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EXPERIMENTAL MEASUREMENTS OF RADIATION DAMAGE TO POWER DIODES AT CRYOGENIC TEMPERATURE*

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Summary

The feasibility of a passive quench protection system for the Superconducting Supercollider (SSC) main ring magnets depends on the radiation resistance of the diodes used as current bypass elements. These diodes would be located inside the magnet cryostat, subjecting them to liquid helium temperature and a relatively high radiation flux. An experimental test was performed on five types of power diodes to determine their relative response to neutron radiation at cryogenic temperature. The forward and reverse characteristics of the diodes were monitored as a function of exposure while the diodes were maintained at an ambient temperature of 80 K. The results showed a strong dependence on diode type, ranging from relatively little damage in some diodes to complete failure in other diodes.

Introduction

A passive quench protection system under consideration for the main ring magnets of the SSC would use power diodes to bypass current around a quenched magnet. Installing the diodes inside the magnet cryostat would maintain them at liquid helium temperature and subject them to relatively high levels of radiation. Previous investigations of power diode response to these environmental factors involved irradiations at room temperature with subsequent testing at room temperature and liquid helium temperature. [1,2] This prevents a direct extrapolation of the results to SSC conditions where annealing during irradiation would be reduced by the low operating temperature.

An experiment was designed to study the effects of neutron radiation on power diodes maintained at an ambient temperature of 80 K to minimize annealing effects during the irradiation. Five types of commercially available diodes were tested to provide a comparison of radiation hardness under identical conditions. A variety of electrical tests were performed before, during, and after the irradiation to monitor the performance degradation of the diodes as a function of exposure.

Test Setup

A variety of commercially available diodes with significantly different specifications were selected for inclusion in the test. Catalog specifications for the diodes are summarized in Table 1, although modifications were made to the packaging and passivation schemes for some of the devices. The BBC and Siemens diodes were supplied in their standard hockey-puck packages, while the RA20 devices were supplied without packages but with gold flash coatings. The DSA1508 and RA20-A passivation layers had silicon rubber overcoats which were susceptible to cracking at cryogenic temperatures. For the RA20-A, the silicon rubber was simply removed by hand. For the DSA1508, however, the packages were first opened, the silicon rubber was removed, and the packages were then reassembled.

The diodes were mounted in a cryostat designed to maintain all of the devices at the same ambient temperature while permitting electrical tests on individual diodes. Cooling was accomplished by attaching each diode mounting assembly directly to a central copper reservoir which was filled with liquid nitrogen. This allowed single-sided conduction cooling to 80 K with the diodes located in the vacuum space surrounding the central reservoir. Electrical connections into the cryostat were made through a single pair of stainless steel safety leads. Pneumatically controlled G-10 rods operated copper switch contacts inside the vacuum space to connect a single diode to the power leads for each test.

The cryostat and diodes were then installed in the irradiation cell at the Texas A&M University Nuclear Science Center (NSC). The cryostat was positioned near the center of the 16 ft by 18 ft cell to minimize variations in flux among the twelve diodes. The 'swimming pool' type research reactor using FLIP TRIGA fuel [3] was operated at a steady state power level of 100 kW during each irradiation period. Boral and cadmium plates installed in the exposure window between the irradiation cell and the reactor core enhanced the higher energy neutron flux in the cell. Activation foils were used inside and outside the cryostat to provide both integrated dose and spectral information. The foil analysis has not yet been completed by NSC personnel, but an initial estimate of the neutron exposure dose was given as 1.2×10^{13} neutrons/cm^2.

Forward Bias Tests

The low current forward bias IV characteristics of the diodes were investigated under essentially steady state conditions using a 0-20 A power supply. This power supply was incremented from 0 A to 20 A and back to 0 A in 2 A steps. The current and voltage were measured at each step after a short delay to allow the power supply current to settle.

Table 1. Summary of diode specifications

QTY	DIODE	MANUFACTURER	I_{FRMS}	V_{RRM}	DIAMETER
3	DS6000	BBC Brown-Boveri	15600 A	200 V	50 mm
3	DSA1508	BBC Brown-Boveri	5600 A	2000 V	50 mm
3	SSiRV60	Siemens	3930 A	1500 V	54 mm
1	RA20-A	Powerex	7535 A	1200 V	67 mm
2	RA20-D	Powerex	3920 A	3000 V	67 mm

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A standard dc power supply was used to obtain moderate current IV characteristics as well as information concerning the temperature coefficient of the diode's forward voltage. The power supply was programmed to provide a 750 A current pulse with .1 sec rise and fall times and a 1 sec flattop. The upramp of the actual current waveform was generally much shorter than the desired .1 sec and had a significant overshoot in some cases due to the regulator's response to the switching load. The current and voltage waveforms were digitized simultaneously during the pulse at a 1 kHz sampling rate.

Higher current IV characteristics were obtained with a fast pulse power supply providing 1 kA, 300 μsec sinusoidal current pulses. The current and voltage waveforms were digitized simultaneously during the pulse at a 2 MHz sample rate.

Reverse Bias Tests

A single test provided both the CV and IV characteristics of the diodes under steady state reverse bias conditions. The bias power supply was programmed to step the applied voltage from 0 V to 150 V in variable size increments, providing greater resolution at lower voltages. The capacitance and leakage current were measured at each step after a short delay to allow the power supply voltage to settle.

Test Procedure

A complete set of electrical performance tests were conducted under various conditions before, during, and after the irradiation procedure. Pre-irradiation tests were performed at both 300 K and 80 K to measure the dependence of the diodes' parameters on temperature. The diodes were then maintained at an ambient temperature of 80 K for the duration of the irradiation procedure. Reactor operation was suspended five times during the irradiation procedure to maintain uniformity of dose while a complete set of tests were performed on all diodes. Post-irradiation tests were performed at temperatures of 80 K, 300 K, and again at 80 K to measure the effect of a room temperature annealing cycle. Table 2 summarizes this information and includes the incremental and integrated exposure time for each of the data sets.

Maintaining the diodes at 80 K during the irradiation reduced annealing effects significantly below the level which would have been experienced at room temperature. As the diodes began to sustain significant damage, however, the higher power levels generated by the electrical tests themselves increased the junction temperature sufficiently to cause observable annealing.

Table 2. Summary of test procedure

DATA SET	AMBIENT TEMP.	INCREMENTAL EXPOSURE	INTEGRATED EXPOSURE
1	300 K	—	—
2	80 K	—	—
3	80 K	0.55 hr	0.55 hr
4	80 K	0.55 hr	1.10 hr
5	80 K	2.20 hr	3.30 hr
6	80 K	3.33 hr	3.63 hr
7	80 K	3.33 hr	9.97 hr
8	80 K	3.33 hr	13.30 hr
9	300 K	—	13.30 hr
10	80 K	—	13.30 hr

Results of Experiment

The following sections summarize the results of an initial analysis of the data obtained in this experiment. In these discussions, the results for a single diode of each type are reported since variations among diodes of the same type were negligible.

Forward Voltage vs Exposure

The increase in forward voltage across each diode was monitored as one of the critical indicators of radiation damage. Figure 1 shows the change in forward voltage versus exposure for each diode at a current of 500 A. The DS6000 showed only a 6% increase in forward voltage after 13.3 hours of irradiation. The RA20-A voltage increased by a factor of approximately five, while the DSA1508 voltage increased by a factor of six. The RA20-D and SSiRV60 sustained such severe damage after 6.6 hours and 13.3 hours, respectively, that they could not conduct current with a forward bias of 40 V.

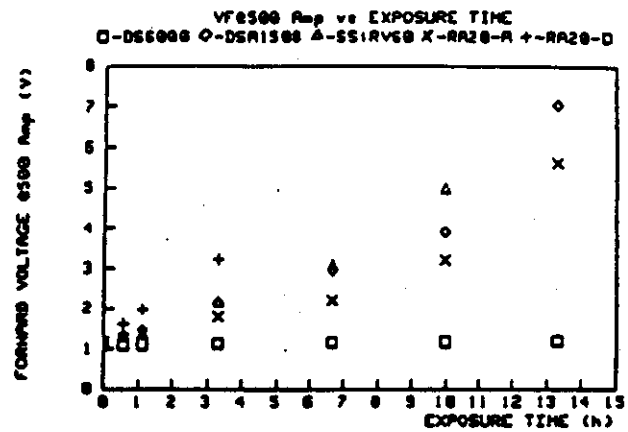

Figure 1. Forward voltage vs exposure; T = 80 K, I = 500 A.

The plot in Figure 2 of forward voltage versus exposure at a lower current of 20 A shows a similar trend. A significant difference is that the DS6000 initially exhibited a decrease in forward voltage with increasing exposure. The voltage decreased 1% below its initial value after 10 hours of irradiation before increasing to roughly its original value after the full 13.3 hours. This decrease in forward voltage at low currents was also observed in a previous irradiation test of RA20-A diodes when the exposure steps were performed in smaller increments. [4] In that experiment, the forward voltage continued to increase beyond its initial value as the dose was increased.

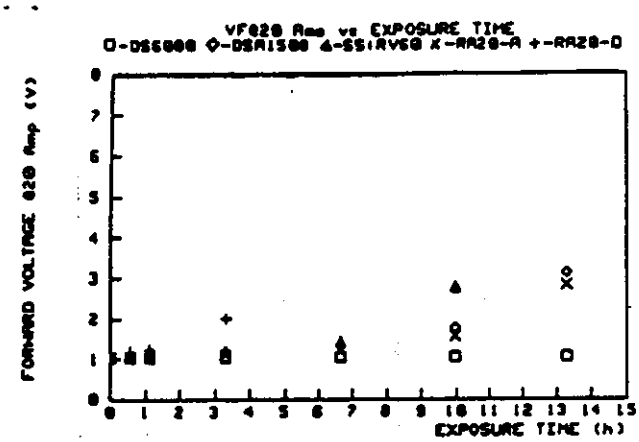

Figure 2. Forward voltage vs exposure; T = 80 K, I = 20 A.

Capacitance vs Exposure

The capacitance at zero volts dc reverse bias is plotted in Figure 3 as a function of exposure and shows the same dependence on diode type as the forward voltage. The DS6000 showed a 20% decrease in capacitance while the RA20-D showed a 90% decrease. In addition to the decrease in capacitance, the shape of the CV curve began to flatten as the diodes sustained radiation damage. The RA20-D and SSiRV60 exhibited very little change in capacitance as a function of voltage after 6.6 hours and 13.3 hours, respectively, corresponding to the time at which they initially failed to conduct forward current. The capacitance value measured for the RA20-D after 9.97 hours was essentially the capacitance of the diode mounting assembly and measurement cables, and showed no further decrease as a function of dose.

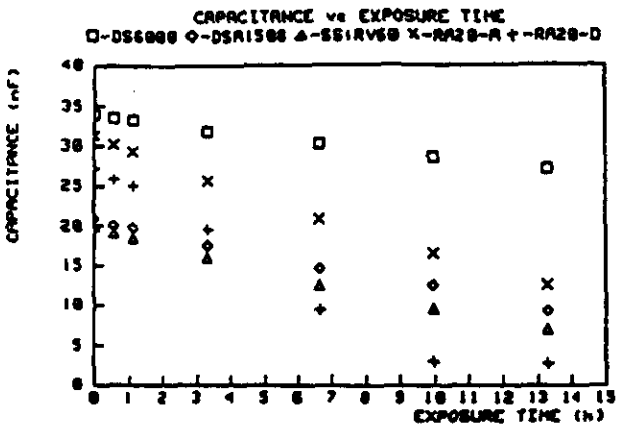

Figure 3. Capacitance vs exposure; T = 80 K, V = 0 V.

Temperature Effects

Figure 4 shows the effect of the irradiation and subsequent room temperature annealing cycle on the forward voltage at 80 K. Prior to the irradiation, the forward voltages exhibited only a small spread among the five diode types. After the irradiation, the DS6000 showed a 6% increase in forward voltage while the RA20-A and DSA1508 voltages increased by factors of five and six, respectively. The RA20-D and SSiRV60 had stopped conducting forward current by the end of the irradiation.

The forward voltages showed a significant effect from annealing after the diodes were warmed to room temperature and subsequently recooled to 80 K. The DS6000 showed a reduction of approximately 50% in the forward voltage increase caused by the radiation damage. The RA20-A and DSA1508 both showed a decrease in forward voltage by a factor of approximately three. The SSiRV60 exhibited even more dramatic improvement since it was once again able to conduct forward current. The RA20-D, however, never recovered forward conduction.

Conclusions

The experimental results show that the DS6000 is significantly more radiation resistant than the other four types of diodes tested. The other devices sustained such extreme damage by the end of the irradiation that they would not have survived a quench pulse in the SSC. Since the DS6000 sustained only minimal damage, further testing will be required to determine a dose limit at which it would fail.

The relatively low reverse blocking voltage design of the DS6000 contributes to its radiation resistance, but could be a

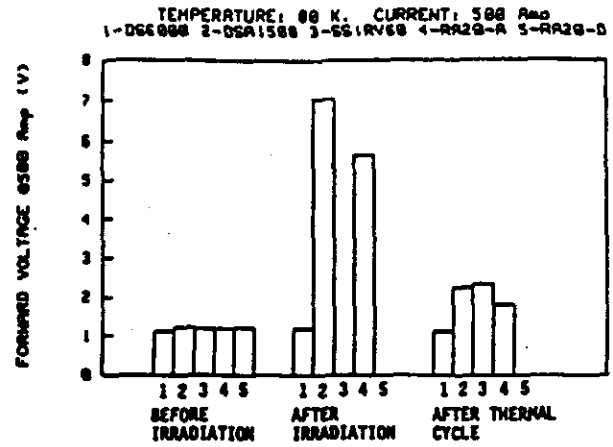

Figure 4. Forward voltage before irradiation, after irradiation, and after thermal cycle; T = 80 K, I = 500 A.

limitation on its use in the SSC. If a single diode is used for each magnet, the DS6000 easily meets the maximum applied reverse voltage requirement of 20 V. If a different configuration using multiple diodes and internal taps in the magnet is required, however, the voltage across individual diodes could exceed the rating of the DS6000. [5,6]

The results of the irradiation experiment also show that it is possible for a diode to fail 'open' after sufficient irradiation at 80 K. A room temperature annealing cycle performed soon after the failure of the SSiRV60 was able to restore its forward conduction at 80 K, although it remained severely damaged. Annealing of the DS6000, DSA1508, and RA20-A reduced the radiation damage effects by greater than 50%, verifying that room temperature irradiations do not provide a valid comparison to the operating conditions in the SSC.

A more accurate evaluation of diode performance in the SSC would be achieved by irradiating the diodes at liquid helium temperature. The further reduction in annealing at this lower temperature may indicate lower acceptable dose limits for each type of diode, but is not expected to create a significant difference in their relative performance. Therefore, of the five diode types tested, the DS6000 appears to be the best quench protection diode candidate if it can meet the reverse blocking voltage requirements of the configuration selected for the SSC.

References

[1] W. B. Sampson and A. J. Stevens, "Radiation Exposure of Bypass Diodes; Initial Results", CBA Technical Note No. 422, August 1983.

[2] A. Ghosh, W. B. Sampson, G. Stenby, and A. J. Stevens, "Radiation Exposure of Bypass Diodes", SSC Technical Note No. 10, February 27, 1984.

[3] G. A. Schlapper and J. L. Krohn, "Use of the Nuclear Science Center Reactor for Diode Response Testing", Workshop on Quench Protection Diodes, Texas Accelerator Center, The Woodlands, TX, July 14–15, 1986.

[4] Internal test report, Texas Accelerator Center, April 1986.

[5] J. G. Cottingham, "Quench Protection Diodes in Accelerators", Workshop on Quench Protection Diodes, Texas Accelerator Center, The Woodlands, TX, July 14–15, 1986.

[6] K. Koepke, "SSC Requirements for Quench Protection Diodes", Workshop on Quench Protection Diodes, Texas Accelerator Center, The Woodlands, TX, July 14–15, 1986.