Effects of High Energy Proton Bombardment (50-280MeV) on dc SQUIDS

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Abstract—**Three thin film dc SQUIDs of varied construction were bombarded with energetic protons in the energy range of 50 to 280 MeV. Measurements of the voltage output of the dc SQUIDs were taken in open loop, as well as flux locked mode, in an environment of proton flux that was varied from 10^4 to 10^7 protons/cm^2/s. Discrete voltage jumps corresponding to 0.01 to 0.001 flux quanta were observed in two of the three SQUIDs in the flux locked mode; discrete changes in the open loop SQUID output voltage were also observed. Some data appear to be consistent with proton-induced flux motion in the body of the SQUID loop.**

I. INTRODUCTION

SQUIDs (Superconductive Quantum Interference Devices) are known to be ultra-sensitive detectors of magnetic flux. Many precision experiments such as the relativity gyroscope experiment, the satellite test of the equivalence principle, and inductive type monopole detectors make use of these devices [1]-[3]. In general, such experiments require very stable magnetic field environments. It has been proposed that energetic particles can drive small volumes of a superconductor into the normal state, thereby inducing magnetic flux motion [4]. In space-based experiments, it is well known that there are situations (such as the South Atlantic Anomaly and solar flare events) in which energetic protons are common [5]. In addition, cosmic protons of ultrahigh energy are known to be incident on the earth's surface. To date, there have been only limited studies on the interaction between high energy protons and superconductive systems [4], [6], [7]. In this paper we report on the measured interactions between high energy protons and dc SQUIDs.

II. EXPERIMENTAL APPARATUS

Three dc SQUIDs of varied construction were tested in this experiment. The first was manufactured by the National Institute of Standards and Technology (NIST), Boulder, CO. The second was manufactured at the Istituto di Elettronica dello Stato Solido of C.N.R., Rome, and the third device was fabricated by Quantum Design, Inc., San Diego, CA. Henceforth we refer to these devices as SQUIDs I, II and III.

TABLE I

Relevant physical and electrical properties of the three SQUID sensors.

ATTRIBUTE	SQUID I	SQUID II	SQUID III
Josephson Junction Area (m^2)	6.1×10^{-12}	4×10^{-12}	7.1×10^{-12}
Silicon Substrate Crystal Orientation	<100>	<111>	<100>
Junction Type	Nb/AlO/Nb	Nb/NbOx/Pb InAu	Nb/AlO/Nb
SQUID Loop Area (mm^2)	0.36	1.3	2.1
SQUID Hole Area (mm^2)	2.5×10^{-3}	0.14	0.017
Loop Material and Thickness (nm)	PbInAu 550	Nb 300 PbInAu 430	Nb 120
SQUID Critical Current (µA)	18.1	38	10
Carrier Material	Sapphire	Sapphire	Fiberglass
B Field at SQUID (µT)	0.2	40	0.2

Table I gives some of the characteristics of the devices.

The devices were operated in vacuum and therefore required a thermally conductive path to the liquid helium bath to allow adequate cooling. The sapphire carriers of SQUIDs I and II were connected to the dewar's cold plate using copper braiding. SQUID III was thermally grounded by connecting its input coil to thermal ground with electrically insulated copper wire. We believe that the thermal grounding of SQUIDs I and II was better than that of SQUID III. All of the SQUIDs were isolated from fluctuations in the external magnetic field by using niobium cans. SQUIDs I and III and their associated niobium cans were then placed within ferromagnetic shields. SQUID II had no ferromagnetic shield. The SQUID's input coils (of order 1µH) were left open circuit to eliminate input coil persistent currents. The experimental configuration allowed us to operate and monitor the simultaneous performance of the three SQUIDs in the presence of proton bombardment.

The experiment was performed at the Paul Scherrer Institute in Villigen, Switzerland, using the proton irradiation facility (PIF). The proton energies were adjusted to 54 MeV and 280 MeV using aluminum plates as degraders. Proton flux was varied by reducing the total beam intensity. The beam was collimated to an area of 2 cm by 6 cm by an Fe collimator and was homogeneous over this area to ±10%. The SQUIDs were oriented approximately normal to the proton beam. The configuration allowed simultaneous proton bombardment of all three SQUIDs. On-line monitoring of the flux was provided by observing single

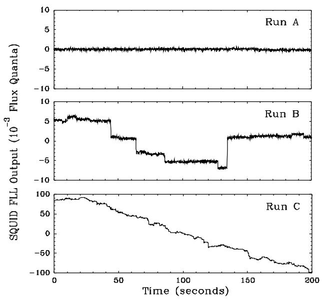

Fig. 1. SQUID III FLL time series output. Run A, no incident protons. Run B, 54 MeV protons with a flux of $1x10^5$ p/cm^2/s. Run C, 54 MeV protons with a flux of $1.6x10^6$ p/cm^2/s.

proton events in a small (1x1x1 mm^3) plastic scintillator in front of the cryostat.

The effects of spurious electromagnetic interference were tested by moving the SQUIDs out of the immediate path of the proton beam. In this test, no observable change was detected in the SQUIDs' output when the beam was cycled on and off at the maximum beam current. The control electronics for the SQUIDs was placed outside the beam during these measurements.

The SQUID temperatures were monitored with two germanium resistance thermometers (GRTs). Based upon our calculations we expected the maximum power deposited into each of the SQUIDs (at a proton flux of 10^7 p/s/cm^2) to be approximately 50 pW, the power deposited into each silicon substrate at this flux to be approximately 200 nW, and the power deposited into each of the niobium cans to be approximately 50 µW. Although we did not expect to see a temperature rise resulting from the absorption of this amount of power, the GRTs did show an apparent instantaneous temperature increase of 5 mK. It is well known that particle bombardment produces electron-hole pairs in semiconductor devices. We attribute the apparent change in temperature to this effect and believe that the actual, proton-induced temperature rise was less than 1 mK.

III. RESULTS

The SQUIDs were operated using conventional flux locked loop (FLL) electronics to linearize the flux to output voltage transfer function. The proportionality factor for each of the three SQUIDs was of order 1 V/Φ_o (where V is the output voltage of the SQUID electronics and where Φ_o is the flux quantum, $2.07x10^{-15}$ Wb). The SQUID flux power spectral densities, S_Φ, for each of the three SQUIDs with no

TABLE II

Noise performance of the three flux locked SQUIDs at a temperature of 5.6 K with no incident protons. Similar results were obtained at 6.3 K.

Attribute	SQUID I	SQUID II	SQUID III
S_Φ @ 100 Hz (Φ_o^2/Hz)	$6x10^{-11}$	$3x10^{-9}$	$1x10^{-10}$
S_Φ @ 1 Hz (Φ_o^2/Hz)	$2x10^{-9}$	$3x10^{-9}$	$2x10^{-10}$
1/f Noise Knee (Hz)	30	<1	1

incident protons is given in Table II. Note that there were significant differences in the noise performance of the three SQUIDs. The low frequency noise performance of SQUID I and the overall noise performance of SQUID II were inferior to our typical laboratory results. We believe that elevated SQUID temperatures may account for the inferior noise performance (the SQUIDs were operated at approximately 6 K). In any case, all of the SQUIDs functioned in a stable manner, allowing us to set a minimum detectable level for potential interactions between the SQUIDs and high energy protons.

The three SQUIDs had varied responses to proton bombardment. SQUID III showed significant output voltage jump events for proton fluxes of 10^5 p/cm^2/s and higher. Fig. 1 gives time series data for SQUID III for three different proton flux densities at an energy of 54 MeV. The frequency of events in the time domain was approximately proportional to the proton flux. The time of transition for each individual jump exceeded the 10 Hz sampling rate of our data acquisition system. SQUID II showed qualitatively similar behavior to SQUID III. SQUID I showed no response to proton bombardment at any flux or energy. No temporal correlation of events was observed between SQUIDs II and III. The observed effects for SQUIDs II and III also varied with proton energy. Both the frequency as well as the amplitude of jumps appeared to be approximately five times larger for the 54 MeV protons than they were for the 280 MeV protons. We note however, that the SQUID temperature was 6.3 K for the 54 MeV run and was 5.6 K for the 280 MeV run. In both cases the SQUID temperatures were held constant to 20 mK.

Fig. 2 shows time domain data acquired before, during and after proton bombardment of SQUID III. Several observations are in order:

1. At the completion of proton bombardment, the SQUID output voltage did not return to its prebombardment value.
2. The response to the protons was faster than our sampling frequency of 10 Hz. This applied at both points A and B.
3. In general, there appeared to be a preferred direction to the drift in the SQUID output (see also Fig. 1, Run C.)

In a second set of experiments, the feedback flux was disabled, allowing us to observe more directly the behavior of the SQUID. The SQUID voltage signal resulting

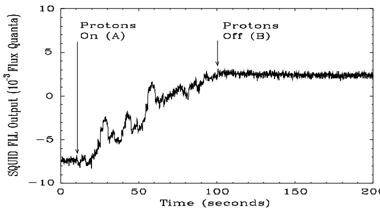

FIG. 2. SQUID III FLL time series output. 280 MeV protons with a flux of 6×10^7 p/cm^2/s.

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the application of a flux modulation signal of amplitude $\Phi_o/4$ was observed on an oscilloscope. This signal is affected by the average magnetic flux state of the SQUID and, in a different way, by changes in the critical current of the SQUID junctions. Flux changes of $10^{-2}\ \Phi_o$ and larger could be detected, as could critical current changes of 0.2 μA or greater.

We observed large, discrete changes in the above signal for SQUIDs II and III during bombardment with 54 MeV protons. These signal changes were of the type expected from changes in the average flux state of the SQUID and were consistent with the amplitude of the signals observed in the flux-locked mode. It was further found that the SQUID signal observed at the conclusion of proton bombardment could be restored to its prebombardment form by applying a dc magnetic flux to the SQUID.

No changes of the type to be expected from critical current variations were observed, nor was any permanent damage noted in the SQUIDs.

IV. DISCUSSION

We believe that thermally induced flux motion in the body of the SQUID loop is the best explanation for the data which has been presented here. Our numerical simulations indicate that a small volume of superconductor is driven into the normal state each time a proton passes through the SQUID loop material. When such a proton passes sufficiently close to a magnetic flux line, the material surrounding this line would be driven into the normal state. This event would allow the trapped flux line to move, thereby causing a jump in the SQUID output. A thermal diffusion model was used to predict the cross-sectional area which was driven normal for each incident proton. For SQUID III, we expected this area to be 0.054 μm^2 for each 280 MeV proton. The corresponding area for each 54 MeV proton was 0.18 μm^2. For this SQUID, the trapped magnetic flux density was approximately $10^4\ \Phi_o$/cm^2. For this trapped flux level and 54 MeV protons incident on this SQUID at a flux of 10^5 p/cm^2/s, we expect direct heating of a magnetic flux pinning site about every 30 seconds. This calculation is in good agreement with the data (see Fig. 1, Run B). It has been suggested that the preferred direction of SQUID voltage drift exhibited in Fig. 1, Run C and in Fig. 2 might be explained by a unidirectional Lorentz force caused by the dc bias current flowing through the SQUID [8].

Our understanding of the data is not complete. Based upon the explanation as given above, one would have expected flux movement in all three SQUIDs. Since SQUID I did not show such behavior, we are attempting to isolate its unique properties. For the observed effects in SQUIDs II and III, we have not completely ruled out nonthermal mechanisms such as charged particle interactions at the band and atomic level. However, if our flux motion explanation is correct, then the implications of this behavior may extend to many superconductive systems which rely on stable magnetic field environments. Experiments are in progress to better understand the overall results reported here.

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