LIFETIME OF PASSIVE QUENCH PROTECTION DIODES IN THE SSC*

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ABSTRACT

A passive quench protection system using cold bypass diodes is being considered for the Superconducting Super Collider, or SSC. The diodes would be located inside the magnet cryostat, subjecting them to liquid helium temperatures and a relatively high radiation flux. In this paper we present results of experimental measurements of radiation damage to a candidate diode at 5 K and an estimate of the lifetime of this diode in the SSC. An unexpected relationship was discovered between the diode turn-on voltage at 5 K and the most recent reverse voltage or temperature excursion. This turn-on voltage as a function of radiation exposure appears to be erratic and indicates a need for further investigation. High current IV measurements indicate that the usable lifetime of this diode, based on an estimate of the peak junction temperature during a quench pulse, is an order of magnitude greater than the expected lifetime of the SSC itself.

INTRODUCTION

A passive quench protection system under consideration for the main ring magnets of the SSC would use power diodes located inside the magnet cryostat to bypass current around a quenched magnet [1]. During a nominal SSC quench, the diodes would be required to conduct a 6500 A pulse with a 20 s exponential decay [1]. Installing the diodes inside the magnet cryostat would maintain them in a liquid helium bath at a temperature of 4.5 K and subject them to a radiation level of approximately 3.2×10^{11} n/cm^2 per year [2]. The voltage controlled switch behavior of a diode operating at liquid helium temperature was the primary reason a quench protection system with cold diodes was first proposed for the ISABELLE magnets [3]. Figure 1 shows this switching characteristic for an ABB DS6000 diode at 5 K, which required approximately 15 V of forward bias before any current was conducted. During a quench, the resistive voltage developed inside the magnet would quickly exceed the turn-on voltage of the diode and commutate the current out of the magnet and into the bypass circuit. The large number of diodes required (about 10,000), and the long replacement time for a failed diode (about 1 week), make the feasibility of this type of system critically dependent on the diode's lifetime in the SSC environment.

Previous experimental measurements of radiation damage at 80K identified the ABB DS6000 as a commercially available diode which appeared to be capable of surviving the SSC environment [4]. In order to confirm this, an experiment was designed to study the effects of neutron radiation on this diode while it was maintained at an ambient temperature of 5 K to minimize thermal annealing effects during the irradiation. Electrical tests were performed before, during, and after the irradiation to monitor the performance degradation of the diode as a function of exposure, and to study the diode turn-on characteristics at 5 K. These results, combined with a model that predicts the junction temperature of the diode during a quench pulse, allowed an estimate of the usable lifetime of this diode in the SSC environment. This estimate considers only systematic diode failures due to radiation damage since the study of all failure modes was outside the scope of this work. Further studies would be required to include other systematic and random failure modes in an estimate of the overall reliability of a passive quench protection system.

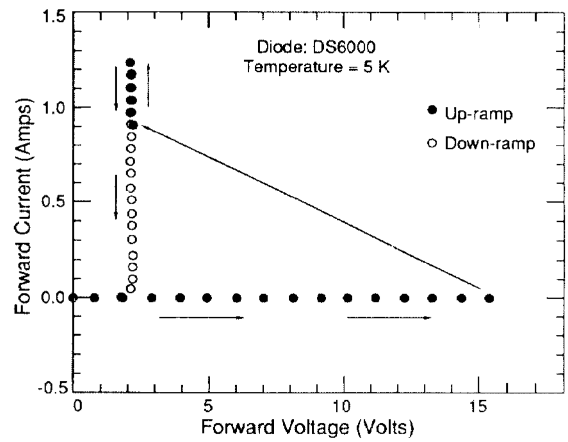

Fig. 1. Switching behavior of DS6000 diode at at 5 K.

TEST PROCEDURE

The test setup will be briefly discussed below; a more thorough description has previously been reported [4]. Catalog specifications for the selected diode are summarized in Table 1.

Table 1. Catalog specifications for the selected diode.

Diode	Manufacturer	IFRMS	VRRM	Diameter
DS6000	"Asea-Brown Boveri"	15600 A	200 V	50 mm

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. The cryostat and diodes were then installed in the irradiation cell at Texas A&M University Nuclear Science Center (NSC). The 'swimming pool' type research reactor using FLIP TRIGA fuel [5] was operated at a steady state power level of 100 kW during each irradiation period.

Two reactor runs were made with a total of 11 diodes. High current IV characteristics were measured during both runs using 7 kA, 300 μsec sinusoidal current pulses. The forward turn-on voltage as well as the low current IV characteristics were measured during the second run using a 2 A, 0.75 s triangular current pulse. These tests and the temperatures at which they were performed during each reactor run are summarized in Table 2.

RESULTS OF EXPERIMENTS

The following sections summarize the results of the data obtained in the two experiments described above.

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Table 2. Tests and the temperature at which they were performed during each reactor run.

	RUN1 (6 Diodes)			RUN2 (5 Diodes)		
	Before irradiation	During irradiation	After irradiation	Before irradiation	During irradiation	After irradiation
High Current IV	300 K, 5 K	5 K	5 K, 300 K	f(300 K > T > 5 K)	5 K	f(5 K < T < 30)
Low Current IV	300 K, 5 K	5 K	5 K, 300 K	f(300 K > T > 5 K)	5 K	f(5K < T < 30)
Turn-on voltage	—	—	—	5 K	5 K	5 K

Forward Voltage vs. Exposure

The increase in forward voltage at high currents was monitored as the primary indicator of radiation damage. Figure 2 shows the change in forward voltage at 7,000 A versus exposure for each diode in the two experimental runs. The data for the two runs match very well, with both data sets exhibiting a moderate spread in the forward voltages at high fluences. A slightly nonuniform flux distribution across the test fixture contributed to this spread, with the highest voltages corresponding to the positions with the highest fluence. Manufacturing tolerances in the diodes also influenced the spread, with slight variations in the base region thickness probably being the most critical parameter. In either case, the spread in voltages does not appear to be significant until well beyond the expected fluence of 9.6×10^{12} n/cm^2 over the lifetime of the SSC.

Forward Voltage vs. Temperature

The forward voltage versus temperature profile for the diodes was critical in making an estimate of the diode lifetime in the SSC. Figure 3 shows the pre- and post-irradiation profiles for the diodes of the second run which were exposed to a fluence of 1.70×10^{14} n/cm^2. Both sets of data exhibit a negative temperature coefficient over the temperature range of 5 K to 300 K. A junction temperature increase over that range could easily be generated by the 6500 A, 20 s current pulse during a quench [6]. A positive temperature coefficient would cause increased heating at the diode junction, ultimately leading to thermal runaway and device failure as has been observed in previously irradiated diode types [7]. Thus, the negative temperature coefficient for the DS6000 after the equivalent of over 500 years in the SSC environment reduces the possibility of this failure mode.

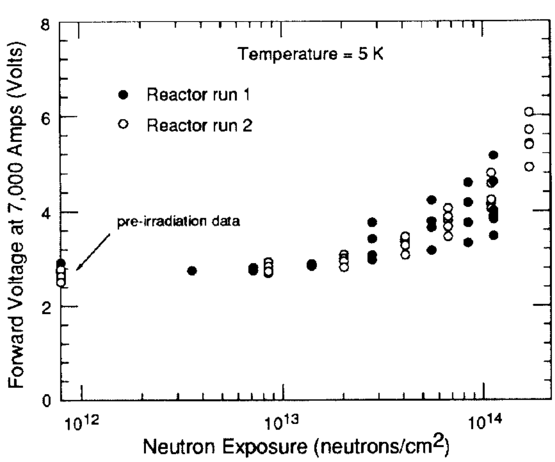

Fig. 2. Forward voltage at 7,000 A vs. exposure for DS6000 diodes irradiated at 5 K.

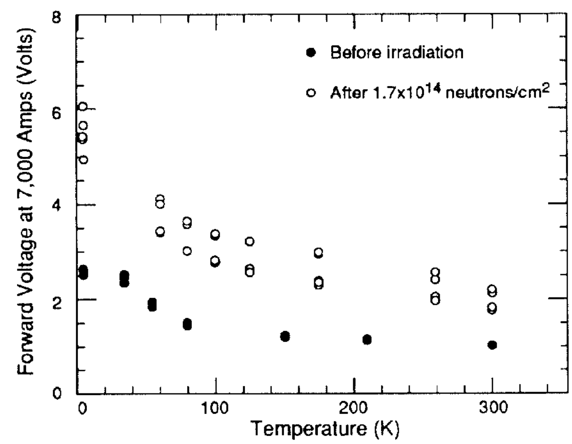

Fig. 3. Pre- and post-irradiation profiles of forward voltage at 7,000 A vs. temperature for DS600 diodes.

Turn-on Voltage

The switching behavior of a diode operating at liquid helium temperature, shown in Figure 1, was investigated in more detail during the second reactor run. Pre-irradiation tests showed that the current through the diode in the 'off' state was well below a microamp. Therefore, the turn-on phenomena appears to be related to the electric field established by the forward bias voltage rather than by heating of the junction caused by small leakage currents.

These tests also revealed that the magnitude of the forward turn-on voltage is dependent on the most recent reverse voltage or temperature cycle. Figure 4 shows the relationship between the turn-on voltage and the amplitude of the reverse voltage preceding the test. After the initial cooldown from 300 K to 5 K, the forward turn-on voltage was on the order of 10 V. Subsequent turn-on voltage measurements gave a value of approximately 2 V for all diodes. If a reverse voltage of 75 V or more was applied between measurements, however, the forward turn-on voltage was increased, even exceeding its original value for large reverse voltages. A similar recovery of the turn-on voltage was observed if the temperature of the diode was increased sufficiently between measurements of the turn-on voltage. Warming the diode to a temperature of 35 K was enough to restore the initial turn-on voltage of approximately 10 V.

During irradiation, a 200 V reverse bias was applied to the diodes before each measurement cycle to ensure full recovery of the turn-on voltage. The subsequent measurements of forward turn-on voltage as a function of exposure are shown in Figure 5. A minima of 1.8 V was observed immediately after the first irradiation period, which was equivalent to about 20 years in the SSC. This drastic decrease from the pre-irradiation value of 23 V for the same diode was unexpected and no consistent relationship was apparent between turn-on voltage and fluence.

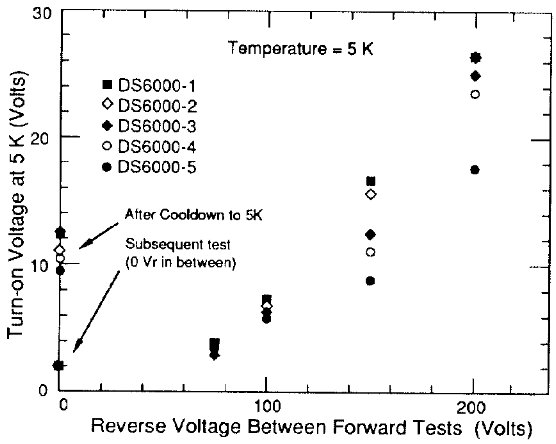

Fig. 4. Turn-on voltage at 5 K vs. reverse voltage between forward tests.

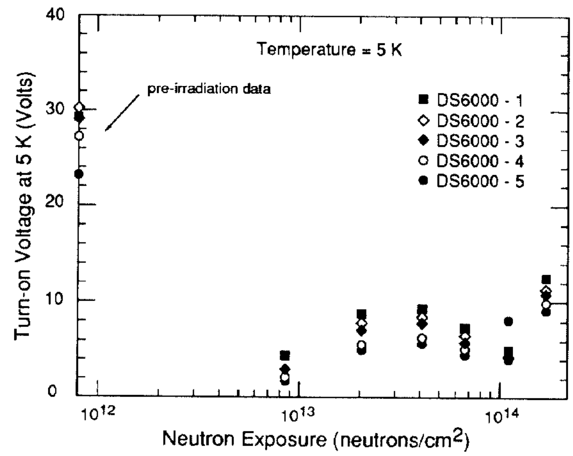

Fig. 5. Turn-on voltage at 5 K vs. neutron exposure.

ESTIMATE OF DIODE LIFETIME IN THE SSC

For the purposes of this study, the lifetime of the DS6000 diode in the SSC environment was considered to be limited solely by the peak junction temperature reached during a quench pulse. This systematic failure mode was selected since the dominant effect from radiation damage is an increase in the forward voltage, and therefore power dissipation, in the diode. The catalog specification of 170°C was used as the maximum acceptable junction temperature.

A Finite Element model was developed to predict the junction temperature of the diode during an SSC quench pulse as a function of forward voltage [6]. This model includes the temperature dependence of the material properties and thermal contact resistances associated with the diode, its package, and its mounting assembly. Due to the low specific heat of these materials at liquid helium temperatures, the junction temperature quickly exceeds 80 K during a quench pulse. Above this temperature, the magnitude of the temperature coefficient decreases and the junction temperature increases more slowly. Therefore, a conservative estimate of the peak junction temperature was obtained from the model by assuming a constant forward voltage drop throughout the quench pulse equal to the forward voltage drop at 80 K.

The result of this simplified model predicts a relatively linear relationship between the peak junction temperature and the forward voltage drop. This relationship can be approximated by

$$Tj_{max} = 170 \times VF(80\ K) - 221 \quad (1)$$

where VF(80 K) is the value of the forward voltage drop at 80 K. From this equation, the maximum allowable junction temperature of 170°C will be reached when VF (80 K) is about 2.3 V, a 77% increase above the 1.3 V pre-irradiation value.

From Figure 3, a 77% increase in forward voltage at 80 K should roughly corresponds to a 77% increase in forward voltage at 5 K. From Figure 2, this increase at 5 K occurs at a fluence of about 10^{14} n/cm^2, equivalent to more than 300 years of SSC operation.

CONCLUSIONS

The forward turn-on voltage of the diode at 5 K appears to be related to the electric field established by the forward bias since no significant current flows during the 'off' state. This eliminates concern that normal ramp rates for the magnets would generate uncontrolled leakage currents through the bypass diodes and adversely affect the tuning of the machine.

A strong relationship was discovered between the forward turn-on voltage of the diode and the most recent reverse voltage or temperature cycle. During a quench pulse, the power dissipation in the diode would raise its junction temperature well above the 35 K level which was found to be sufficient to restore the original turn-on voltage. Therefore, a diode which has conducted a quench pulse will automatically have its forward turn-on voltage restored as the junction temperature cools back down to the 5 K ambient temperature.

The turn-on voltage as a function of exposure exhibited erratic behavior and unexpectedly low values at moderate exposures. This behavior creates concern over the effects that a background level of neutron radiation, ionizing radiation, and other energetic particles will have on this critical parameter. Further theoretical and experimental studies should be pursued to evaluate these relationships and their potential impact on the proper operation of diodes in the SSC.

The lifetime of ABB DS6000 diodes in the SSC radiation environment at an ambient temperature of 5 K appears to be on the order of 300 years. This estimate was based on the peak junction temperature expected during a quench pulse after radiation damage has increased the forward voltage of the diode at high currents. Since this is an order of magnitude greater than the projected 30 year lifetime of the SSC itself, systematic failures of diodes due to accumulated radiation damage does not appear to impact the feasibility of a passive quench protection system for the SSC.

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