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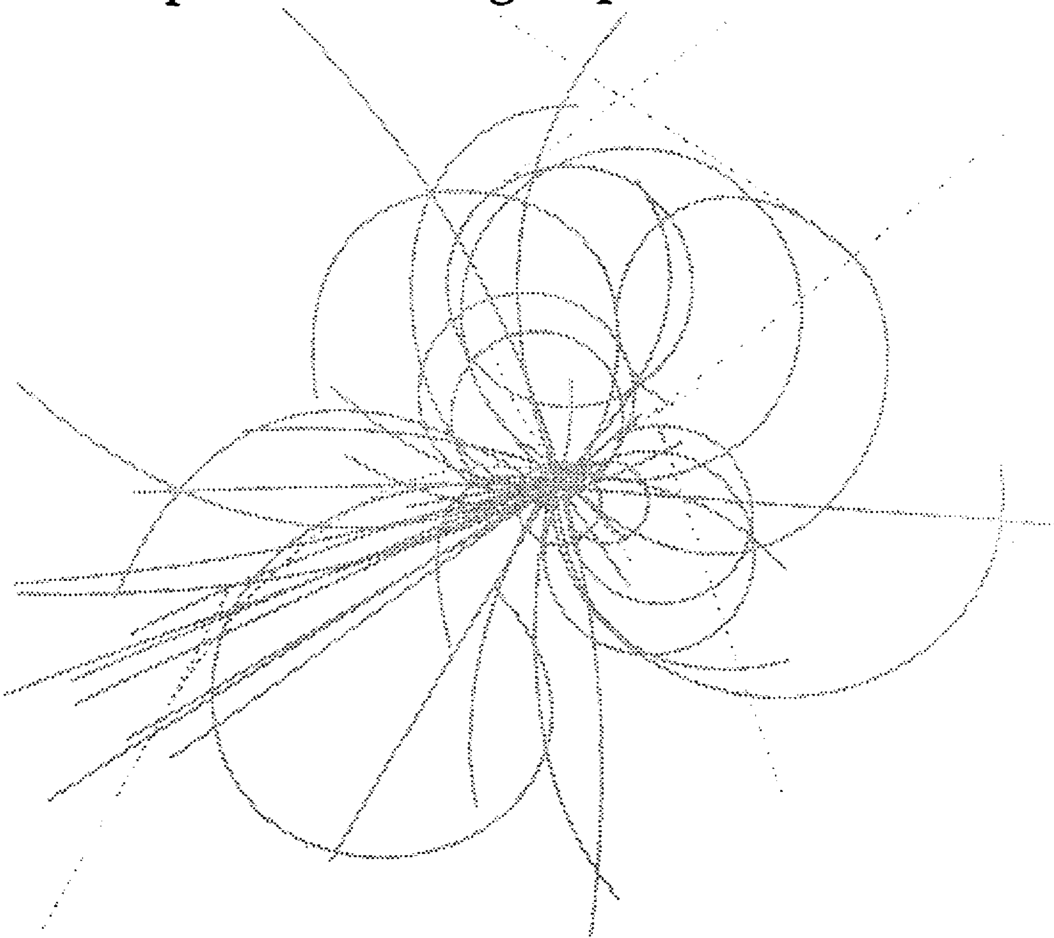

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R. Carcagno

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R. Carcagno

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

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STUDIES OF COLD PROTECTION DIODES

Ruben Carcagno

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

John Zeigler

Texas Accelerator Center
4802 Research Forest Dr., Bldg #2
The Woodlands, TX 77381

Abstract: The feasibility of a passive quench protection system for the Superconducting Supercollider (SSC) main ring magnets depends on the radiation resistance and reliability 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. Experimental and theoretical efforts have identified a commercially available diode which appears to be capable of surviving the cryogenic temperature and radiation environment of the accelerator. 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 then than the expected lifetime of the SSC itself. However, 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.

INTRODUCTION

A reliable quench protection system is essential for superconducting accelerator magnets. If a superconductor is warmed sufficiently, current no longer flows through it without resistance. The phenomenon of going from the superconductive state to the normal resistive state is called quenching. The current must be able to bypass a quenching magnet or the total stored energy of all the magnets in series can be deposited in this one magnet, producing joule heating that can easily overheat and damage the quenching magnet. Schemes

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used to bypass the current around a quenching magnet are called quench protection schemes. Quench protection schemes can be active (the quench is detected and suitable switching is performed by elements in the protection circuit), or passive (no detection is required), with current shunting occurring automatically. The SSC Conceptual Design Report[1] specified an active quench protection system, in which room temperature diodes shunt a half-cell of six magnets. This type of active, heater-assisted quench protection with warm bypass loops is utilized in the Tevatron at Fermilab, and has proved to be very effective and reliable, and it was a conservative choice for the SSC conceptual design. However, it is also mentioned in the SSC Conceptual Design Report that an alternative passive system utilizing cold diodes would be an attractive option if uncertainties concerning the voltage distribution within a quenching magnet and radiation damage to cold diodes can be solved and if it can be shown that the magnets can be passively protected without quench heaters. A passive quench protection system with cold diodes would be an attractive option because of its inherent simplicity and reduced thermal loads to the cryogenic system. It was first proposed for the ISABELLE magnets,[2] and is now being implemented at HERA.[3] One of the problems of using cold diodes for the SSC is the relatively high radiation environment expected. The literature contains very little information relevant to this application of diodes which combines cryogenic temperatures, high currents, and neutron radiation. Therefore, in order to determine the feasibility of using a passive quench protection system with cold diodes for the SSC, the SSC Central Design Group, in cooperation with the Texas Accelerator Center, has performed a series of experimental and theoretical studies on the effects of low-temperature irradiation on several commercial semiconductor power diodes. In this paper we report the results obtained and we propose what further R&D is needed.

PASSIVE QUENCH PROTECTION SYSTEM WITH COLD DIODES

The main rings of the SSC are each divided into ten independently powered circuits, or sectors. For the latest SSC conceptual design,[4] each of these sectors is approximately 8.6 km long and contains a 300 V, 6500 A power supply connected in series with 480 dipoles and 96 quadrupoles. The total sector inductance is approximately 26 H, with 1.01 MJ of energy stored in each dipole and 0.145 MJ of energy stored in each quadrupole. As shown in the simplified schematic of Figure 1, each sector also includes four 0.27 ohm dump resistors which can be inserted in series with the power supply and the magnets. If a quench is detected anywhere in the sector, these resistors are used to extract the energy stored in the remaining superconducting magnets. The resulting exponential current decay has a time constant of approximately 24 sec, much longer than the 0.52 sec required to adequately limit joule heating in the quenched magnets.[5]

The passive quench protection system proposed for the SSC uses a diode installed in parallel with each magnet to provide an automatic, fast operating bypass path around a quenched magnet. The diodes are inside the cryostat to eliminate the need for external connections and take advantage of the voltage controlled switch behavior of a diode operating in liquid helium. This characteristic, shown in Figure 2 for an ABB DS6000 diode at 5 K, requires approximately 15 V of forward bias before any significant current is conducted. During normal charging and discharging of the magnet, the inductive voltage across the diode is sufficiently low that no current flows in the bypass path. During a quench, however, 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 unit. If the magnet is self-protecting, or able to absorb its own stored energy without overheating under all quench conditions, this passive bypass circuit will safely protect the quenching magnet with no further actions such as firing heaters. After current begins to flow in the diode, the heat

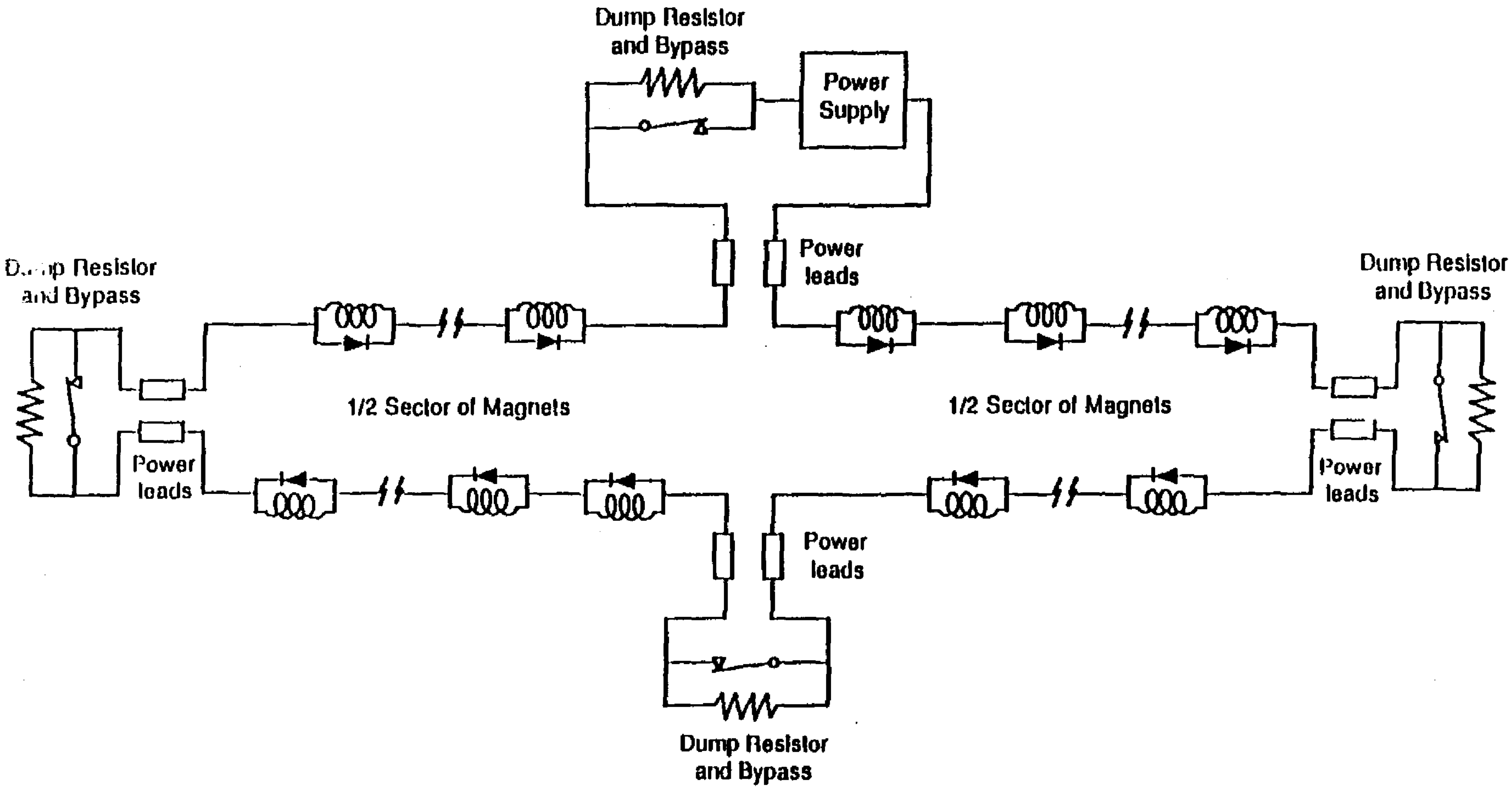

Figure 1. Simplified schematic of a passive quench protection system for one sector of the SSC.

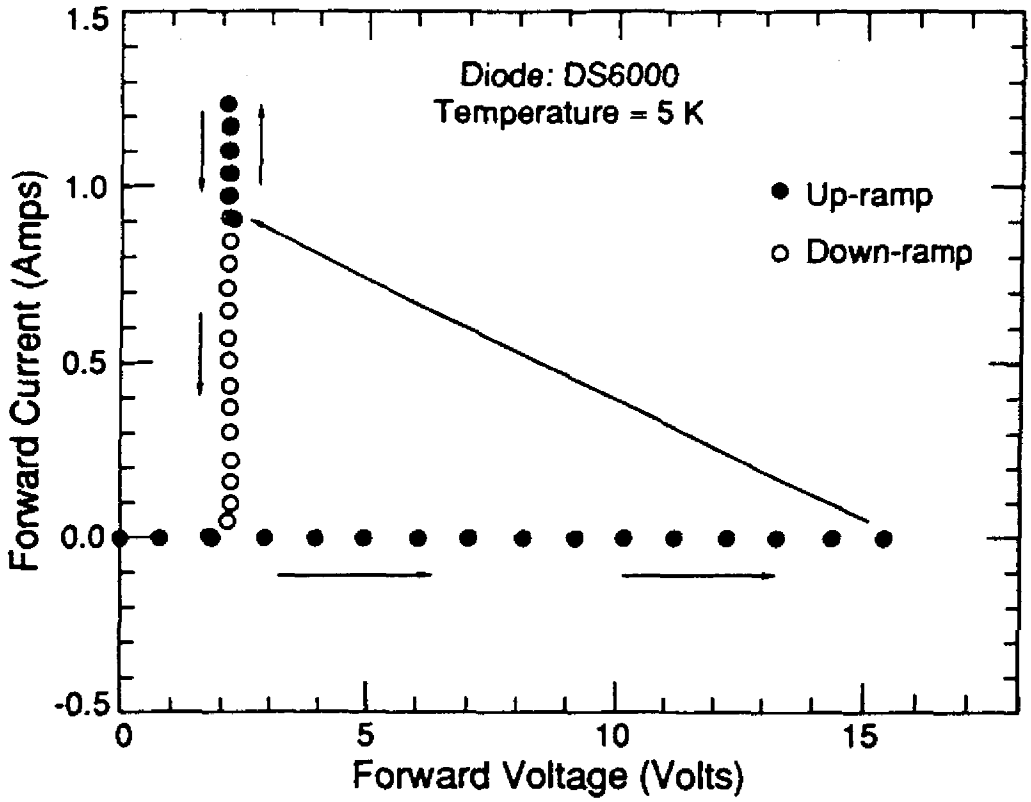

Figure 2. Switching behavior of DS6000 diode at 5 K, using a bias voltage step delay time of 1 second.

generated at the diode junction is sufficient to raise its temperature and restore a relatively normal I-V characteristic.

The large number of cold diodes required in the SSC (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 and reliability in the SSC environment. During a nominal SSC quench, the diodes would be required to conduct a 6500 A pulse with a 24 sec exponential decay.[1] Installing the diodes inside the magnet cryostat would maintain them in a liquid helium bath at a temperature of 4.35 K and subject them to a radiation level of approximately 3.2×10^{11} n/cm^2 per year.[6] This flux is produced by nuclear cascades created through beam losses and interactions with residual gas molecules in the bore tube.

RADIATION HARDNESS OF COLD DIODES

Energetic neutrons displace atoms in the lattice of the diode, increasing the forward voltage drop during conduction and therefore increasing the energy dissipation during a quench pulse. If the junction temperature exceeds a specified limit (typically 200–300° C), the diode may be permanently damaged and subsequently degrade or prohibit proper operation of the accelerator.

The majority of published radiation damage studies, including those performed in the past specifically for quench protection systems,[3,7] have been based on room temperature irradiations of semiconductor devices. In these studies, a significant level of thermal annealing, or repairing, of the radiation damage occurred simultaneously with the radiation induced defect formation. Since the annealing rate is a nonlinear function of temperature and is very small at cryogenic temperatures,[8] these results cannot be used to directly extrapolate the performance of SSC cold bypass diodes.

A series of experimental and theoretical studies have therefore been performed to evaluate the radiation hardness of commercially available power diodes under simulated SSC operating conditions. The main results of these studies will be briefly discussed below; a more thorough treatment of portions of this information and results of additional tests has previously been reported.[5,9,10]

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.[10]

Table 1. Summary of Diode Specifications

Qty	Diode	Manufacturer	I_{FRMS}	V_{RRM}	Diameter
3	DS6000	ABB Asea Brown-Boveri	15600 A	200 V	50 mm
3	DSA1508	ABB Asea 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

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 or helium. This allowed single-sided conduction cooling to either 80 K or 5 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 swimming pool type research reactor using FLIP TRIGA fuel[11] 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 attenuated the lower energy neutron flux in the cell.

IRRADIATION TESTS AT 80 K

A preliminary irradiation test was performed at 80 K to evaluate the relative radiation hardness of the five diode types shown in Table 1. This operating temperature was chosen to minimize thermal annealing effects without requiring the additional complication and expense of a liquid helium coolant system. A variety of experimental procedures were used to monitor the forward and reverse performance characteristics of the diodes as a function of exposure.[10]

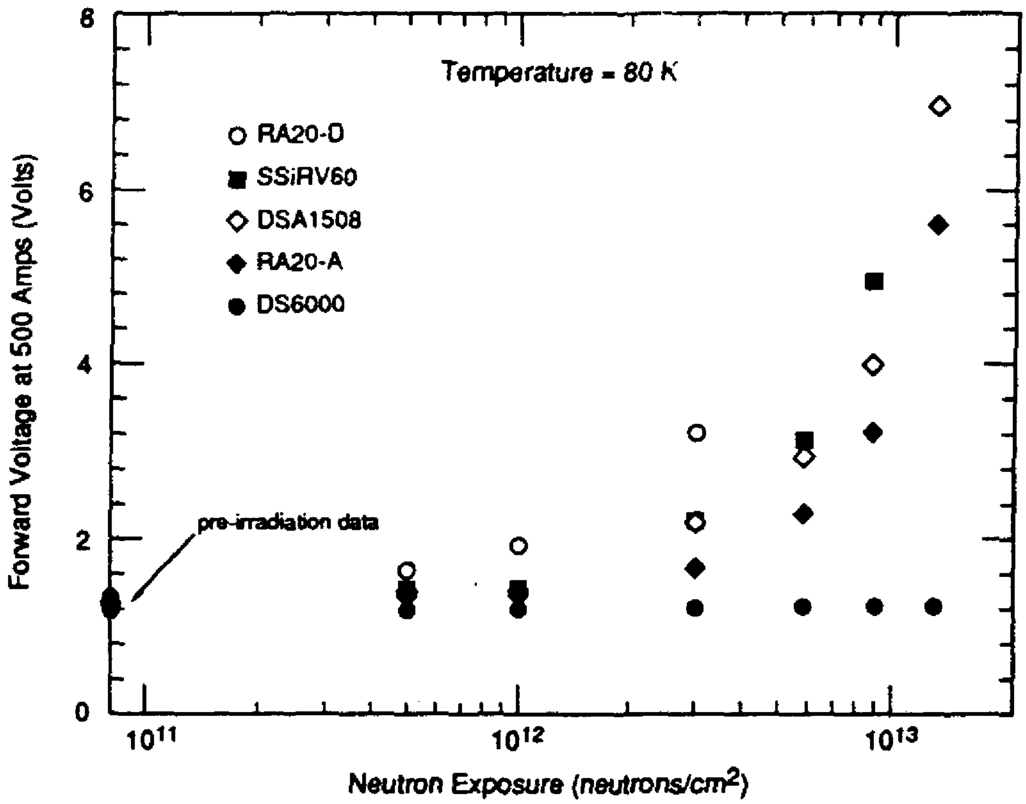

Figure 3. Forward voltage at 500 A vs. exposure for power diodes irradiated at 80 K.

The data in Figure 3 shows the change in forward voltage at a current of 500 A as a function of exposure for a representative of each diode type. One of the diode types, the ABB DS6000, showed only a 5% increase in forward voltage after the full exposure of 1.2×10^{13} n/cm^2. The four remaining diode types showed sufficient degradation by the end of the irradiation that they would have failed if subjected to an SSC quench pulse.

Annealing

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 5% increase in forward voltage while the RA-20 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 RA-20 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.

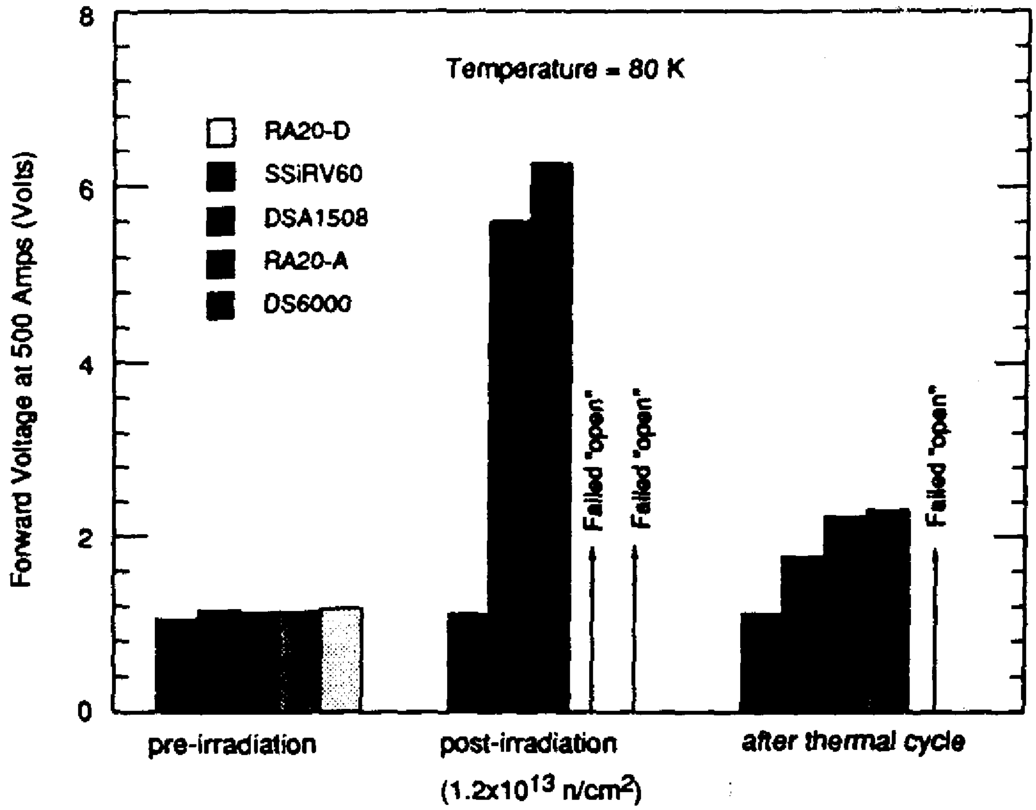

Figure 4. Forward voltage at 500 A before irradiation, after irradiation, and after thermal cycle.

The significant effect of room temperature annealing shown in Figure 4 supports the need to perform radiation damage studies at the expected irradiation temperature of 5 K.

IRRADIATION TESTS AT 5 K

The comparative irradiation test at 80 K showed the DS6000 to be the most radiation resistant of the diode types tested and indicated that it might be a suitable candidate for use as an SSC quench bypass diode. This diode type was therefore selected for further irradiation testing at 5 K to more accurately simulate the actual SSC environment.

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 sec triangular current pulse. These tests and the temperatures at which they were performed during each reactor run are summarized in Table 2.

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(5 K < T < 30)
Turn-on voltage	—	—	—	5 K	5 K	5 K

Figure 5 shows the change in forward voltage at 7000 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.

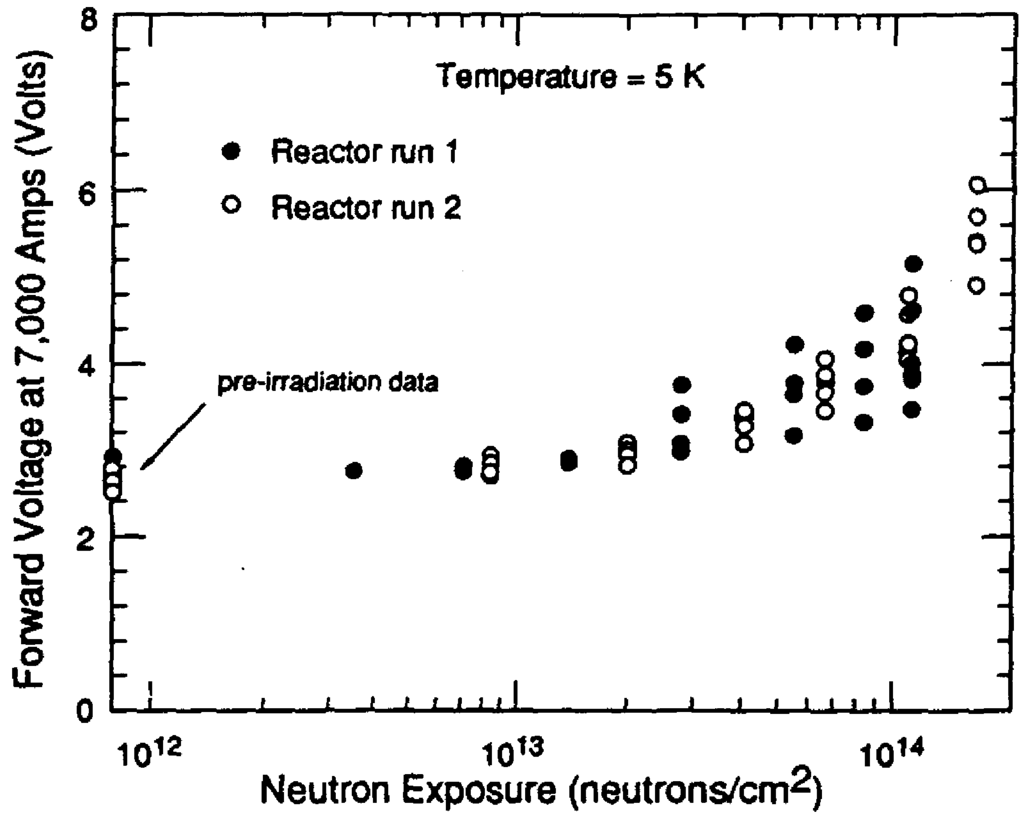

Figure 5. Forward voltage at 7000 A vs. exposure for DS6000 diodes irradiated at 5 K.

The switching behavior of a diode operating at liquid helium temperature, shown in Figure 2, was investigated in more detail during the second reactor run at 5 K. 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 6 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.

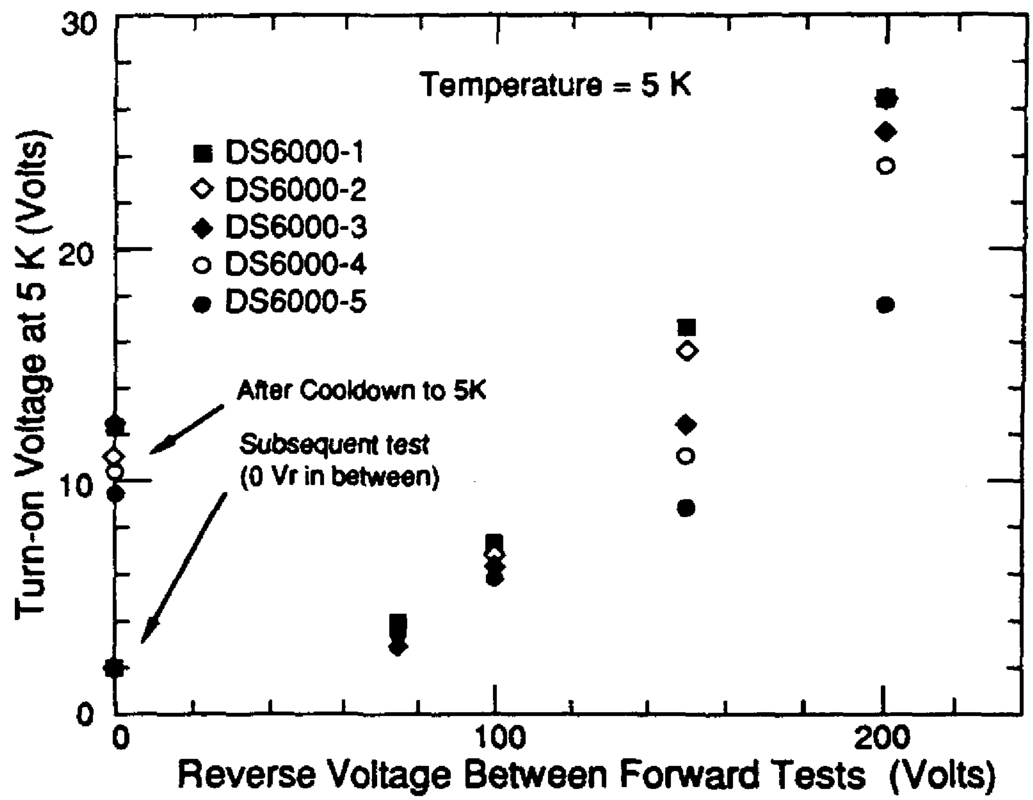

Figure 6. Turn-on voltage at 5 K vs. reverse voltage between forward tests.

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 7. 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.

THEORETICAL SIMULATIONS OF RADIATION EFFECTS

Computer simulations of the classical radiation damage mechanisms were performed and correlated to the damage observed in the diodes irradiated at 80 K.[12] These simulations were performed with SEDAN III, a one-dimensional program for the solution of differential equations governing the motion of carriers in a semiconductor material.

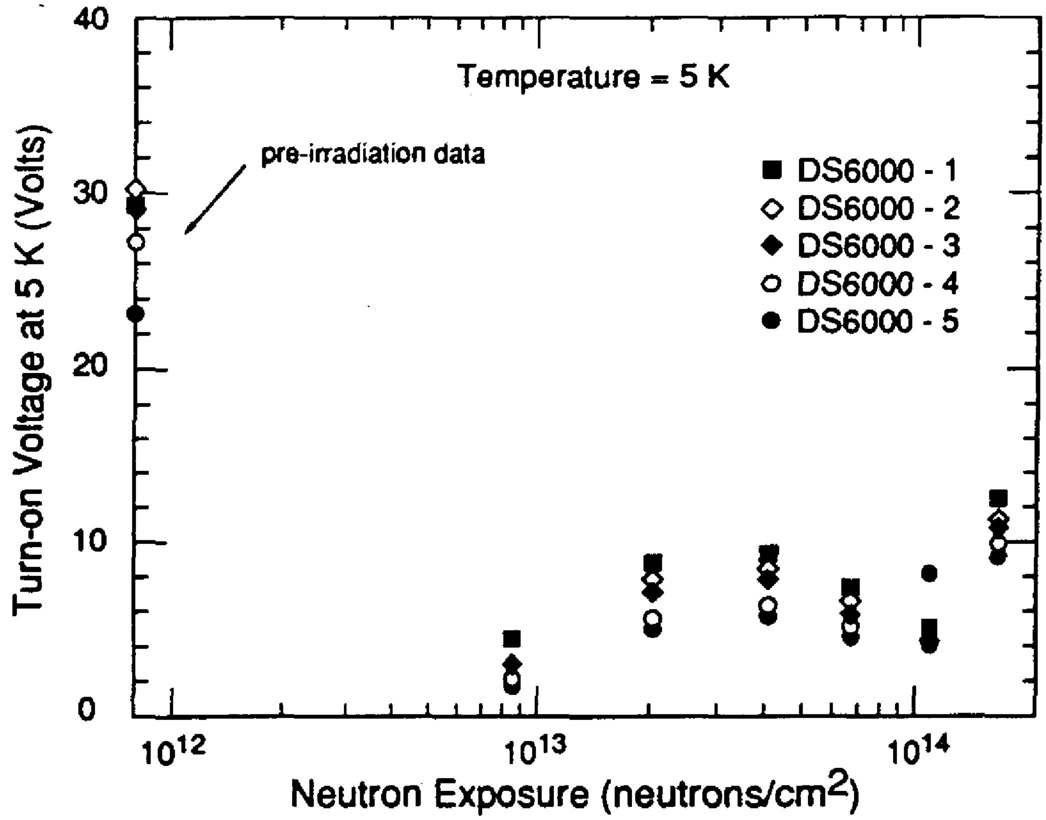

Figure 7. Turn-on voltage at 5 K vs. neutron exposure.

The theoretical simulations evaluated the relative contribution at cryogenic temperatures for the three major room temperature radiation damage mechanisms: reduction in carrier lifetime, carrier concentration, and carrier mobility. The results showed that the reduction in carrier lifetime remains the dominant damage mechanism even at cryogenic temperatures, with effects from reduced carrier concentrations only becoming significant after lifetime degradation has already rendered the diode unusable for the intended application.

The results of simulations for diodes of varying base widths were then correlated to the experimental data as shown in Figure 8. The carrier lifetimes for the experimental data points were calculated from:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + \frac{\Phi}{k_r}$$

where τ = post-irradiation carrier lifetime
τ_o = pre-irradiation carrier lifetime
Φ = neutron fluence
k_r = carrier lifetime damage constant

A single value of $k_r = 2.7 \times 10^6$ n-sec/cm^2 provided reasonable agreement between the experimental and theoretical data sets over a wide range of base widths and exposure levels.

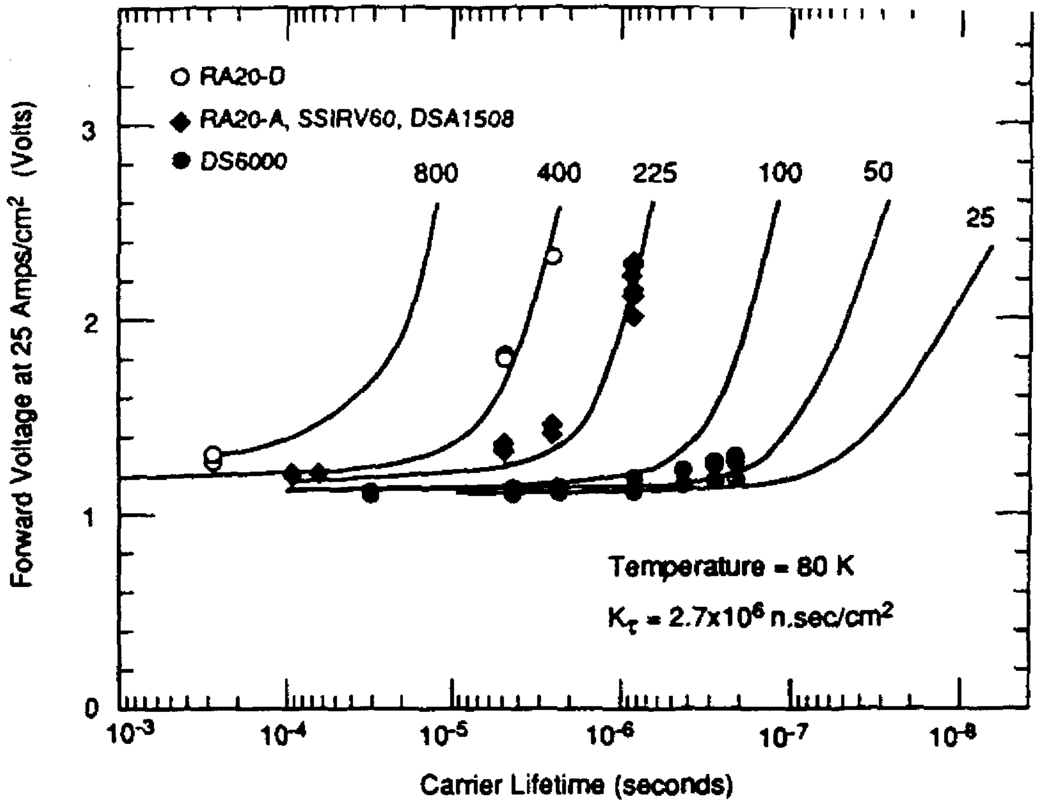

Figure 8. Forward voltage at 25 A/cm^2 vs. carrier lifetime for power diodes irradiated at 80 K. Discrete symbols are measured values; curved lines are computer simulations for diodes with the base widths labelled in microns.

A strong relationship between base width and radiation hardness is apparent in both the theoretical and experimental data. Proper diode performance in the high injection regime requires that the majority of the injected carriers traverse the full width of the base region before recombining. As radiation damage reduces the carrier lifetime, the number of carriers traversing the base is reduced and the voltage required to support the current is increased. Therefore, a diode with a narrow base width, and consequently shorter base transit times, will appear more radiation resistant than a thicker diode. However, the reverse blocking voltage capability of the diode is proportional to base width and may impose a severe constraint for a radiation resistant diode if blocking voltages greater than 100-200 V are needed.

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.[13] This model includes the temperature dependence of 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 temperature, 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 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:

$$T_j\,(\max) = 170 \times VF(80\ K) - 221$$

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 temperature coefficient measurements as a function of temperature,[9] a 77% increase in forward voltage at 80 K should roughly correspond to a 77% increase in forward voltage at 5 K. From Figure 5, 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.

RELIABILITY OF COLD DIODES

The only reliability information available for diodes actually operating under SSC type conditions is a result of experiments performed at DESY using standard DS6000 diodes in modified packages.[14] In these tests, 1250 of diodes were cooled to 4 K and subjected to 19 high current pulses very similar to those expected in the SSC. Only four diodes were destroyed during forward current tests.

CONCLUSIONS

The experimental results show that the ABB DS6000 diode is significantly more radiation resistant than the other four types of diodes tested, and theoretical simulations have shown that this diode is more radiation resistant than the others because of its thinner base width. The lifetime of the DS6000 in the SSC radiation environment has been estimated 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.

The relatively narrow base width of the DS6000 contributes to its radiation resistance. However, a narrow base width could be also a limitation if multiple diodes and internal taps in the magnets are required, because in this case the reverse voltage across individual diodes could exceed the rating of the DS6000. If a single diode is used to bypass each magnet, the DS6000 easily meets the maximum applied reverse voltage requirement of 20 V.

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 cold diodes in the SSC.

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 cycle, 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.

If the SSC magnets are self-protecting, a passive quench protection scheme using one cold bypass diode is an attractive option because of its inherent simplicity and reduced thermal loads to the cryogenic system. The theoretical and experimental results presented here suggest that using cold diodes is a feasible option for the SSC. However, further studies should be performed in the areas of optimum mechanical design of the diode holder, experimental and theoretical studies of turn-on voltage behavior, and reliability studies with statistically meaningful sample sizes of the DS6000 diode including all possible stress factors.

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