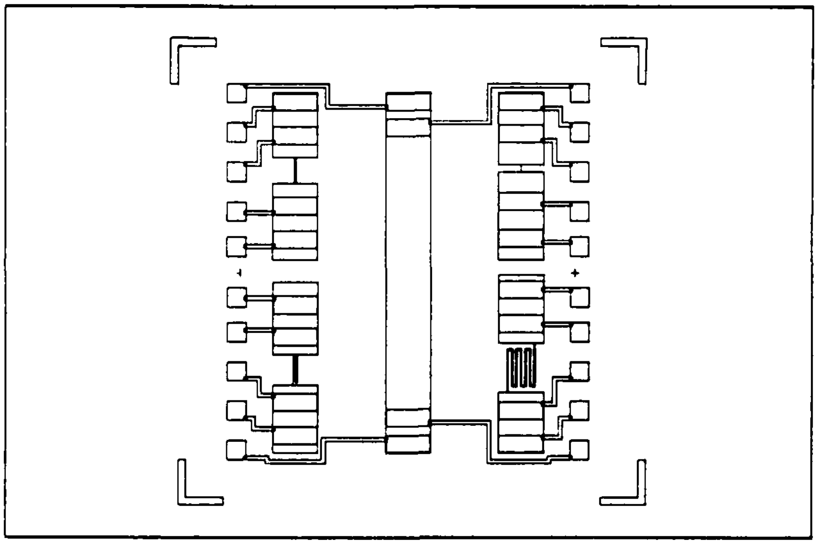

Figure 2. Thin film bridge array.

The samples were tested in a Dewar charged with liquid nitrogen in an outer chamber and liquid nitrogen or liquid helium in an inner chamber. Liquid from the inner chamber was bled through a copper cold foot. A test sample was mounted on the face of the cold foot. A platinum temperature control sensor was mounted in the cold foot and a platinum measurement sensor was mounted on the face of the cold foot adjacent to the test sample. The temperature of the cold foot was regulated by supplying constant power to a heater within the cold foot and controlling the flow rate of the liquid nitrogen or helium through the cold foot. The flow rate was controlled with a regulator designed and built in-house. This system kept the temperature stable to within several hundredths of a degree Kelvin of the set temperature and performed considerably better than a commercial system that regulated somewhat differently. The commercial unit varied the power input to a heater mounted in the cold foot while allowing the liquid nitrogen or helium to flow through the cold foot at a constant rate.

The Febetron 705 FXR machine employs focusing magnets that generate a substantial magnetic field at the face of its target area. To minimize the effects of this magnetic field on the superconductivity of the test samples during irradiation, the base of a drift tube was attached to the faceplate of the Febetron, and the Febetron's tantalum target was moved from the faceplate to the other end of the drift tube. The drift tube telescoped from approximately 13.6 to 31.9 in. It was then necessary to determine how far the drift tube should be extended to minimize the magnetic field effects and still deliver a reasonable X-ray dose. This was accomplished as follows.

First, the effect of a magnetic field on the superconductivity of a sample was measured as a function of the magnetic field density at the faceplate of the Dewar. This, in turn, was done by measuring the magnetic field density at various distances from a fixed magnet, positioning the face of the Dewar at each distance and acquiring a plot of the resistance versus current at each distance. By comparing the resistance-versus-current plots made at various field densities with the ambient field plot (Fig.3), it was determined that at a temperature of 60 K the effects of a field density less than about 80 G on the superconductivity of the sample were below the detection threshold of the instrumentation. At lower temperatures the magnetic field effects were even less pronounced, and their detection thresholds were at higher field densities. Using a gauss meter, the field generated

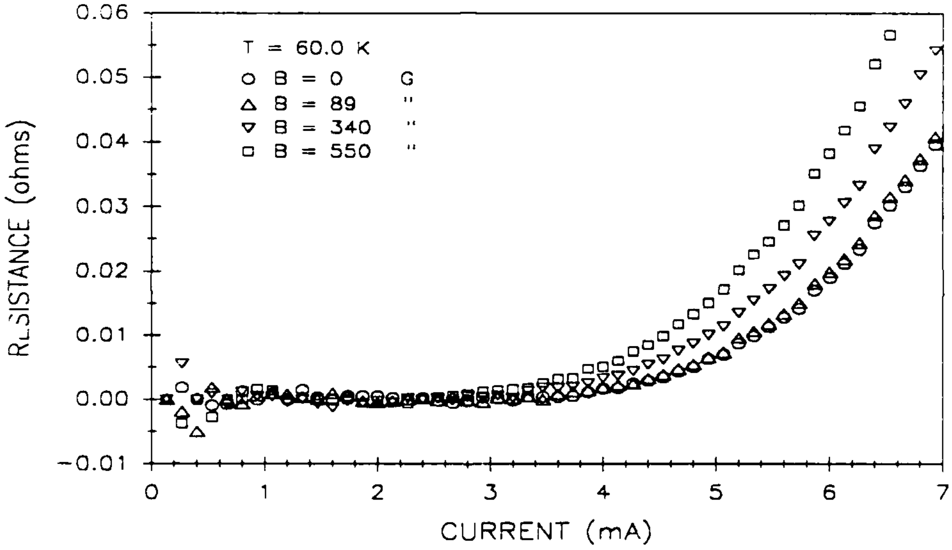

Figure 3. Magnetic effects on resistance versus current.

by the focusing magnetics was mapped as a function of axial distance from the Febetron faceplate. Finally, the drift tube was extended to approximately 15.1 in, at which extension the field density was measured to be approximately 55 G when the focusing magnets were operating. Since all bridges were tested at temperatures of 60 K or less, any magnetic field effects were below the detection threshold of the instrumentation.

To perform a test, a sample was mounted on the face of the cold foot so that the surface of the sample was normal to the axis of the Febetron when the Dewar was located with its faceplate flush against the faceplate of the drift tube (Fig. 4). Calibration of the dose seen by the sample was accomplished by mounting thermoluminescent detectors where a sample would normally be mounted and irradiating them at the same machine settings as used for testing samples. The dose delivered to the sample area was measured to be 85 rad(Si)/shot. The duration of the pulse was nominally 20 ns. Data from testing bridge no. 1 was taken on a Tektronix R7844 Dual-Beam Oscilloscope with a C-50 Oscilloscope Camera and was recorded on photographs. No attempt was made to digitize the photographed waveforms, consequently no values for V_{signal} were computed for bridge no. 1. Measurements on bridge

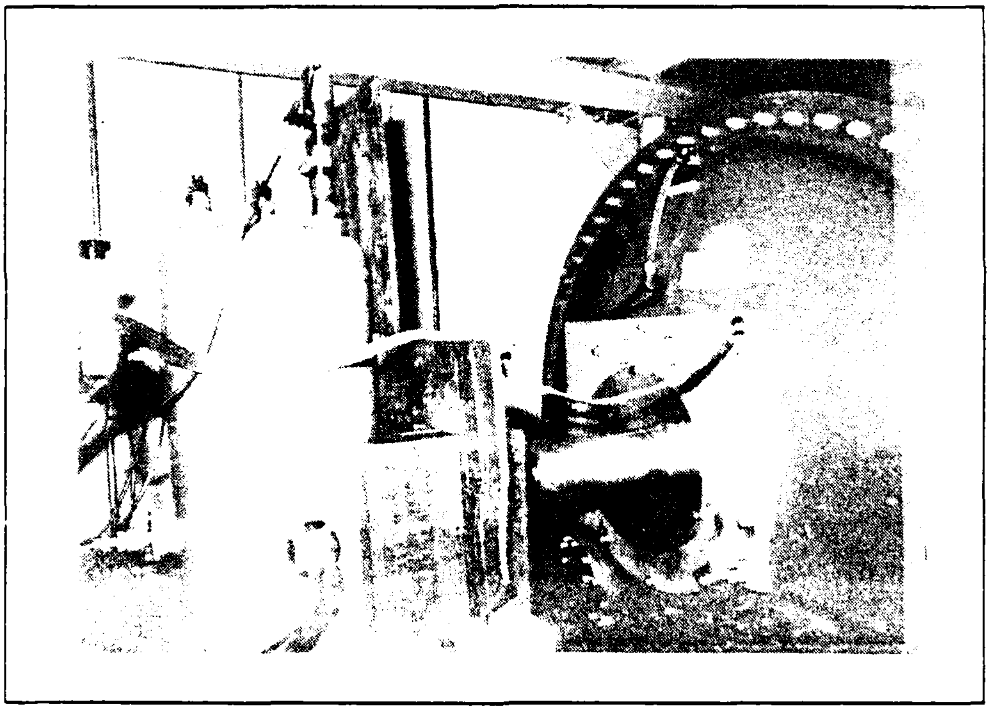

Figure 4. Dewar in place against Febetron drift tube.

no. 1 were also made before a differential transformer was added to the measurement system to reduce noise levels. Consequently, the voltage measurements were approximately a factor of 10 higher than they would have been had the measurements been made with the differential transformer included in the measurement system. With that in mind, visual comparisons of the photographed waveforms recorded for bridge no. 1 with the digitized waveforms recorded for the other bridges were made. No inconsistencies were observed, and there is no reason to believe that conclusions based on analyses of the other bridges would not hold for bridge no. 1.

After bridge no. 1 was tested, the test setup was reconfigured to acquire data on a Tektronix 7104 Oscilloscope with a Tektronix DCS01 Digitizing Camera System. A differential transformer was also added to the data acquisition system to reduce the noise levels and increase the signal-to-noise ratio. Instrumentation control and data storage were handled with a portable IBM-compatible PC.

The procedure followed for testing each bridge was to cool the sample to a temperature below its T_c and regulate at that temperature for the remainder of the test. Resistance-versus-temperature measurements were made during the cooling phase to establish T_c for the sample under test. The sample was then current biased incrementally to provide resistance-versus-current plots. From these plots, the current bias values to be used for transient testing were chosen. To perform the transient tests, the bias was first set to zero, the sample irradiated by the FXR machine and a waveform of the voltage across the sample as a function of time was acquired during the X-ray pulse. Then, for each bias value that had been chosen from the resistance-versus-current plot, the sample was again irradiated and a voltage waveform was obtained during the pulse. After the series of transient measurements was completed for a given bridge, a second resistance-versus-current measurement was made for comparison with the same measurement made prior to the transient measurements.

DISCUSSION

Two devices were supplied by LANL. Each device consisted of four bridges of high T_C superconducting thin film deposited on a substrate. Each bridge had different dimensions. The thickness of the deposited film was essentially constant, however the lengths and widths of the bridges were varied to provide different aspect ratios (ratio of length to width) and different resistances. A few of the bridges had developed opens as a result of thermal cycling, and one developed an open during a pretest T_C measurement. Table 1 lists the bridges that were tested successfully. The resistance measurements listed for each bridge were made at room temperature. The WL measurements were made a number of months after the LANL measurements. The differences in resistance were attributed to a slight degradation of the material.

Table 1. Test sample specifications.

Bridge No.	Device No.	Bridge Width (μm)	Aspect Ratio	Resistance LANL (k ohms)	Resistance WL (k ohms)
1	1/5/89-5	30	20:1	0.862	0.950
2	1/5/89-5	10	20:1	0.848	0.900
3	10/19/88-1	30	20:1	0.866	0.900
4	10/19/88-1	30	200:1	7.24	7.93
5	10/19/88-1	10	200:1	10.2	11.0

Before each bridge was tested for transient radiation effects, it was cooled to a temperature reasonably below its T_C and regulated at that temperature throughout the test. Resistance-versus-current curves are a very sensitive indicator of changes in superconductivity within the material. Therefore a resistance-versus-current curve was generated before and after each series of shots (i.e., irradiations). These two curves were compared to confirm that no permanent changes in the material had occurred as a result of the additional total dose exposure resulting from the accumulated transient exposures. (Note that because of the configuration of the test samples, it was not possible to isolate a given bridge to limit its total dose to the accumulated dose from a single series of shots. Therefore, comparisons for the purpose of looking for total dose effects were based on differences in accumulated total dose rather than absolute total dose.) Comparison of the resistance-versus-current measurements showed no change for all bridges except bridge no. 2, which showed a slight upward shift. The difference in accumulated total dose for this bridge was 1,275 rad(Si). No changes were observed in any other bridges even though the accumulated total dose differences were as high as 4,414 rad(Si). It is conjectured that some of the superconducting paths in bridge no. 2 were lost between the two measurements and that the second measurement was current saturating the superconductive paths earlier than during the first measurement.

The absence of any measurable change (except for the case just discussed) in the resistance-versus-current measurements before and after irradiation in the FXR is consistent with results obtained by other experimenters on the effects of gamma total dose on high T_C superconductors. However, the primary objective of this test was to measure any effects on the superconductivity of the material that might occur <u>during</u> the X-ray pulse. The sample under test was biased with a constant current source and instrumentation was setup to measure any changes in voltage across the superconductor during the X-ray pulse. A differential amplifier was incorporated into the measurement system to reduce system noise as much as possible. Measurements were made at three different bias currents. The bias currents were chosen to represent three different regions on the resistance-versus-current curves. The lowest value was chosen from the region below the critical current, the second from where critical current effects began to appear and the third from where the critical current effects had raised the resistance measurably. For example, Figure 5 shows the bias currents chosen from the resistance-versus-current curve for bridge no. 2.

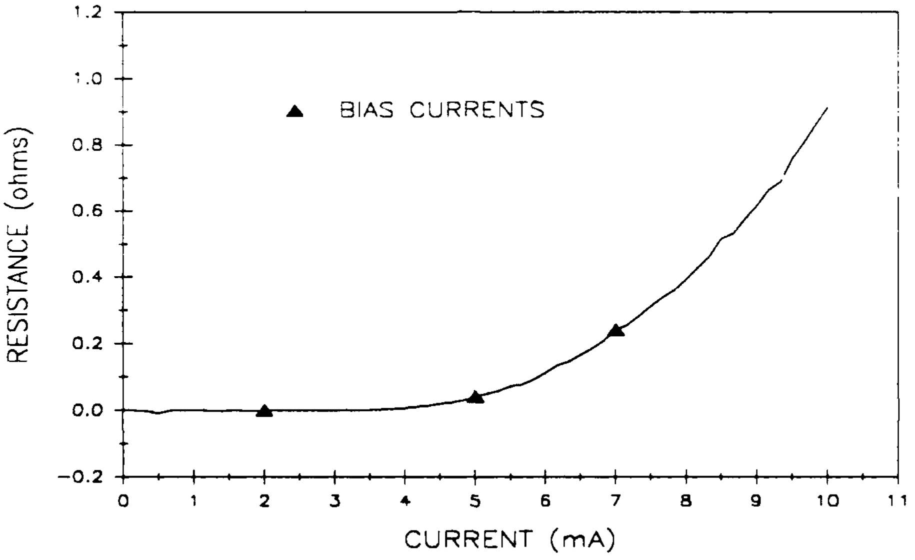

Figure 5. Bias currents for bridge no.2.

Next, the maximum voltage that would have been possible to measure had the sample been driven completely out of the superconducting state was found. This value was derived by extrapolating a straight line to the zero resistance point from a point on the resistance-versus-temperature curve lying to the right of the transition region (Fig. 6). On this line there is a point that corresponds to the temperature at which the sample was regulated during the test. This point also corresponds to the resistance one would have expected to see had the material been cooled to that temperature, but remained in a nonsuperconducting state. This resistance was then used together with I_{bias} to calculate the maximum or open circuit voltage that would have been measured had the sample been driven nonsuperconducting during illumination by the X-ray pulse. Note that the magnitude of the potential or voltage of all the pulse measurements as seen by the oscilloscope were one fourth of the open circuit potential across the superconductor. Therefore, the open circuit voltages calculated above were divided by four to make them consistent with the oscilloscope readings, and the resulting potentials were recorded in Table 2 as $V_{max\ poss}$.

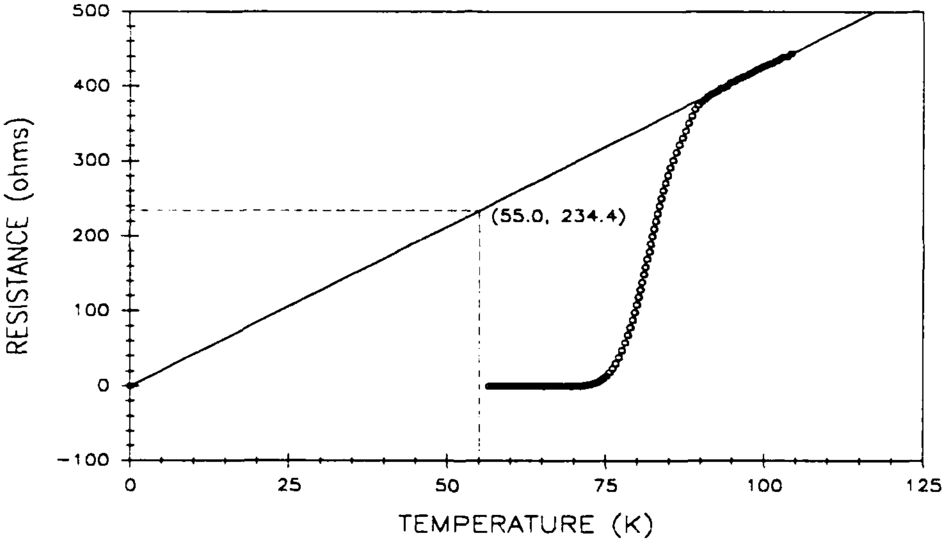

Figure 6. Critical temperature.

When a sample under test was irradiated with an X-ray pulse from the FXR machine, an electromagnetic pulse was also generated. This pulse induced currents on the surfaces of coaxial cables and excited resonances in the circuitry, thereby adding noise to the data acquisition system. (This noise was large compared to any thermal noise that may also have been present.) Some of this noise reached the oscilloscope before the time at which any signal pulse that might have been generated would have arrived, but was not yet dissipated by the time the signal pulse would have arrived. Noise generated in the vicinity of the superconductor by the X-ray pulse and picked up by the signal cables arrived at the oscilloscope at the same time that a signal pulse would have arrived. Consequently, the noise seen by the oscilloscope increased during the time that a signal pulse would have arrived.

Table 2. $V_{max\ poss}$ for each test measurement.

Bridge No.	Temperature (K)	Resistance (ohms)	I_{bias} (mA)	$V_{max\ poss}$ (mV)
1	60.1	272.7	3	204.5
			4	272.7
			5	340.9
2	55.0	234.4	2	117.2
			5	293.0
			7	410.2
3	50.1	233.2	5	291.5
			8	466.4
			13	757.9
4	50.1	2055.0	1	513.8
			3	1541.3
			5	2568.8
5	29.4	1966.0	0.5	245.8

For a given shot, the waveform was assumed to consist of a signal, a repeatable noise component, and a random noise component. A significant portion of the noise was repeatable from pulse to pulse, especially during the expected time of arrival of the signal pulse. When the shot was taken at zero bias, the signal component was absent.

To reduce noise in the data taken for a given bias current, three shots were taken with the superconductor biased and three shots were taken with it unbiased (zero biased). From these, an average biased waveform and an average zero biased or noise waveform were obtained. The noise waveform was then subtracted from the biased waveform. As a result, any signal component of the resulting waveform or processed trace was unchanged from any of the original waveforms, the repeatable noise was eliminated, and the random noise was reduced to approximately 0.8 of that present in any of the original shots. Figures 7 and 8 provide a visual comparison of a noise waveform and a bias waveform for the same bridge (for illustration, bridge no. 2 with zero bias and with 5 mA bias were selected).

From each of the processed traces for the various bridges and bias currents, the signal value, V_{signal}, was defined to be the difference of the mean value of the trace over the interval of the pulse (70 to 90 ns) and the mean value over an interval at the beginning of the trace (0 to 30 ns). The noise standard deviation, V_{noise}, was computed from all 10 processed traces over the interval of the pulse. Its value as seen by the oscilloscope was 0.52 mV. Table 3 shows that in each case, with the exception of bridge no. 5 which will be discussed later, V_{signal} was less than two noise standard deviations.

Figure 9 illustrates the comparison of a biased waveform during illumination by the FXR machine with the maximum absolute value, $V_{max\ poss}$, that would have been expected had the X-ray pulse driven the material entirely out of the superconducting state at any time during the pulse. Table 3 provides a numerical comparison of the waveform with $V_{max\ poss}$ by listing $V_{max\ poss}$ and V_{signal} for each bridge and each bias at which measurements were made. Table 3 shows that (with the exception of bridge no. 5 discussed below) all values of V_{signal} were less in absolute

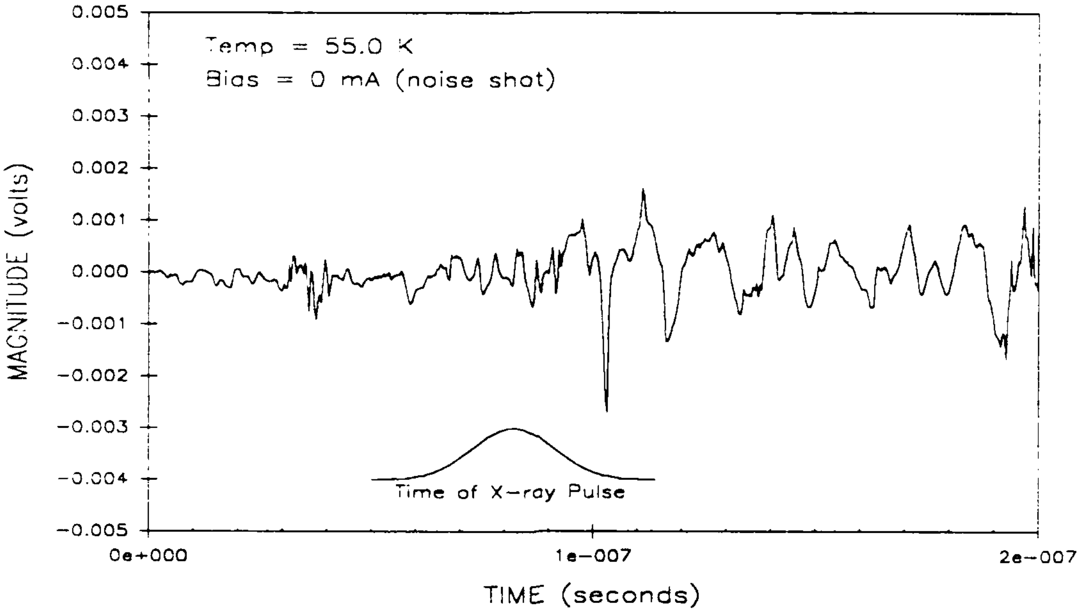

Figure 7. Bridge no. 2 pulse measurement at zero bias.

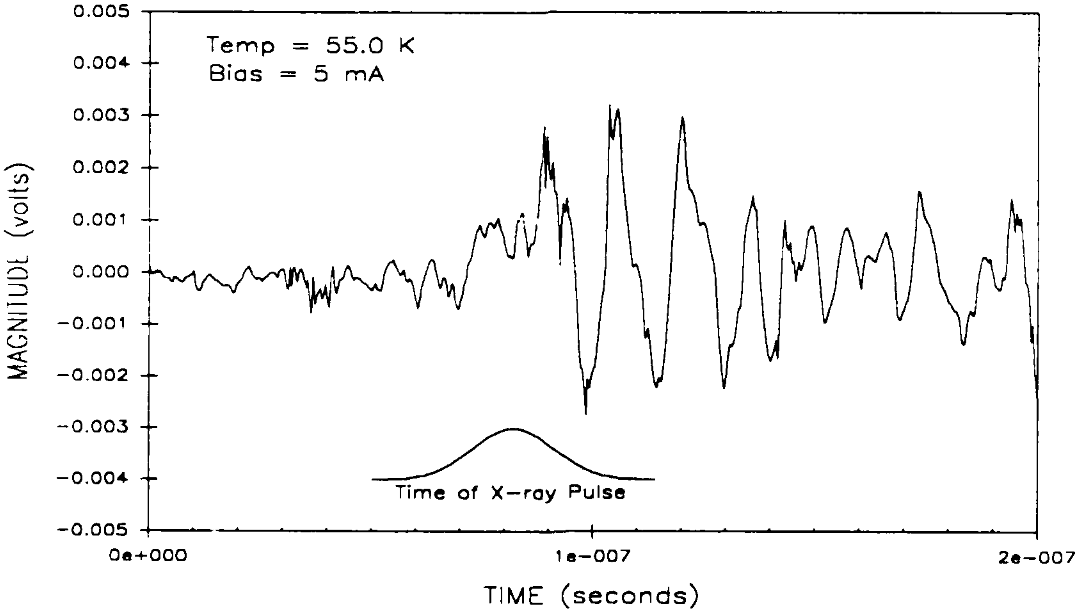

Figure 8. Bridge no. 2 pulse measurement at 5 mA bias.

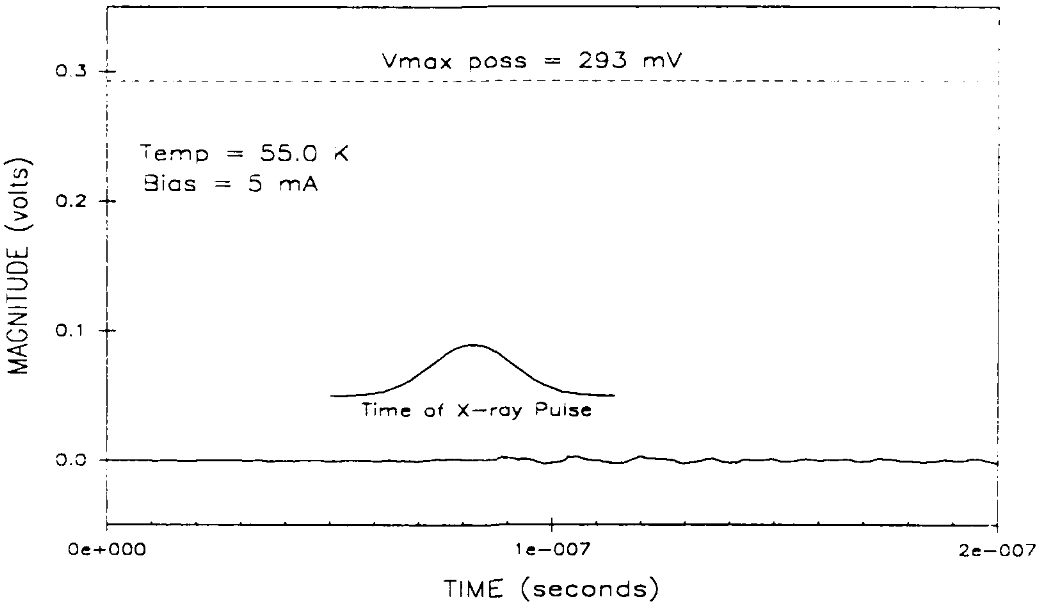

Figure 9. Comparison of pulse waveform with $V_{max\ poss}$.

Table 3. Comparison of $V_{max\ poss}$ and V_{signal}.

Bridge Number	I_{bias} (mA)	$V_{max\ poss}$ (mV)	V_{signal} (mV)	1 mV / $V_{max\ poss}$
1	3	204.5	NA	0.0049
	4	272.7	NA	0.0037
	5	340.9	NA	0.0029
2	2	117.2	0.52	0.0085
	5	293.0	0.89	0.0034
	7	410.2	-0.087	0.0024
3	5	291.5	0.096	0.0034
	8	466.4	0.074	0.0021
	13	757.9	-0.36	0.00013
4	1	513.8	-0.041	0.0020
	3	1541.3	0.24	0.00065
	5	2568.8	0.47	0.00039
5	0.5	245.8	-1.9	0.0041

value than 1 mV, the resolution limit of the data acquisition system.

V_{signal} for bridge no. 5 was almost four noise standard deviations in magnitude. However, it was in the wrong (i.e., negative) direction for it to represent a loss of superconductivity. This bridge was somewhat erratic in behavior, as it would open unpredictably and tended to open when the bias current exceeded 0.6 to 0.7 mA. Thus measurements were made for only one bias value, 0.5 mA. (Instrumentation limitations precluded making measurements for bias values any lower.) The repeatable noise in the raw data was twice as large as was typical for the other bridges tested, with the zero bias amplitudes exceeding those taken at the 0.5 mA bias. This leads one to speculate that the bridge was defective and as a result, opened during the pulse. Assuming this to be the case, the observed measurements can be explained by considering the following.

When a bridge was pulsed in the measurement setup, Compton electrons were emitted from the superconductor, its terminations, bondwires, etc. These currents had a peak magnitude of 1.5 mA. Normally, when the superconductor was intact, the Compton emission produced a repeatable common mode noise pulse which was largely eliminated by the differential transformer. However, if the Compton currents were not uniformly distributed over the superconductor but favored one side, and if the bridge opened during the pulse as speculated above, then the Compton noise pulse could have easily produced the large, negative value for V_{signal} measured at bridge no. 5. Also, under those same conditions, V_{signal} with a zero bias would be larger than V_{signal} with a positive bias current, as was observed.

Finally, Table 3 also lists the ratios 1 mV/$V_{max\ poss}$. These ratios show that if an effect signal did occur, but was masked by the noise, then the magnitude of the effect was less than 1 percent of the magnitude of an effect representing a complete loss of superconductivity.

CONCLUSION

The super-conductivity of the material tested was not measurably affected by X-ray irradiation, even when the material was actively superconducting. This conclusion is supported by the following observations. First, there was no consistent positive signal observed during irradiation of the sample by the FXR machine. That is, no positive signal above say two noise standard deviations, or equivalently, 1 mV seen at the scope, was measured. The signals were less than two noise standard deviations in amplitude (in most instances less than one) and had both positive and negative polarities. Second, with one exception, all values of V_{signal} were less in absolute value than 1 mV, the resolution limit of the data acquisition system. And finally, if an effect signal did occur, its magnitude was less than 1 percent of the magnitude of an effect representing a complete loss of superconductivity.

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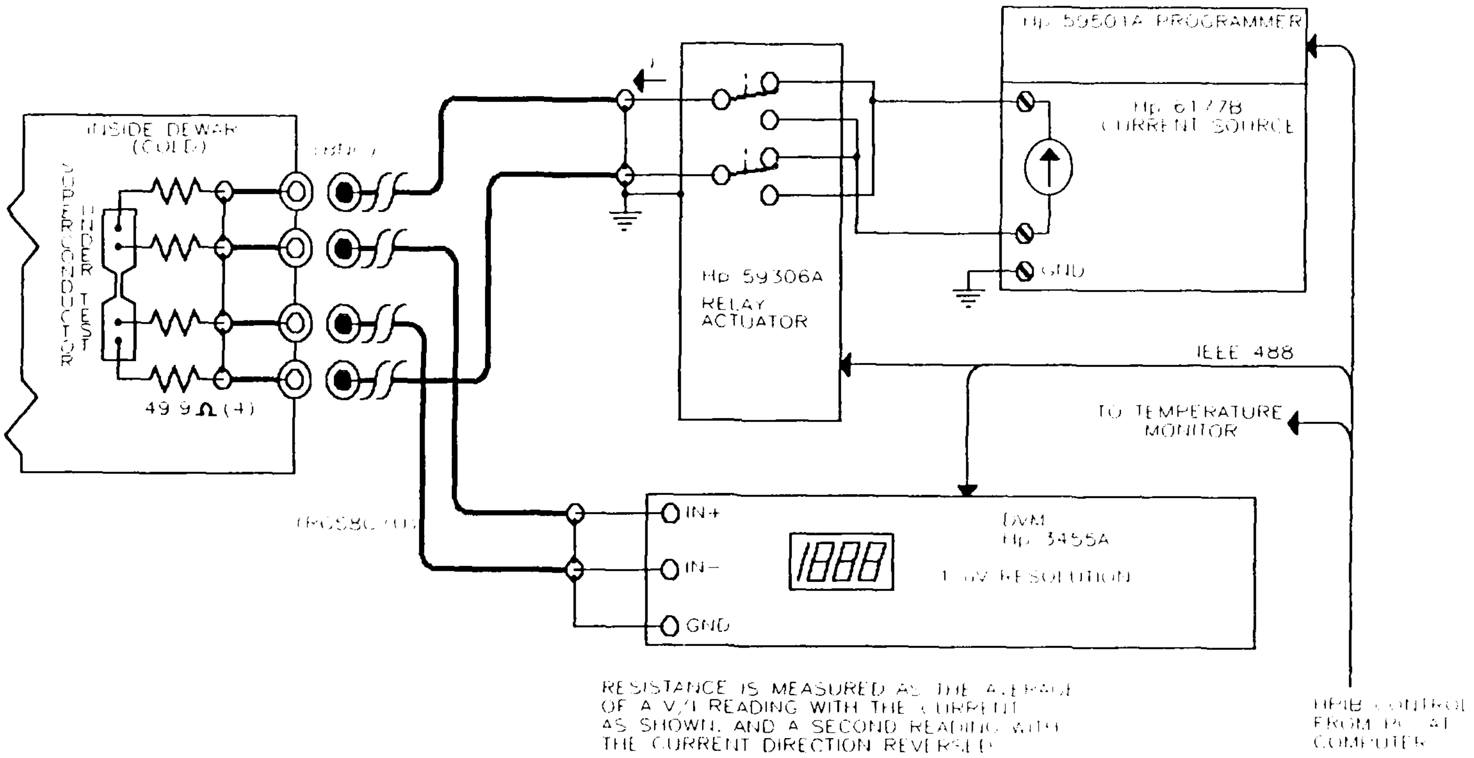
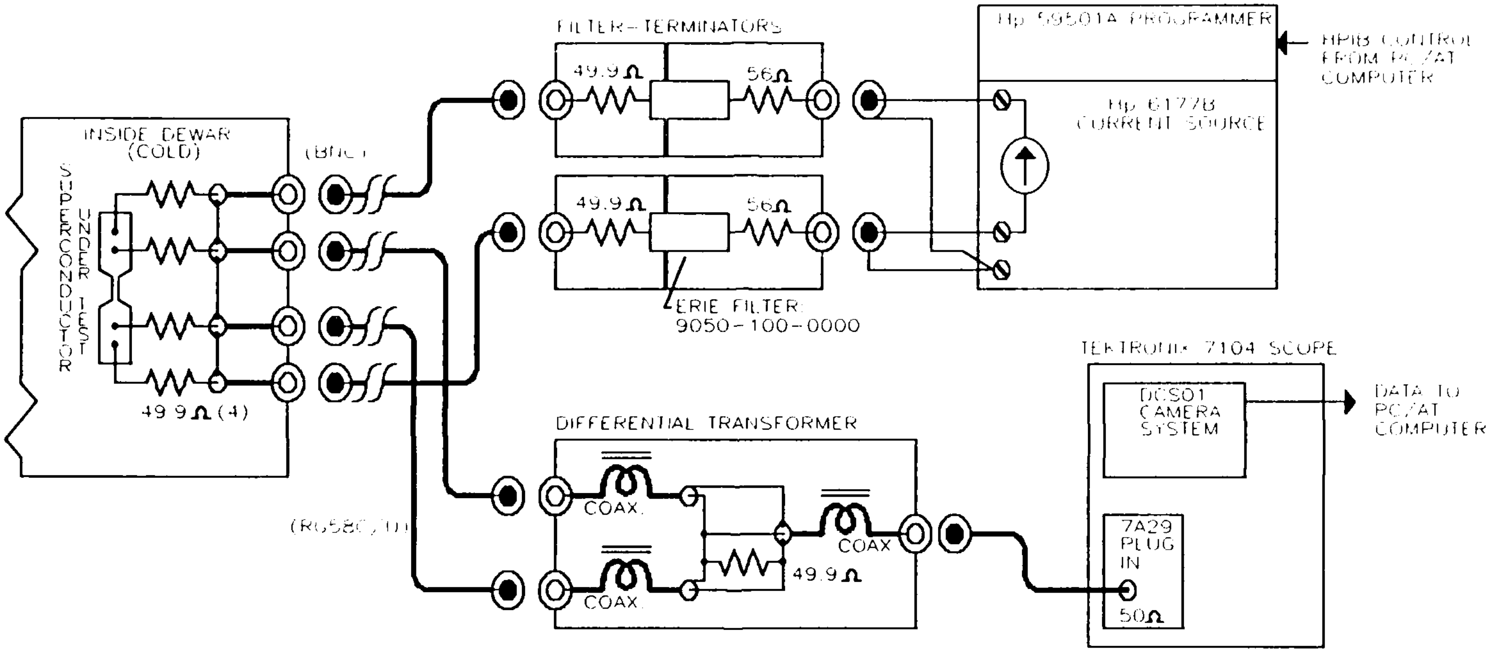
APPENDIX

Figure A-1 shows the setup employed for making resistance-versus-current and resistance-versus-temperature measurements. Figure A-2 shows the setup used for making transient measurements on a superconductor during irradiation by an X-ray pulse.



RESISTANCE IS MEASURED AS THE AVERAGE OF A V/I READING WITH THE CURRENT AS SHOWN, AND A SECOND READING WITH THE CURRENT DIRECTION REVERSED

Figure A-1. Circuit for making resistance-versus-current and resistance-versus-temperature measurements.



FOR FAST PULSES, THE SUPERCONDUCTOR IS LOADED WITH 100 Ω

POTENTIAL ACROSS THE 50 Ω SCOPE INPUT IS 1/4 OF THE POTENTIAL DEVELOPED ACROSS THE SUPERCONDUCTOR.

Figure A-2. Circuit for high-speed pulse measurement on a superconductor.